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Review

Assessing the sustainability of livestock socio-ecosystems in the drylands through a set of indicators

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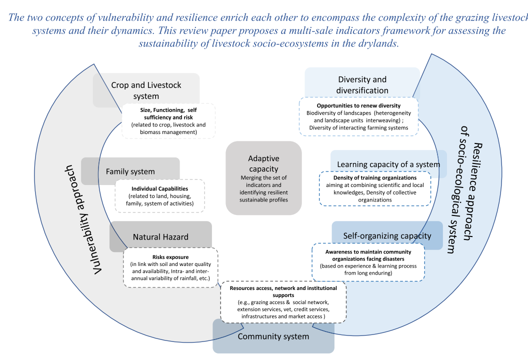
HIGHLIGHTS

- Assessment of livestock sustainability is facing a challenge of contextuality and scale.
- The review presents a set of sustainability assessment frameworks applied in grazing livestock farming systems (GLFS).
- The review compiles a set of indicators to inform the processes of assessing the sustainability of grazing livestock systems.
- It is proposed an integrated framework combining spatial, temporal, and social scales to address the sustainability of GLFS

GRAPHICAL ABSTRACT



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ABSTRACT

Analyzing the sustainability of grazing livestock farming systems in the drylands at the farm and household or territorial levels (in terms of food security, well-being, value chain performance, feed supply, and maintenance of common grazing resources) constitutes a major challenge in the context of global changes. In particular, social–natural interdependency in an entanglement of spatial and temporal scales complicates the development of a common and systematic framework for assessing the sustainability of these grazing livestock systems. Our objective is to give an overview of some fundamental sets of indicators usually used and elaborate on some principles to guide the sustainable assessment of grazing livestock systems in drylands. To do so, this paper reviews a set of empirical, theoretical, and methodological studies related to the analysis of risk, adaptability, vulnerability, resilience, and sustainability of livestock systems in drylands based on grazing (mostly pastoral systems, but also some integrated crop-livestock systems). More concretely, this review seeks to compile a set of indicators to inform the processes of assessing the sustainability of livestock socio-ecosystems.

It points to the wide range of approaches that have been used to address the sustainability of grazing livestock systems, ranging from those that focus on ecological or social approaches to more integrated and systemic approaches; from indicator-based approaches to those focusing on processes; from quantitative approaches to those

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that point out the need to take qualitative aspects into consideration; and from research-based assessments to participatory approaches. Based on this review, we propose a multi-scale indicators framework combining scales of space, time, and coordination to address the sustainability of these livestock systems. This framework aims to constitute a sound basis for elaborating a system of information that will contribute to and support policymakers and development agencies in developing their policies and measurements in order to ensure the sustainable development of pastoral and agropastoral systems in the short and medium-term. However, this study also warns about the multiple contextual scopes of the indicators and their implications, which reveal differing dynamics (and therefore adaptive capacities) of these systems.

1. Introduction

Analyzing grazing livestock farming systems' (GLFSs) sustainability in the drylands raises multiple challenges in the context of global changes. Among these challenges we can cite food security, purchasing power, and social status at the farm and household level; and local food security, value chain performance, employment, and preservation of natural resources at the local and regional level. These dryland systems cover more than 47% of the world's land surface and 39% of the world's population (Koutroulis, 2019), who derive their primary source of livelihood from the breeding activity, and about 13% of these drylands are already degraded (Burrell et al., 2020). The most characteristic systems are the pastoral and agropastoral systems in arid and semiarid areas based on feed grazing accompanied by herd mobility (Neely et al., 2009). Several recent research studies have established the comparative advantage of these grazing livestock systems, notably in facing global environmental challenges related to methane emission and other greenhouse gas emissions (Vigne et al., 2013; Manzano and White, 2019) and carbon sequestration (Reid et al., 2004). Overall these systems are considered the most sustainable systems in these constrained and fragile environments, as shown by Behnke (1994), Thébaud and Batterbury (2001), and recently by Nori and Farinella (2021). However, due to increasing aridity and flood events coupled with increasing animal pressure in some locations, these dryland zones show a dramatic trend of soil and biodiversity degradation that affects the primary resources of the GLFSs.

In the present research, we propose to review and analyze the approaches to assess the sustainability of GLFSs based on how the global changes threaten the actual functioning of GLFSs and trigger their capacities to adapt to external shocks. In this perspective, vulnerability and resilience concepts have opened vast research areas to address the adaptive capacity of GLFSs to changes, especially to climate change. We can see that the sustainability of a farm system is not only a matter of duration; it is also characterized by its ability to change and adapt (Folke et al., 2010; Vermeulen et al., 2018; Meuwissen et al., 2019). However, in the GLFSs, interdependencies between social and natural system components are usually diverse, often rooted in the locality. Therefore, applications of both concepts – vulnerability and resilience – need to take account of context (such as scale and specificity of the farming systems, among others) (Scoones, 1998; Berkes and Folke, 1998; Ellis and Swift, 1988; Ellis and Mdoe, 2003; Haddad et al., 2021). Within each socio-ecosystem, we can also observe feedback effects between the socioeconomic and ecological processes; for example, (agro)pastoralists, through their livestock management, can affect the resources that will impact their livelihoods. Moreover, the sustainability of GLFSs depends on various social and environmental resources that extend beyond the current well-defined agricultural systems at the local level and that can induce structural shifts of the production systems in unexpected ways (Scoones et al., 2020).

This social–natural interdependency in an entanglement of spatial and temporal scales makes the development of a standard and systematic framework for the sustainability assessment of GLFSs tricky. This complexity of scales and challenges creates a lot of confusion and, consequently, calls into question the development of an evidence-based assessment analysis for policymakers to implement coherent measures. Research has highlighted the issues of (im)balance between livestock management and resource use at the interaction between agronomy and ecology. Some major challenges are soil and biodiversity degradation at the local or regional level and the effects on methane emissions at the global level (see the IDEA Method in Zahm et al., 2008). In socioeconomic science, we can see the emergence of several integrated frameworks to address adaptative capacities focusing either on multi-criteria approaches (Carof et al., 2013; Alary et al., 2020) or comprehensive system approaches (Darnhofer, 2014; Meuwissen et al., 2019). These works refer directly or indirectly to the conceptual approaches widely developed by the Resilience Alliance (2010) and Stockholm Resilience Centre (2014) community. Other research proposed operationalizes frameworks to assess the socioeconomic or environmental sustainability and discuss sustainable development pathways (see the LSIPT toolkit presented in Dutilly et al., 2020 or GLEAM tool presented in FAO, 2018a). These toolkits attempt to gather a set of indicators usually used when characterizing these livestock systems. However, while all these approaches attempt to reconcile many indicators, the nature of the indicators and their arrangements and combinations raise complex issues of scale and aggregation when addressing grazing livestock systems and their sustainability. Our objective is to review and analyze some fundamental sets of indicators usually used and elaborate on some principles to guide the sustainable assessment of grazing livestock systems in drylands. Here we will focus on the socioeconomic sustainability of GLFSs.

In the present paper, we thus propose to revisit a set of empirical studies focusing on the sustainability assessment of GLFSs in drylands by pinpointing a list of pertinent indicators that constitute the basis of the analysis (part 3). Furthermore, these indicators have often been operationalized by referring to the conceptual frameworks of vulnerability and resilience (parts 4.1 and 4.2). From this review, we propose to derive a guideline for use when establishing and combining the indicators at different scales (part 4.3), discussed in the last section (part 5).

2. Materials and methods

Before starting our present review on the sustainability assessment of GLFSs in drylands, we have revisited the different concepts of vulnerability, resilience, and adaptive capacity that constitute the pillars of the sustainability of socio-ecological systems. Our central hypothesis was that vulnerability and resilience provide a sound conceptual background to analyze risk management and sustainability of livestock systems in uncertain environments, especially for grazing ruminant systems. Vulnerability is related to the capacity of addressing and managing exposure to risk in the short and medium-term (Adger, 2006). At the same time, resilience refers to the adaptive capacity of the whole ecosystem in the medium and long term (Berkes and Folke, 1998; Folke et al., 2010; Resilience Alliance, 2010). Both concepts historically mobilize different time horizons, spatial scales, and disciplines. Still, when considering more social dimensions, they become intimately linked to addressing the socio-ecological systems' adaptive capacity and sustainability. Moreover, vulnerability and resilience overlay a complex and multidisciplinary field of study.

