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Review

Global principles in local traditional knowledge: A review of forage plant-livestock-herder interactions

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ABSTRACT

An understanding of traditional ecological knowledge systems is increasingly acknowledged as a means of helping to develop global, regional and national, but locally relevant policies. Pastoralists often use lands that are unsuitable for crops due to biophysical and climatic extremities and variabilities. Forage plants of pastures are utilized by herding communities by applying locally relevant multigenerational knowledge. We analyzed the forage-related knowledge of pastoralists and herders by reviewing scientific papers and video documentaries on forage plants and indicators, their use in land management, and plant-livestock interactions. Semi-structured interviews were also conducted with key knowledge holders in Iran, Mongolia, Kenya, Poland and Hungary. We found 35 indicators used by herders to describe forage species. The indicators described botanical features, livestock behavior during grazing, and the impact of plants on livestock condition and health. The indicators were used in context-specific management decisions, with a variety of objectives to optimize grazing. We identified ten global principles, including, among others, a livestock-centered perspective, close monitoring and targeted pasturing of various (preferred or avoided) forages, and the use of different livestock types and well-planned spatial movements at multiple scales to optimize the utilization of available plant resources. Although pastoralists vary greatly across the globe, the character and use of their traditional forage-related knowledge do seem to follow strikingly similar principles. Understanding these may help the local-to-global-level understanding of these locally specific systems, support bottom-up pastoral initiatives and discussions on sustainable land management, and help to develop locally relevant global and national policies.

1. Introduction

Traditional ecological knowledge (TEK) systems are contextual frameworks that provide the basis for the use of local natural resources by Indigenous Peoples and local communities (Berkes et al., 2000). Though local in origin and application, TEK and the related practices are

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regionally manifested and thus are globally relevant (IPBES et al., 2019; Brondizio et al., 2021). Some recent authors (e.g. Hill et al., 2020; McElwee et al., 2020) warn that in global syntheses, TEK may lose its local or regional cultural and ecological contexts. However, Posey (2002) argues that traditional knowledge is actually not local per se, but "universal as expressed in the local". Thus global syntheses may work if we build on these global aspects.

Pastoralism comprises a wide family of livestock-based livelihood and nature-positive food production systems that are highly diverse, but which all share a specialization in improving the diets (and welfare) of animals by managing their grazing itineraries at a variety of scales in time and space (FAO, 2021). Pastoral systems exist in different biomes (tundra, savanna, steppe, desert, mountains) (Reid et al., 2008; LPP, 2021). Pastoralists use TEK to manage spatio-temporally variable resources for the production of protein-rich food (Meuret and Provenza, 2014; Roué and Molnar, 2017; FAO, 2021).

Despite recent gains in the appreciation of pastoral TEK, several knowledge gaps exist (Johnsen et al., 2019). Unexpectedly, some of these knowledge gaps relate to the central issue of herding, namely, which plant species livestock feed on and how, and what herders know about this relationship (Sharifian et al., 2022).

The pastoralist world is diverse, as cultures, landscapes and pastures are diverse, yet there are some striking similarities in the way herders (cf. pastoralists and other traditional animal keepers) perceive the plants found on their pastures, learn about forage species, and manage natural resources (Molnár Zs et al., 2020). However, pastoral cultures, practices, livestock breeds and especially folk names of forage plants and pasture types can be highly specific (Dong, 2017; Stolton et al., 2019; LPP, 2021; Molnár Zs, 2017), and these specificities may easily obscure the common dimensions of pastoral TEK.

These issues are relevant not only for analyzing the scalability of TEK, but also for some key sustainability issues. Understanding the drivers behind reliance on forage is key to determining the resilience of pastoralists. Taking the provision of leaf fodder and dry fruits as an example, it is crucial as a fodder source in times of drought and in dry or winter seasons (Reid and Ellis, 1995; Bergmeier and Roellig, 2014; Hejcmanová et al., 2014). Indicators to evaluate forage quality and condition constitute a crucial element of traditional rangeland management (Oba, 2012). The maintenance of varied forage and fodder sources from the herb, shrub and tree layers of rangelands is important to maintain their ecological integrity and functionality (Perea et al., 2016; Rolo et al., 2016; Torralba et al., 2018).