In the first part of the review, we focused our search on specific literature related to pastoral and grazing livestock systems on one hand (part 3.1) as well as on rural and agricultural economies with additional insights from ecology and political geography on the other (parts 3.2. and 3.4). The selection of papers resulted from online research using keywords, highly cited references, or scientific articles that have done synthetic work on one of these domains. We mainly mobilized Google scholar and Scopus search engines. The search focused on arid and semiarid areas of the dryland regions, characterized mostly by low rainfall, high temperature, and high evapotranspiration, with a main (but not solely) focus on studies from North and South Mediterranean countries and sub-Saharan African countries. In these drylands, grazing livestock systems are dominant livestock systems with seasonal or annual mobility as a part of the living mode. The animal species are sheep, goats, and cattle in the semiarid zone, with camels in the arid areas. Fig. 1 represents the bibliography path through keywords and authors. In total, 66 papers have been selected in the review on GLFS sustainability, with an average citation rate of 375 per paper (based on Google scholar statistics in January 2022). We compiled the list of indicators as we read the articles. In a first step, we systematically listed the indicators as soon as they were new during our review; this inventory was made according to the different organizational and spatial scales (from the farm system to the local or regional level). In a second step, we selected the most-cited indicators for each considered scale. We finally chose the references which provided sufficient details on the considered indicators.

In the second part of the review, we focused on how the concepts of vulnerability and resilience have been mobilized and formalized to understand the social dynamics with the grazing livestock practices and the level of sustainability of the GLFSs. Additional references have been thus selected based on their contribution to laying the foundations of the concepts of vulnerability and resilience. We first proposed a brief synthesis of the conceptual frames related to vulnerability and resilience. This synthesis mobilized ten references that recorded a high citation level (a citation rate of 2142 per article). This review led to a rich literature of empirical works. In section 4.2, we selected seven references that allowed us to link the conceptual and operationalized framework on the sustainability approach of GLFSs (with a citation rate of 163 on average). The proposed multi-scale indicators framework in part 4.3 was thus generated from bibliography review (already presented in parts 3 and 4) on these recent research works. 13 references have been mobilized with a scoring citation rate of 822 on average (from google Scholar statistics, January 2022). Fig. 1 represents the overall search path under a mind map with the principal combinations we searched for.

3. Review of pinpointing indicators to analyze grazing livestock farming system sustainability

Research has strongly invested in ecological and social approaches by considering the ecosystem's bio- and socio-complexity and diversity

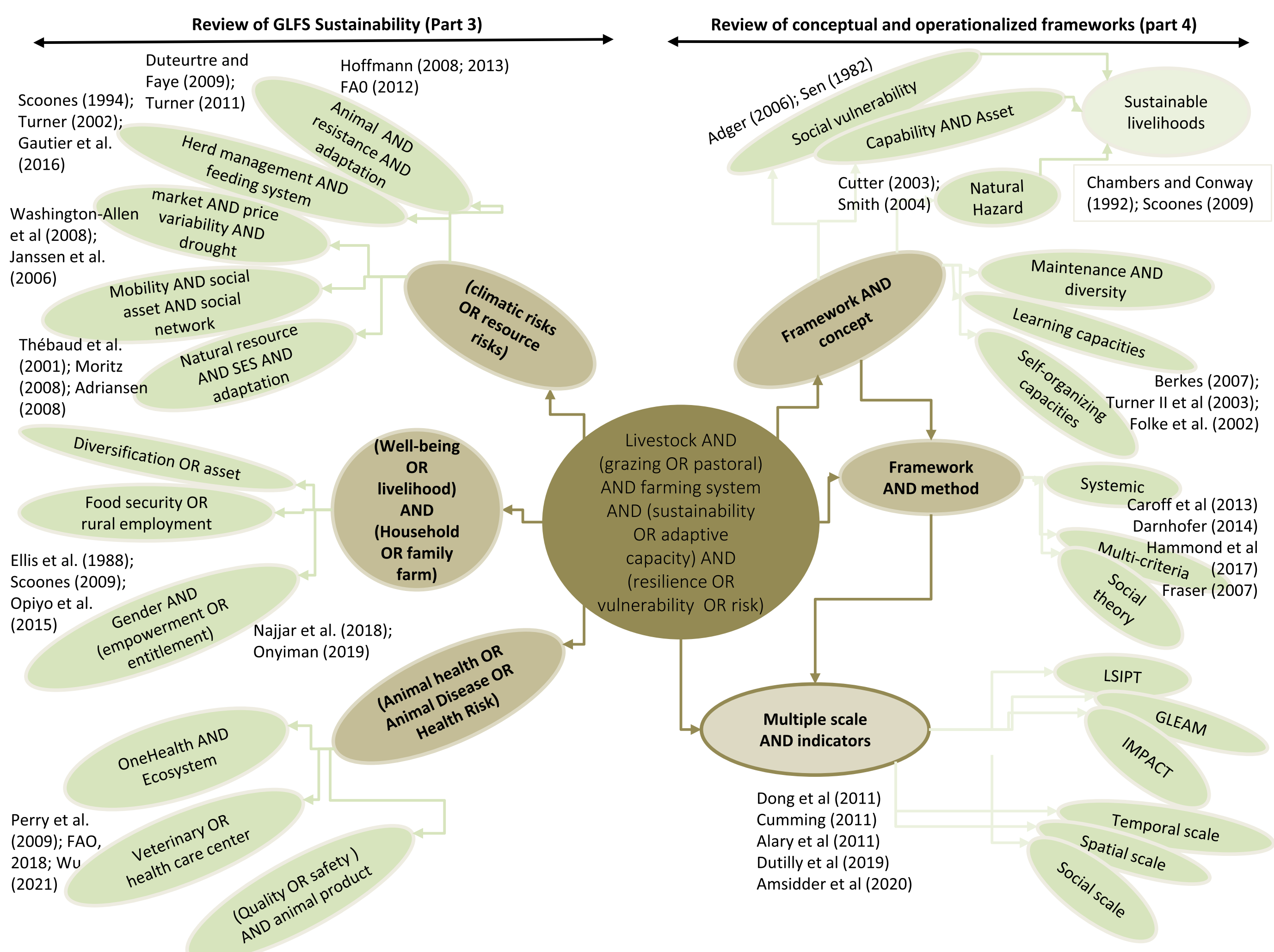

Fig. 1. The methodological approach of the bibliography review on GLFS sustainability (the link represented by an arrow corresponds to a liaison 'AND' in the review)(Cutter et al., 2003; Sen, 1982; Smith, 2004).

in approaching GLFS sustainability. The present review reveals the different sets and scales of indicators mobilized to understand the adaptive mechanisms of people faced with the significant risks and uncertainties regarding GLFSs in drylands. We proposed to address the natural (climate), agronomic (resource-use), socioeconomic, and health risks successively.

3.1. Livestock and risks related to climate and resources

Research on GLFS sustainability in drylands has long highlighted a set of capacities of adaptation of breeders to changes, particularly to the prevailing climate-related risks in dryland areas. We can cite the works focusing on connections with the physiology of the animal capital (biological rhythm, relative resistance to extreme conditions according to animal species and breed) (Homann et al., 2008; Hoffmann, 2008; Hoffmann, 2013) and the link of livestock management with society and space (Gallais, 1977; Thornton et al., 2007; Duteurtre and Faye, 2009). Indeed, we can see an increasing interest in local breeds due to the overall climate changes in these arid and semiarid zones and the dramatic forecast in terms of increasing temperature and water scarcity. This research focuses on identifying and characterizing the multiple functions of adaptation of local breeds to resource scarcity (for example, Hoffmann, 2010; FAO, 2012; Qian et al., 2013; Flori et al., 2019). From a socioeconomic perspective at the family level, because pastoral-based societies are regularly subject to climatic stresses such as droughts, they usually maintain multi-species herds and capitalize on breeding females in good years to cope with drought events as long as possible (see Duteurtre and Faye, 2009; Turner, 2011; Richard et al., 2019).

In African contexts, some research work also highlights the contribution of animal transfer (generational and community transfer, *confiage*, inheritance, dowry, etc.) to reduce uncertainties. This practice allows diversifying external risks by exploring spatial and social diversity through mobility (Thébaud and Batterbury, 2001; McCarthy and Di Gregorio, 2007; Moritz, 2008; Adriansen, 2008; Alary et al., 2011). Furthermore, these transfers of animals also allow coping with multiple risks in different locations and reinforce social networks to address present or future climate-related risks.

However, pastoralists' responses to external shocks, including droughts, are influenced by public support measures. State-sponsored storage or destocking (via grain subsidies or livestock pricing policies) often lead to new balances (sometimes imbalances) in the human-environment system (Scoones, 1994). Turner (2002) and Gautier et al. (2016) also highlight the role and functioning of rural markets (access and distance to the market, price of trading, and advance/debt system in negotiation) that influence livestock management faced with a shock. If livestock markets can play an important role in adjusting animal stocks to the resource base subject to natural hazards (Fafchamps and Minten, 1998), some empirical studies show imbalanced terms of trade between livestock and grain during periods of drought (Swinton, 1988).

Based on these various empirical works, different authors have adapted or used the livelihood framework to approach the role of livestock as a means of survival in arid and semiarid areas faced with dramatic events like droughts (Ellis and Swift, 1988; Scoones, 2009; Nori et al., 2009). Recently, the resilience of (agro)pastoralist societies has been more and more sought in their ability to mobilize their social networks and their ability to explore spatial variability via mobility and the diversification of income (Opiyo et al., 2015; Gonin and Gautier, 2016; Vigan et al., 2017). From the different research works applied to GLFSs' adaptation to climate change, we can derive a set of common indicators used to characterize the degree of vulnerability or resilience – the two faces of a common goal of adaptation to climate change – of GLFSs, summarized in Table 1.

However, interactions between livestock farming and natural resources (soil, water) through the feeding and grazing system vary in different livestock systems due to farmers' diverse livelihood strategies (including livestock- or crop-focused livelihoods) and types of available biomass resources. Hence, it is difficult to understand the strategies of livestock breeders without considering the whole natural and agricultural-based system, including space and social relationships within and between pastoral and agricultural communities. Therefore, many researchers have searched for ways of encompassing the land resources and social systems beyond the farm (for example, Bodin and Tengo, 2012; Villamor and Badmos, 2015; Linstädter et al., 2016). Ecosystem resilience and pastoral activities are regularly mentioned in these works, often jointly when dealing with the different natural or social risks.

Table 1
List of indicators used in assessing grazing livestock farming systems' sustainability faced with resource scarcity and variability.

Domain	General indicators	Indicators (unit)	Sources
Herd level	Herd size (asset)	Animal species count	Mace and Houston, 1989; Mace, 1990; Sieff, 1999; Nozières et al., 2011; Hoffmann et al., 2008; Alary et al., 2020
	Species composition (intra-herd diversity)	Animal count per species and physiological stage	
	Animal breed composition	Count of animal breeds per species	
	Capacity of renewal after destocking	Percentage of reproductive females in the herd	
Feeding system level	Pastureland grazing period (in months)	Count of grazing months per year	Seré and Steinfeld, 1996; Dougill et al., 2010
	Grazing fees	Annual cost of range grazing access	
	Crop residues grazing period out of the farm (in months)	Count of grazing months in croplands	
	Crop residues' contractual arrangement	Cost of crop residues grazing access	
	Feed storage	Months of feed autonomy with the feedstock	
	Forage system (in the cropping system)	Percentage of the area in green fodder and grain crops for animals in the cultivated area	
Animal transaction	Seasonal and annual animal sale and purchase	Count of animals sold/purchased	Lopez-Ridaura, 2005; Eakin, 1995; Cecchi et al., 2010; Ellis and Mdoe, 2003
	Market place (and distance)	Distance to market in km	
	Price variability (ratio livestock–grain price) and subsidies	Ratio meat price (kg) compared to grain price (kg)	
Social networks	Animals loaned/received	Counts of animals given and received	Thébaud and Batterbury, 2001; Moritz, 2006, 2008; McCarthy and Di Gregorio, 2007; Adriansen, 2008
	Animal transfers in inheritance, dowry, or marital arrangements	Counts of animals exchanged per transfer arrangement	
Pastoral mobility management	Mobility duration and distance	Months in mobility (or km)	Amsidder et al., 2021
	Water access in pasturelands	Water fees or water availability	
	Keeping management (external worker or family)	External workers (shepherds) in months per year	
	Moving alone or with another flock (in interaction with the social network)	Count of animals in the moving flock and count of livestock owners in the moving flock	

Going further, when addressing resource-related risks, some researchers refer to the concept of complex adaptive systems for analyzing the co-evolution between pastoral activities and resources from a socio-ecological system resilience perspective (Gunderson and Holling, 2002). For instance, applying this to Australian pastoralism, McAllister et al. (2006) describe the overall system evolving between four reference-states of the adaptation process: growth, conservation, release, and reorganization. Other studies pay more attention to the mechanisms of adaptation and the adaptive capacity of social systems (such as institutions) to learn and adapt in response to disturbances (Folke et al., 2005). These approaches allow us to characterize the changes of 'identity' of the socio-ecological system and chronicle the key events. They, therefore, shed light on the mechanisms of co-evolution between pastoral activities and the whole socio-ecological system, as well as pathways. For that, case studies mobilize a set of ecological and social indicators that are summarized in the research works of Washington-Allen et al. (2008) and Janssen and Ostrom (2006) (see Table 2).

Combining the indicators usually collected at the family farm level (Table 1) and at the community or local/regional level (Table 2) allows us to address the different spatial and social scales of resource management of the grazing livestock system. However, the overall adaptive capacity of herders needs to consider the other agricultural and non-agricultural alternatives to herding.

Table 2
Ecological and social indicators for assessing grazing livestock farming systems.

Domain	Type of indicator	Definition of indicator	Example metrics
Ecological indicators (from Washington-Allen et al., 2008)	Inertia	Resistance to change	Level of grazing pressure (carry capacity) that affects changes in percentage of vegetation cover (counts of animals per grazing area unit)
	Elasticity	Restoration period to recover a reference state after a disturbance	Months needed to return to a percentage of plant cover (e.g., 70% plant cover)
	Amplitude	Magnitude of changes from the initial state to the end of the disturbance	Amount of reduction in plant cover from initial conditions and after a disturbance (e.g., a drought)
	Hysteresis	Extent to which the restoration path is an exact reversal of the degradation path	Recovery period to reference conditions compared to the disturbance period (in months or years)
	Malleability	Extent to which the state established after a disturbance differs from the original state	Percentage of vegetation cover before drought compared to that after drought
	Damping	Model of the oscillations of a component of the system after a disruption of the ecosystem	Variation in the vegetation cover (or biodiversity) after a disturbance (counts of plant species)
Social indicators (from Janssen and Ostrom, 2006)	Connections	Density of links within the network	Number of contacts divided by the maximum possible number of links in the studied population
	Accessibility	Extent of the social network	Accessibility between each network node (category of stakeholders)
	Centrality	Distribution of the links between the nodules and the structure in space	Position of each actor within the social network (distance to the nodes)

3.2. Livestock and risks related to economic and social well-being

If livestock is widely recognized as an essential factor to cope with climate- and resource-related risks in arid and semiarid zones, rearing livestock is also a way for small-scale family farms to adapt to the different types of uncertainties they face, such as climate variability but also land fragmentation and crop price fluctuations, or extra unforeseen or substantial family expenses (in connection with family events such as marriages, deaths, or health problems). In 2009, 70% of the poorest people in the world were partially dependent on livestock for their livelihoods (FAO, 2009). The role of livestock to face shocks is embedded in the multitude of livestock activity products and services like milk and meat production for family self-consumption; exchange or sale for ensuring purchasing power or means to invest in transport and labor; and saving for investment or a safety net. Moreover, in very densely populated areas, farmers tend to develop small grazing livestock activities to diversify their incomes and adapt to increasing land constraints, as was observed in Egypt (Alary et al., 2015). In these arid and semiarid areas, therefore, livestock is often the last productive asset during prolonged droughts before the definitive or temporary rural exodus.

Of course, the degree of vulnerability of farmers or the ability of farmers to cope with one or more shocks will depend on their initial animal capital endowments, but also the potential and opportunities allowed by on- and off-farm diversification and the accompanying measures in and out of the community. Addressing the sustainability of GLFSs needs to consider pluri-activities as structural and functional components of livestock systems' sustainability, including for nomadic populations wrongly known for an exclusive pastoral model – for instance, as shown by Santoir (1994) in sub-Saharan Africa countries and Sandron (1998) in North Africa. Considering the potential or current activity diversification in these systems, some authors have shown that livestock activity can be a fallback activity in the case of non-success, and vice versa: non-agricultural activities can be a means of capitalizing on livestock as a stepping stone to a new life cycle (Santoir, 1994). Hence, the initial animal capital endowment and the on- and off-farm diversification constitute interrelated key indicators for understanding the capacity of breeders' societies to survive in harsh environments like arid and semiarid areas of Saharan and sub-Saharan countries, or the capacity of agricultural societies to sustain themselves in very dense agricultural zones.

On- and off-farm diversification is linked to the external environment, including the market, infrastructure, and formal or informal institutions that condition the opportunities in terms of accessibility and conditions for this diversification. Among institutions, we can cite access to credit, community facilities like schools, health care centers, and also extension agricultural services.

Over the last two decades, the literature has highlighted the valuable role of livestock as a means of women's empowerment through livestock accumulation and livestock production (Bassett and Turner, 2007; Flintan, 2008; Galiè et al., 2019). Onyima (2019) highlight the significant contributions of pastoral women economically involved in livestock activities like herding or indirect complementary activities – "milking, processing, and sale of dairy products (cheese, butter, and milk), crop farming, petty trading, skin/leather works, extracting rangeland products like firewood, and charcoal, among others". Najjar et al. (2018) show how this activity can be a footbridge allowing their economic involvement and empowerment.

From these various socioeconomic approaches, a set of indicators is commonly used to address the role of livestock in household viability at different time scales (Alary et al., 2019, 2020). In the same line, the LSIPT toolkit (Dutilly et al., 2020) proposes a set of indicators addressing conjointly the income diversification, food security, and family employment generated by livestock activity, to which we can add more specific indicators related to women's empowerment (for example, from Najjar et al., 2018). All of these indicators are summarized in Table 3.

This set of indicators allows us to capture the resilience of a farm family-based grazing system over time by considering the short-term viability (in terms of incomes and food security), pluriannual viability (related to the trade-offs and diversification of activities faced with shocks), and intergenerational viability (related to the transmissibility of assets). We suppose that the viability assessment at the farm level needs to also consider the community facilities and institutions at the community or local level.

3.3. Livestock and risks related to animal disease

Among the shocks and stresses related to grazing livestock systems, animal diseases (and especially epidemics or pandemics) are often cited as high risks that expose households and herders to poverty as direct or indirect effects (FAO, 2018). The main weaknesses of pastoral systems facing animal disease-related risks are of two orders: the natural risks of contracting multiple diseases linked with mobility; and the social and institutional risks of not getting health care support in time due to the remoteness and sometimes the non-capacity of veterinary services to intervene.

However, each disease acts differently on animals' metabolism and can have different socioeconomic consequences. Three main types of impact can be distinguished: (i) diseases that threaten household assets through increased mortality, like Newcastle disease and rinderpest; (ii) diseases that threaten consumers, like food-borne diseases caused by pathogenic microorganisms (bacteria, viruses, parasites) that contaminate animal products; and (iii) diseases that hinder the process of intensification of animal production systems, like vector-borne diseases, parasitism, and bacterial and viral diseases (Perry and Grace, 2009). Diseases can also modify certain functions of animals that are very useful for poor households, such as maintaining fertility in cultivated fields through pasturing of crops residues, or the use of animal traction for transport or land preparation. Finally, zoonotic diseases like Rift Valley fever and avian influenza can also have dramatic effects on human health. All these types of diseases affect the functions of the market, either through the quality and safety of animal products or the quantity due to massive mortality.

Studying this vulnerability calls for assessing and measuring the effectiveness, availability, and accessibility of veterinary and health services, in order to select interventions that have an effective capacity to reduce the global impact of diseases. We consider services provided to poor producers as part of the social network (safety net) that protects them. Different indicators illustrating the services' availability and access are proposed in Table 4. Furthermore, services should also be examined in terms of capacity, such as activity and impact on herd health and household well-being, to provide a better sense of the context of health risks.

Recently, faced with global changes that notably include increasing deforestation and urbanization and the subsequent growing interactions between animal and human health, we can see the extension of the socio-ecological systems approach to animal health through the One Health concept (The World Bank, 2010; Roger et al., 2016). The recent COVID-19 pandemic generated relevant evidence on the interrelated effects between animal and human health and the environment (Wu, 2021; Soga et al., 2021). The pandemic also revealed the effects of human disease on livestock management and production due to the reduction of labor input, the need to cover health care, or the interruption of public health services during the lockdown (FAO, 2020).

Through the sets of indicators according to these three perspectives, this review of the literature on GLFS sustainability in dryland areas highlights how difficult it is to address the issues of adaptive capacity of these livestock systems without considering the diversification of assets at the farm level; their multitude of arrangements in relation to the natural and social environment at different scales; and disasters related to climate change or disease. This entanglement of risks and uncertainties justifies the increasing importance of integrated, conceptualized, and operationalized frameworks in a holistic perspective to address GLFS sustainability.

4. Operationalized frameworks to address the sustainability of grazing livestock farming systems

4.1. Brief review of conceptual frameworks related to integrative approaches

In the vulnerability body of literature in the social science, notably in link with the approaches on assets and entitlements' constraints and opportunities, the Sustainable Livelihood Framework (such as presented by Chambers and Conway, 1992; Scoones, 2009) provides a set of quantitative and qualitative indicators that range from resource endowment to resource use and pass through the means and rights of access to these resources. Overall, the global frame of the Sustainable Livelihood Framework attempts to encompass and approach a loss of security affecting the level of well-being at the individual or local level.

Focusing on fragile natural environments like grazing lands, the approach in terms of adaptive capacities of socio-ecological systems has grown in importance, and primarily relied on the social component. In this perspective, Turner II et al. (2003) emphasize the importance and specificity of the learning capacities of (agro)pastoral systems in response to disturbances like drought. Berkes (2007) based the adaptability of socio-ecological systems in arid and semiarid zones on their social components, that is, the human arrangements that affect the ability of stakeholders to influence or manage resilience. Based on Folke et al. (2002), Berkes (2007) identified four factors that highly influence the properties of (agro)pastoral systems to enhance adaptability: (i) the ability to 'learn to live' with changes and uncertainties; (ii) the maintenance of diversity within the system; (iii) the combination of different sources of knowledge; and (iv) the safeguarding of self-organizing capabilities and multi-scale connections.

In summary, analyses of the adaptive processes of socio-ecological systems based on resource use have given more and more attention to the shapes and forms of social organizations, combining social and ecological factors and considering interrelated changes. This approach strengthens the links between vulnerability studies and studies on the resilience of systems to establish a common analytical framework related to the 'adaptation process' (represented in Fig. 2).

However, as mentioned by Chambers (2006, 35), "the range of means which poor rural people use for subsistence, to maintain their livelihoods, and to cope with contingencies, is impressive". This has been shown in various agricultural contexts (see Alary et al., 2011, 2020; Robert and Lallau, 2016; Hammond et al., 2017; Volpato and King, 2019). In particular, these empirical research studies have underlined the diversity of on- and off-farm activities and the diversity of marketing strategies with the function of providing for urgent cash expenses and food self-sufficiency in the short term and the overall family plan in the medium or long term, varying with the age and number of potential heirs (related to Chayanov, 1966). In these research works, the most difficult challenge when applying their approach to GLFSs is to capture the multiple and correlated contributions of livestock in terms of production and investment assets, allowing the researchers to assess the buffering and adaptive capacity of livestock activities within household strategies in response to natural and social changes.

4.2. Brief review of some operationalized 'sustainable' frameworks

The first set of operationalized frameworks was searched to find inspiration from existing approaches developed for crop-livestock integrated systems (Hammond et al., 2017; Carof et al., 2013; Darnhofer, 2014). In these approaches, attention is mainly given to adaptive

Table 3
Indicators related to livestock functions at the household level.

Scale	Domain	Example of metrics	Unit
Household or farm level	Short and medium terms viability (see Dutilly et al., 2020)	Part of livestock income in total family net income	Ratio or percentage
		Part of crop and non-farm activity in total family net income	Ratio or percentage
		Livestock net income by family working member (FWM) (involved in livestock activity)	Amount per FWM
		Benefit-cost ratio (profit)	Ratio
		Meat and milk self-sufficiency (grams of protein from milk and meat production divided by the total grams of protein required per family member)	Ratio or percentage
		Contribution of animal annual cash flow to cover total family expenses (or basic family expenses)	Ratio or percentage
	Pluriannual term or intergenerational economic viability (see Alary et al., 2020)	Net income per FWM (compared to the minimum wage)	Amount per FWM
		Animal value stock (animal asset valued at selling price) per family member (compared to the poverty line)	Amount per person
		Animal value stock (animal asset valued at selling price) per child (transmissibility)	Animal value stock (amount) per child
	Social viability (derived from Najjar et al., 2018)	Contribution of women in decisions on management of livestock production	Count of decisions taken by women
		Women's control over livestock assets	Count of animals owned by women in the farm household
		Women's control over milk and meat activity management	Count of tasks related to milk and meat managed by women
Community or extra-community level	Economy (market)	Market access	Distance (km) or market fees
		Supply and demand	Counts of animals marketed by trader and per month
		Price variability and volatility	Short-term price deviation from the long-term trend in monthly
		Price variability and volatility	prices
	Institutional economy	Infrastructure	Km roads
		Ways of communication and infrastructure (telephone, internet, road, electricity, etc.)	Counts of communication means
		Extension service availability (proximity, visits)	Visit count of extension services per year
	Social economy	Rural–urban ties	Flux of money to or from villages /Emigration rate to urban areas
		Social networks	Involvement in community-based organizations
		Empowerment	Count of people having responsibilities within the community Associations/ institutions counts

Table 4
Indicators reflecting accessibility to animal health care services (from Perry and Grace, 2009).

Institutional scale	Hypothesis	Examples of indicators
Economy (market)	Lack of means to purchase and/or access basic goods and services	Availability and cost of medicines per animal Distance to veterinary service centers (km)
Institutional economy	Inadequate access to basic goods	Counts of animals in the community per veterinary worker Specific credit or insurance for herders to cover health care (amount)
	Weak social institutions and gaps in information flow	Availability of veterinary extension services (proximity, number of visits per year) Ways of communication and infrastructure (telephone, internet, road, electricity, etc.)

capacities and strategies based on the trade-offs of assets. However, the use of these frameworks for GLFSs rapidly becomes insufficient to approach resource access and social networks at different spatial and temporal scales, which constitute the main pillars of the resilience of GLFSs (as shown in part 1). The issue of scale in GLFSs explains researchers' and developers' recent and growing interest in designing, testing, and implementing specific and appropriate frameworks for GLFSs. In this trend, we can cite additional research and development initiatives from national and international research institutes, among them the IMPACT, LSIPT, and GLEAM toolkits supported by the Food and Agriculture Organization of the United Nations (FAO) and other research institutes like the International Livestock Research Institute (ILRI) and the French agricultural research and cooperation organization CIRAD.

Other operational frameworks have searched more to capture overall adaptive capacities, focusing on resource and social-based systems. For instance, based on the general frame of vulnerability to climate change developed by Fraser (2007), Dong et al. (2011) proposed to address the vulnerability assessment of pastoral areas to global change in various contexts. In this work, Dong et al. (2011) mobilized three key factors – agroecosystem resilience, livelihood options, and institution capacity – which are considered as the significant axes that reflect the ability of social-ecological systems in pastoral settings to absorb disturbances while maintaining their primary function and structure. This research underlined the multiple dimensions of the pastoral systems that need to be considered to assess and enhance their sustainability. A territorial declination of this approach was developed for two Mediterranean pastoral systems in France and Egypt (Lasseur et al., 2016). This territorial approach emphasizes three drivers influencing overall sustainability. A first driver opposes fragility to the robustness of the natural environment in line with the spatial biodiversity, constituting a causal link between achieving sustainable livelihoods, maintaining diversity, and adjusting to natural hazards. A second driver is based on the 'wealth' of the socioeconomic environment and assesses households' access to the resources needed to implement alternatives and maintain their livelihoods in case of shocks. This refers to the causal links between sustainable livelihoods and the learning capacities of a system in interaction with its political and institutional environment (including the

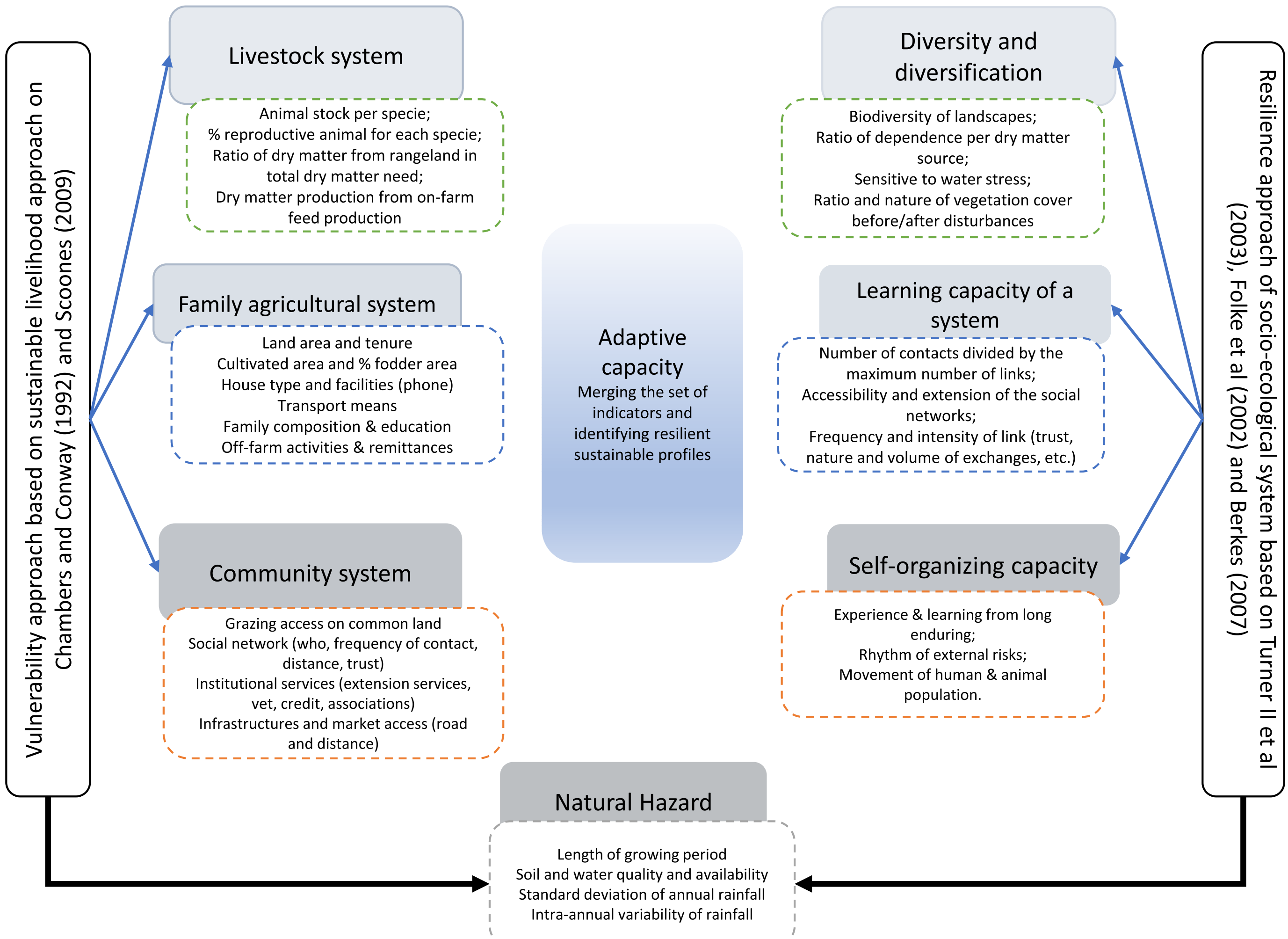

Fig. 2. Schematic representation of main discriminating factors and indicators that can guide the research studies on the sustainability of GLFS.

market system). The third driver is focused on the capacity of institutions to respond to a crisis. This last driver refers directly to governance and the capacity of actors to mobilize their social networks. Referring to a set of attributes characterizing governance (such as in Lebel et al., 2006), the aim has been to analyze the more or less critical inscription of the actors from the livestock sector in networks or instances of governance, as well as the capacity of the institutions to integrate actors in their development or action plans.

Other research work proposes integrated indicators of the vulnerability or resilience of systems. For instance, Opiyo et al. (2014) propose a vulnerability index positively correlated to adaptive capacity, explained by socioeconomic indicators related to household and farm characteristics, and negatively correlated to sensitivity and exposure. Both sensitivity and exposure reflect the ability of a system to be affected and the incidence of one event. Separately, FAO (2016) has proposed a methodological resilience approach through the Resilience Index Measurement and Analysis (RIMA) tool. The Resilience Capacity Index measures the capacity of households to cope with events (shocks). In contrast, the Resilience Structure Matrix explains how much each dimension determines the resilience capacity.

Another emerging approach seeks to explore the social interconnectivity of a system – that is, the relationships in terms of nature and intensity of interaction between the system's components. Using this social approach on GLFSs, Bodin and Tengo (2012) and Linstädter et al. (2016) proposed to analyze long-term dynamic relations between social and ecological components by considering the herd at the interaction between the two components (social and natural) and the use of external resources (rangelands) as a way to mediate these relationships. Herd owning and management is consequently at the core of the system's resilience, allowing access to external resources as long as institutional and political rules allow for it.

From this review, it appears clear that the existing sustainable livelihoods and resilience frameworks feed into each other to enhance analysis and understanding of the complexity of the GLFSs. This joint approach also allows identifying different levers of actions, explaining the various means and paths of adaptive capacity of livestock socio-ecosystems. However, one major weakness of these frameworks, particularly when addressing the adaptive capacity of grazing systems, is the time scale. The temporal scale for most indicators on natural systems is longer than any research project in agricultural science. As a result, the intra-variability of the adaptive process due to human factors is rarely addressed. Moreover, each indicator can play a different role at different spatial scales according to interference with the organizational levers. So, from this tremendous literature, a recurrent question arises: How can we implement this integrated framework faced with the time variability of indicators and the different functions of livestock at different time and spatial scales?

4.3. Toward a multi-scale indicators framework to address the sustainability of GLFSs

In this section, we will merge the previous reviews on the conceptual and operationalized frames for assessing GLFS sustainability with our empirical research related to different research projects in North and South Mediterranean countries[1] and the LSIPT toolkit developed for implementing development plans for the livestock sector at the national level (Dutilly et al., 2020; Richard et al., 2019). The LSIPT toolkit has been developed and tested in Mali and Ethiopia, and applied in Zambia, Ethiopia, India, and Egypt (Alary et al., 2018; Dutilly et al., 2020; Rich et al., 2020; Alary and Najjar, 2021). The objective of this section is to organize this reflection on the indicators in a multi-scale indicators framework for assessing the adaptive capacity and sustainability of GLFSs using a multi-scale representation. Notably, this framework combines the dependent multi-scalar (time, space) dimensions of indicators linked with the social (or organizational) levels.

Firstly, from different research works in geography (for example, Gonin and Gautier, 2016 and socio-economy (for example, Lasseur et al., 2016; Alary et al., 2019), two levels of territorial organization come out as pertinent for understanding the dynamics of mobile livestock systems. The first one, the territory of attachment at the community or local level, constitutes the space where people have built strong links with a long-standing commitment to managing herd mobility and transactions (see Amsidder et al., 2021). The territory of attachment usually includes, beyond the settlement camp, all the surrounding agricultural and pastoral areas corresponding to the customary territory of the community (*terroir* in French; see Rabot, 1990). The second level, the territory of engagement, corresponds to pastureland out of the community (for example, out of tribal or ethnic land in the South Mediterranean countries or agricultural areas along the coastal line of the Mediterranean; see Alary et al., 2019), where formal institutional support and policies are generally decided and organized. This territory of engagement fits with the definition of Cox (1998) by encompassing all of the social networks. This first delineation corresponds to the left vertical axis of the proposed operationalized framework shown in Fig. 3.

Secondly, to this territory of engagement or attachment, we observe an overlapping of the family and institutional spheres that interfere in many adaptive processes, such as (i) pluri-activities and/or migration at the family level; and (ii) access to resources (Ostrom, 2001), to the terms of exchanges (Kaplinsky and Morris, 2001; Spaargaren et al., 2006), or by extension to the overall policies and measurements that impact the studied systems, such as the access to basic health goods and services at the household and territorial level (Right vertical axis in Fig. 3). This socio-institutional context has direct and indirect impacts on the livestock value and its variability in the short and medium-term and in regard to shocks.

Finally, the third axis corresponds to the time horizon for the sustainability of livestock systems, which can be ordered in phased terms (short term, medium-term, and long term). Each time scale corresponds to the different horizons of the 'adaptive processes' linked mainly with natural hazards, livestock and vegetation dynamic population, and intra- and intergenerational family 'asset' sustainability. In our conception, we have considered four horizons: (i) the seasonal and annual terms corresponding to the satisfaction of the primary or basic needs (including at a minimum the coverage of food needs, health care and education expenses, and the maintenance of the physical and social assets); (ii) the pluriannual term at medium-term, aiming to answer to climatic and social shocks that regularly occur even if they can be uncertain (such as family events implying extra expenses or climatic shocks); (iii) generational terms corresponding to the transmission of patrimony; and finally (iv) the long term, including land tenure and its conservation (in terms of soil and water maintenance and quality), which can exceed one generation. These time horizons can be adapted case by case, notably the seasonal term, which generally varies all over the dryland zones in interaction with the agricultural section.

These three major dimensions conditioning the sustainability of GLFSs – the temporal scale, spatial scale, and the social and organizational dimension – constitute the principal axes of our proposed multi-scale indicators framework represented in Fig. 3.

This proposed framework illustrates two central hypotheses that underpin the elaboration of the set of indicators to assess the sustainability of GLFSs considering their adaptive capacities. The first one deals with combining indicators to consider interdependencies of time scales in adaptiveness. The second hypothesis deals with spatial scale interplays and their meaningfulness regarding the spatial expression of resilience (Cumming, 2011). Table 5 completes the framework by giving a set of indicators at each temporal, spatial, and organizational scale. This list of indicators derived from the previously cited research works is not exhaustive. We also use standard units of hectares, kilograms, liters, and kilometers, while at the same time, interviews will often provide information in local units such as cans or buckets instead of liters; buckets, wheelbarrows, or lorry loads instead of kilograms; or walking hours instead of kilometers. It is essential to know the equivalent of each local unit in standard units to make the conversion. Therefore, Table 5 mainly constitutes guidance when applying the proposed framework for assessing the adaptive capacity of GLFSs, which should be adapted in the methods of data collection and the measurement of the indicators according to each location.

In this proposed framework, we consider that the relationship between a livestock system and the livelihoods of pastoral families, through the management of the herd component, conditions the livelihood outcomes at different temporal scales, depending on both the dominant livestock species in the herd and the social and institutional context. The role of livestock is mainly embedded in the production and reproduction function of the livestock activities in the short term (which can be approached through the proportion of reproductive females in the herd and/or the young male valorization in the market), but also in the medium and long term in the abilities to shape animals and their genetic potential to face new environmental conditions. Here, the genetic potential for future generations, called the selection pressure, is highly dependent on short-term decision rules such as the percentage of reproductive females. Of course, the adaptive capacity in each time scale varies as a function of the dominant livestock species and the degree of animal species diversification. For example, during drought events lasting several years, herders are often obliged to market the female young (threatening the renewal rate of the reproduction stock) or increase the culling rate to destock the reproductive stock – reducing the stock of the adult females that should have secured the annual products over the medium term (from five to ten years, according to the animal species and their breeds and in line with the environmental context). However, as already mentioned, these mechanisms differ according to the animal species. If sheep and goat flocks can allow rapid and gradual response to shocks, the destocking of camel or cattle herds will affect livelihood outcomes longer. Vice versa, large ruminants represent a larger capacity of investments. Therefore, the livestock asset is alternately a buffering stock in case of climate or other shocks (short-term management) or an investment stock in good conditions (medium term based on household cycles). But the investment vs. buffering capacity allowed by livestock is not only embedded in the physical asset (usually represented by the animal stock per species). In traditional pastoral or agropastoral societies, the animal stock also ensures a certain status and guarantee for different social or economic transfers that can be captured by the flux of gifts and loans received and given to face short- or medium-term events.

Indeed, considering spatial embedding with the three spatial scales for studying GLFSs, it clearly appears that social organizations and solidarities have to be particularly analyzed within the social networks of the territory of attachment. Likewise, communication and infrastructure

[1] Projects ELVULMED, 'Rôle des activités d'élevage dans les processus d'adaptation et de réduction de la vulnérabilité des sociétés méditerranéennes face au changement global' (projet ANR, 2011–2015); and CLIMED, 'The Future of Mediterranean Livestock Farming Systems: Opportunity and Efficiency of Crop–Livestock Integration' (Arimnet call 2011; 2011–2016).

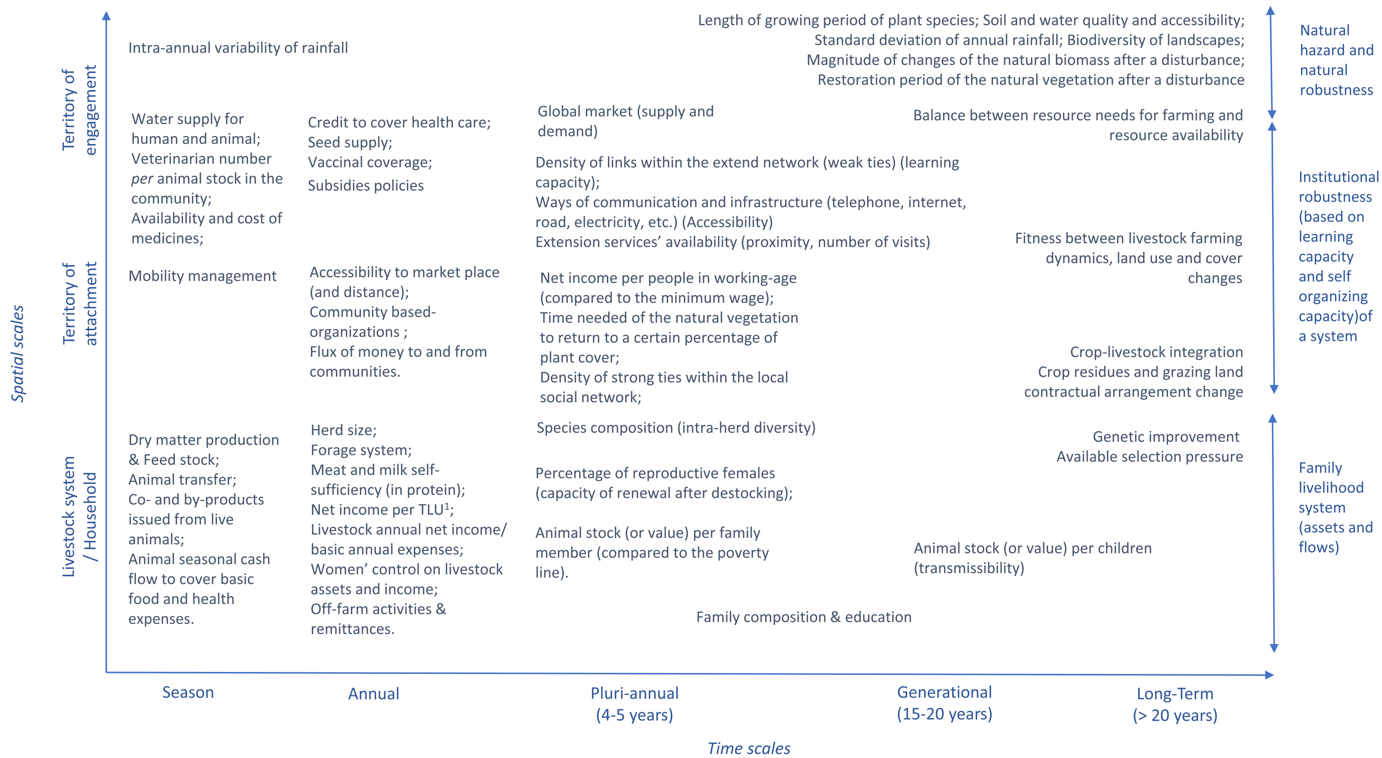

Fig. 3. Multi-scale operationalized frame for assessing GLFS sustainability.

conditioning physical and knowledge accessibility and flow are particularly important to conducing mobility and allowing complementarities within the territory of engagement. These two spatial scales enable abilities to face shocks and build general consistencies between the livestock-framing institutional landscape and resource management. For instance, with the development of pastoral laws and the growing incidence of drought events on pastureland vegetation diversity and availability, pastoralists are more and more constrained in their mobility – a key factor of their adaptability (see 3.1.). Faced with these challenges, many countries have instituted systems of livestock insurance or feed subsidies. If these systems prevent cash insecurity in the short term or limit animal destocking in the short and medium-term, they also induce a greater dependence of these GLFSs on purchased fodder and consequently on market prices. This factor continues to aggravate market dependence, recognizing that the food system of pastoral families is becoming highly dependent on purchased grain covered by livestock transactions, in particular in arid or desertic pastoral areas. This explains why the indicator of the terms of exchanges between grain and meat has been frequently used to understand the animal stock dynamics following severe droughts events (for instance, following the droughts events of the 1970s and 1980s in the Sahel; see Fraser, 2007) or overall sustainability (see Salmon et al., 2018).

In summary, agropastoral and pastoral families are accustomed to adjusting their mix of activities and the functions thereof according to their own circumstances and the changing context in which they live. Linked with climatic or resource variability, livestock can be alternatively a stock of saving and investment (in favorable climates) or a social safety net in case of drought (through available funds with destocking, loan access, social support, etc.), and this for each time scale. Livestock are also used as cultural markers of identity and dignity for some communities, which condition access to various contextual social resources or security such as access to natural resources, social transfers or loans, or mutual aid in case of difficulties (Castells, 1996; Alary et al., 2011). This functioning is at the interaction between the sustainable livelihoods approach (as described by Chambers and Conway, 1992), the maintenance of diversity in the ecological, social, and economic sense for new opportunities and options to cope with risks and changes (Berkes, 2007), and self-organizing capacity when faced with natural shocks (Folke et al., 2002).

5. Discussion

5.1. Main challenges related to the interactions of scale levels

This review, based on literature enriched with empirical research works on pastoral and agropastoral systems, leads us to consider that understanding and evaluating the sustainability of GLFSs in drylands areas calls for more integrated approaches to livestock socio-ecosystems at different social, spatial, and temporal scales. If different research works have already built up evidence on the spatial and social scales (for example, Scoones, 2009), the temporal scale combining household and herd live cycles has rarely been mentioned. Our work also confirms how far social and natural systems are entangled and how concepts of both vulnerability and resilience are extremely interlinked in the adaptive capacity of pastoral livestock farming activities to survive or develop, as already shown by Dong et al. (2011) and Linstädter et al. (2016). This review not only proposes a documented set of key indicators related to GLFSs (Fig. 3 and Table 5), it also pinpoints the central intricacies of establishing a standard list of indicators for these systems. Guidance in elaborating a proper set of indicators (and the weight they should have in the analysis according to a local situation) may be found relying on the analytical framework for adaptation processes presented in Fig. 2. For instance, in a situation of a strong increase in a natural hazard, a special menu could be elaborated that would give particular attention to the natural hazard box to characterize this exposure to risk, coupled with (i) the family system box to identify response capacities relying on off-farm activities and/or means of transport to remove animal from the area; and (ii) the community system box to address social networks involved in getting new forage resources. Medium-term abilities to respond to the new situation could be addressed by assessing the learning capacities of the system. Other combinations of indicators could be stated when the local situation is characterized by strong

Table 5
A proposed list of indicators to implement the multi-scale indicators framework.

Temporal scale	Spatial and organizational scale	Indicator	Examples of indicators	Units	Source
		Dry matter production and feedstock	Months of feedstock over the duration of the season	ratio	Interview
		Animal transfer	Counts of animal per species received from or given to…	animal heads	Interview/ Animal counts
			Milk production	liter day^{-1}	Interview/ Measurement
	Family farm level	Animal co- and by-production	Wool production	kg	Interview
			Other animal services (animal traction, transportation, touristic riding, etc.)	hours	Interview
		Animal seasonal cash flow	Cash flow from animal products during the season	amount	Interview
			Animal seasonal cash flow compared to family food and health expenses.	ratio	Interview
			Distance	in km or hours	Focus group/ Interview
	Territory of attachment	Mobility management	Seasonal fees to access pastureland	amount	Focus group/ Interview
Seasonal viability			Supplementation during the mobility	Eq. kg grain day^{-1} animal^{-1}	Interview
		Water supply for human and animal	Access to water supply on rangelands	y/n	Focus group
			Quality of water on rangelands	Likert scale (interview) or official microbiological analysis	Focus group/existing analysis
			Expenses for water access on rangelands	amount year $^{-1}$	Focus group
			Animal stock per veterinarian in the community	Number of animals/vet	Administration
	Territorial engagement		Distance of veterinary services from family house	km	Map use
		Veterinarian service access	Distance of veterinary service from rangeland in the territory of attachment	km	Map use
			Distance of veterinary pharmacy from family house	km	Map use
			The average cost of veterinary medicine per animal	amount animal^{-1}	Interview/focus group
		Intra-annual variability of rainfall	Seasonal rainfall	mm/ month	Administration
		Herd size	Counts of animals per species	Number	Interview
		Forage system	Area of fodder and grain crops for animals/total cultivated land	ratio	Interview
		Meat and milk self-sufficiency (in protein)	Animal protein intake in the daily ration	gr/day	Interview
		Livestock revenue	Livestock net income	amount	Interview
		Livestock contribution to annual expenses	Livestock annual net income/ basic annual family expenses	ratio	Interview
		Women' control of livestock assets and income	List of livestock assets and income owned or/and managed by women	Counts of tasks	Interview
		Crop farm activities and crop income	Crop income compared to total annual family income	ratio	Interview
	Family farm level	Off-farm activities and remittances	Out-of-farm income compared to total annual family income	ratio	Interview
		Accessibility to market place (and distance)	Distance to market for animal transaction	km	Map use
			Road infrastructure	km	Administration
		Community based-organizations	Pastoral institutions and organizations	count	Focus group
	Territory of attachment	Flux of money to and from communities.	Remittance from migrants	amount	Interview
			Emigration rate	ratio	Administration
		Credit to cover health care	Credit access for livestock activity	y/n	Focus group/ Interview
		Seed supply	Fodder seed supply	y/n	Focus group/Interview
		Vaccinal coverage	Proportion of vaccinated animals	% of the herds	Administration
Annual viability	Territorial engagement	Subsidies policies	Amount of subsidies par animal at the territorial level	amount animal $^{-1}$	Administration
		Capacity of livestock renewal after destocking	Percentage of reproductive females in the herd per animal species	ratio	Interview
		Value of animal stock	Animal value stock (animal asset valued at selling price) per family member (compared to the poverty line).	ratio	Calculated
		Species composition (intra-herd diversity)	Counts of species in a herd	Number	Calculated
	Family farm level		Counts of animal breed	Number	Interview
Pluri-annual (4–5 years)	Territory of attachment	Household income	Net income per person in working age (compared to the minimum wage)	ratio	

(*continued on next page*)

Table 5 (*continued*)

Temporal scale	Spatial and organizational scale	Indicator	Examples of indicators	Units	Source
					Interview/calculated from household incomes
		Capacity of the natural vegetation	Time needed for the natural vegetation to return to a certain percentage of plant cover		Research report/ Field measurement
		Social networks	Density of strong ties within the local social network	Contacts par category of stakeholders	Interview
		Means of trasmission of knowledge and communication	Density of links within the extended networks (administration, traders, etc.)	Contacts par category of stakeholders	Interview
			Equipements: telephone, internet, road, electricity, etc.	Counts of equipment	Administration
		Extension services' availability	Proximity	km	Map use
			Number of visits/year	Number	Interview
	Territorial engagement	Market changes (supply and demand)	Elasticity of animal product demand	ratio	regional statistics
			Animal supply dynamic	% variation	regional statistics
			Household size	number	Interview
		Family composition	Working-age persons in the household	number	Interview
			Household dependency ratio	ratio	Interview
		Family education	Number of people with higher education	number	Interview
	Family farm level	Inter-generational transmissibility	Value of animal stock (valued at the selling price) per children (transmissibility)		Interview/ calculated
		Breeding	Genetic improvement	Counts of animals per breed	Interview
			Available selection pressure	% of the dominant breed	Interview
		Crop-livestock integration	Proportion of fodder crop area in the cultivated area	ratio	regional statistics/map
			Manure production	Tons of Nitrogen	regional statistics
		Land arrangement	Proportion of cropping encroachment	ha	Map
			Number of conflicts on land	Number	Focus groups/ administration
			Carrying capacity on rangelands	TLU* per km^2	Estimated
Intergenerational and Long-term	Territorial attachment	Fitness between livestock farming dynamics, land use, and cover changes	Biomass production	Tons of dry matter per ha per year	Estimated
			Pasture quality	Likert scale (interview)	Focus group
			Species richness and diversity	Counts of plant species	Focus group/ Field measurement
			Soil nutrients	Soil organic matter content, soil pH, Olsen P	Available data/ soil sampling
		Balance between resource needs for farming and resource availability	Dry matter availability from pastoral and crop areas	tons	Estimated
			Dry matter requirement of the community herd	tons	Estimated
			Length of growing period per plant species	In months	Focus group/research
			Soil and water quality and availability	Likert scale/ analysis	Focus group/ Fiel measurement/ Existing data
			Standard deviation of annual rainfall	mm per year	Administration
			Biodiversity of landscapes		Map
			Magnitude of changes of the natural biomass after a disturbance	Variation of plant cover	Focus group/Field measurement
	Territorial engagement	Natural changes	Restoration period of the natural vegetation after a disturbance	counts of months	Focus group/Field measurement

disorganization of social norms and rules for access to resources, addressing indicators that rely on self-organization capacities in the family and community system, for instance.

5.2. *Main challenges related to indicator selection*

This proposed framework shows that understanding the role of livestock in buffering, adaptive, or transformative capabilities requires us to analyze conjointly the trends of animal stocks (describing the system and its response time) and the flows (animal transactions and transfers) that reflect the changes. Only this trade-off between animal stocks and flows over time will reflect the actual adaptive capacity of GLFSs. This underlines the necessity of developing a coherent information system in these zones, allowing us to capture the two dimensions of livestock activities as production and saving of assets at different spatial and temporal scales. Only the ratio between stock and fluxes (the trade-off between self-consumption and marketing; in- and out-flows of animals) can allow us to understand the studied systems and identify the dramatic failures or misfunctioning in (agro)pastoral zones that call for appropriate interventions by the public or development sector. Consequently, the information system on the dynamics of livestock population should be thought out and organized jointly by socio-economists, livestock scientists, agronomists, and even ecologists.

Another key set of indicators to address the livelihoods of families based on GLFSs is often the net livestock income based on the added value calculation or gross margin. However, the contribution of livestock to the net family income to satisfy the primary family needs (food, health, education) does not correctly reflect the different roles of livestock in terms of reducing vulnerability in pastoral or agropastoral systems (see Alary et al., 2011 in Mali; Wane et al., 2010 in Senegal).

This issue is mainly due to the overestimation of the importance of monetary transactions to the detriment of the buffering capital embedded in animal stock. And this buffering capital, estimated at the selling price, hardly reflects the other buffering capacity linked with the indirect human capacity created by this activity (notably at the community level). Livestock can be alternately a source of income/enrichment and a buffering stock according to the environmental and social conditions. Both functions operate differently according to the degree of on- and off-farm diversification and the social mechanisms and beliefs in the local society. This calls for data collection over time or close attention to the realization of retrospective surveys, because indicators create different values about time and/or thresholds.

In summary, the search for indicators to analyze the sustainability of livestock socio-ecosystems suffers from the same problems that fueled debates about risk perception in the 1970s and 1980s and poverty indicators in the 1990s. Furthermore, the degree of vulnerability or fragility depends on human experience and social processes that are difficult to quantify (even qualify) overtime where the needs fluctuate. In Burkina Faso, Cote and Nightingale (2011) highlighted this difficulty when trying to develop indicators that focused more on the properties of diversity and connectivity than the dynamics of agropastoral systems. Davies and Bennett (2007) also showed how pastoralists seek to maximize what the authors called the "human support capacity" or "human condition support capabilities" of their core resources, livestock, more through production and milk consumption than through monetary income. Consequently, up to now, work focused on livestock sales strategies has tended to underestimate the weight of this resource as capital or safety in pastoral survival strategies. This alternate function of the same indicators calls for a dynamic and evolutive approach to the weights of indicators when conducting a sustainability assessment of GLFSs.

5.3. Co-evolution of the sets of indicators to address the transformative process

Finally, the adaptive capacity of a system is a dynamic process in time and space that involves contextuality. Thus the delimitation of the system is dependent on each local context (Chuang et al., 2018). As mentioned in our framework in reference to Cox (1998), agropastoral systems usually function within two spaces: a space of dependence related to their origin, and a space of engagement when grazing out of their community or marketing their products. Consequently, it appears evident that only a multi-scale framework can reveal the complexity and genius of the adaptive capacities of GLFSs. In this way, Fig. 3 can help to conceive an appropriate framework of the sustainability of GLFSs by pointing out the different components of the overall capacity of these systems. This framework can serve as a sort of model to organize and link the different dimensions explaining the overall sustainability in dryland grazing systems. As mentioned by Meadows (1998, 22), "the information should be organized into hierarchies of increasing scale and decreasing specificity".

However, another challenge when addressing the sustainability of GLFSs is the notion of threshold or rupture, supposing that the system becomes unsustainable. For instance, by considering the dynamics of systems, some researchers have shown that thresholds or levels of vulnerability or resilience change over time with the constant evolution of the social environment and its values (see Alwang et al., 2001) and the continuous transformational adaptation of populations (see Vermeulen et al., 2018). Hence, a 'vulnerability' map can only give an image at a given moment of social differentiation. Moreover, measuring vulnerability as the threshold of resilience implies judgments or interpretations about acceptable risk depending on social and cultural values and preferences (Adger, 2006, 276) and is limited to research knowledge about the natural processes. As in the passionate debate on the objective or subjective nature of risk to address risk aversion (see Simon, 1966), there are also gaps between perceived and lived vulnerability based on the experience of agents and their perception (Kasperson and Kasperson, 2001), which conditions self-organizing capacity. Turner II et al. (2003) highlight feedback effects between individuals and their environment "so that a response in the human subsystem could make the biophysical subsystem more or less able to cope, and vice versa". This has also been shown by Sterk et al. (2017) in the ecological approach using an example of pasture management systems.

All of these challenges related to the necessity to approach the perceptions of actors, the delimitation of the system, and the substantial weight of contextuality to understand the functioning of livestock socio-ecosystems make it difficult to base development interventions on quantitative approaches based on a set of indicators alone. In this paper, the review of indicators is aimed at giving an overall view of the key entry points used for approaching livestock socio-ecosystems and their sustainability assessment. However, a comprehensive approach to the dynamics of these systems in their intra- and inter-connections at different scales constitutes an unmissable opportunity to delineate the systems and to approach their multiple social and natural configurations. This comprehensive approach could contribute to a comprehensive underlying information system and to underlying dynamic models. This explains why it has been relatively tricky to present a common set of indicators while avoiding the risk of masking local lock-in or reducing the strength of local mechanisms to cope with shocks. However, the presentation of this integrated framework for analyzing the sustainability of grazing livestock systems has allowed us to demonstrate that an information system must be linked to the different kinds and forms of livestock assets (capital) and activities (flows) at the interaction of each scale.

6. Conclusion

In conclusion, this paper has reviewed a range of publications related to risk, adaptability, vulnerability, resilience, and sustainability applied to livestock systems in drylands based on grazing systems (mostly pastoral systems, but also some integrated crop-livestock systems). We can see clearly that the two concepts of vulnerability and resilience are conjointly used in operationalized frameworks to assess the adaptative capacities of grazing farming systems and their sustainability. They usually enrich each other to encompass the complexity of the GLFSs and their dynamics. As such, this review has shown how individual vulnerability compared to collective vulnerability, or socioeconomic vulnerability compared to ecological vulnerability, were not always correlated but always interlinked with feedback effects.

Concretely, this review has searched to compile a set of indicators to inform the processes of assessing the sustainability of livestock socio-ecosystems. This multi-scale indicators framework can constitute guidance when assessing adaptive capacity in the short, medium, and long term from the current situation, or with the objective of approaching the potential effects of the current situation of vulnerability in the medium and long term. These proposed indicators are considered as key entry points to understanding the degree of fragility or sensitivity of (agro) pastoral systems, but their value and scope should be completed with a comprehensive qualitative assessment with stakeholders. This underlines the necessity of considering each proposed indicator as a widely accepted qualitative or quantitative element, enabling users to envision the properties of adaptability of observed systems and allowing greater ease in their governance. This mixed quantitative and qualitative approach allows users to adapt the scope of each indicator to its context. The approach could constitute a sound basis for elaborating a system of information that will contribute to and support policymakers and development agencies in developing their policies and measurements in order to ensure the sustainable development of pastoral and agro-pastoral systems in the short and medium-term.

CRediT authorship contribution statement

Véronique Alary: Conceptualization, Methodology, Investigation, Resources, Writing – original draft. **Jacques Lasseur:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft. **Ayman Frija:** Conceptualization, Writing – review & editing. **Denis Gautier:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

None.

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