One of the main goals of the UN International Year of Rangelands and Pastoralists (in 2026, IYRP, https://iyrp.info) is to draw attention to the need for better policies that favor pastoral production systems and resolve obstacles which restrict herders' rights to conduct their practices. Such policies should include respect towards Indigenous and Local Knowledge (e.g. of forage indicators) in regulations that affect rangelands and pastoralism, such as rangeland exclosures, protected areas, stocking rate, and non-pastoral land-uses (e.g. mining, timber industry, oil extraction).

In this paper, we review 1) the pastoral TEK on forage plant species as reflected in the indicators used by herders to describe these species and the observed plant-livestock interactions; 2) how these indicators are applied in pastoral management (spatial and temporal aspects of grazing, livestock reproduction and health, and pasture status); and 3) how pastoral TEK about forage species and plant-livestock interactions is generated. Finally we identify some global principles related to forages and their use by pastoralists and herders. We focused on the herders' understanding of forages, presenting the original herders' quotes in the text, and especially in the tables and in the supplementary material.

2. Data collection and analysis

We used three sources for our global review: scientific papers, video documentaries, and specific interviews with knowledgeable herders (Fig. 1). We used 372 papers selected by a detailed keyword search in WoS for a global review on the TEK of herders (see Appendix A in Sharifian et al., 2022). From this database, we selected papers that provided detailed information on the emic understanding of forage species and indicators used by pastoralists for plant description and/or pastoral management. Seven papers describing pastoral TEK using science-based indicators (pre-defined scientific categories) were excluded from the analysis. Papers documenting TEK on cultivated fodder plants of sown grasslands and arable lands were also excluded. After these exclusions, a total of 24 papers were reviewed. We built a database according to 1) TEK on forage plants; 2) TEK on indicators of forage plants; 3) the use of forage indicators in management; 4) plant-livestock interactions; we also entered the data regarding plant local name, scientific name, family, life form and life cycle.

An internet search was carried out to collect video documentaries in which herders describe forage species, indicators and their use. We selected 105 (Appendix B) from 1278 available video documentaries on the aforementioned topic on https://vimeo.com/and YouTube. We conducted our search using the English terms 'herder' (150 videos), 'pastoralist' (955 videos) and 'shepherding' (173). Additional videos were found by sending emails to all of the first authors of the above mentioned 372 reviewed papers (altogether 260 first authors). The authors also connected us with 33 additional researchers. In parallel, a request was broadcasted through the Forum of the Pastoralist Knowledge Hub asking for video documentaries. Out of all the researchers, 76 persons answered our email, of whom 56 helped by suggesting videos (21) or other relevant material (Fig. 1). To select a documentary, we first watched the documentaries overall to see if we could find forage-related quotes from pastoralists being interviewed. For the analysis, we selected 18 information-rich documentaries with seemingly embedded researchers and detailed and disciplined argumentation from the herders in other parts of the video, in order to obtain validated statements from herders. After selecting the relevant documentaries, we watched them carefully and transcribed all the information relevant to our analysis (pastoral TEK on indicators and on forage plants, their use in management, and plant-livestock interactions), and integrated the data into the above-mentioned database.

Additionally, we conducted semi-structured interviews on forage indicators with Iranian, Mongolian, Hungarian, Polish and Kenyan herders. We also asked questions related to the findings of the review of the scientific papers. We interviewed three knowledgeable herders in each country in 2020 and 2021, mostly people we have been working together with for years. The main interview questions were: "What are the main characteristics that make a plant good for grazing/feeding the animal? How did you learn this knowledge about forage plants?" and "I have heard some herders in other countries use […] to describe forage plants, what do you think?". Listening to knowledgeable herders speaking about forage species, indicators and plant-livestock interactions is like reading a review. These herders summarized and synthetized for us the available local knowledge about forage. Three of these herders were also invited as co-authors.

In our analysis we combined all the emic information found in the scientific papers, the video documentaries and the specific interviews. All the data were organized and categorized in a Microsoft Excel database, and their descriptive frequency was determined. We coded all the indicators, identified common traits and relative clusters based on our own etic perspectives but checked with the co-author herders, and then we abstracted principles from the clusters. A Sankey diagram was made using Rstudio software through the "highcharter" and "dplyr" packages. The script used for this diagram is shown in Appendix C.

3. Results and discussions

Most (ca. 250) of the 372 papers reviewed in Sharifian et al. (2022) emphasized that herders have a deep understanding of their pastures

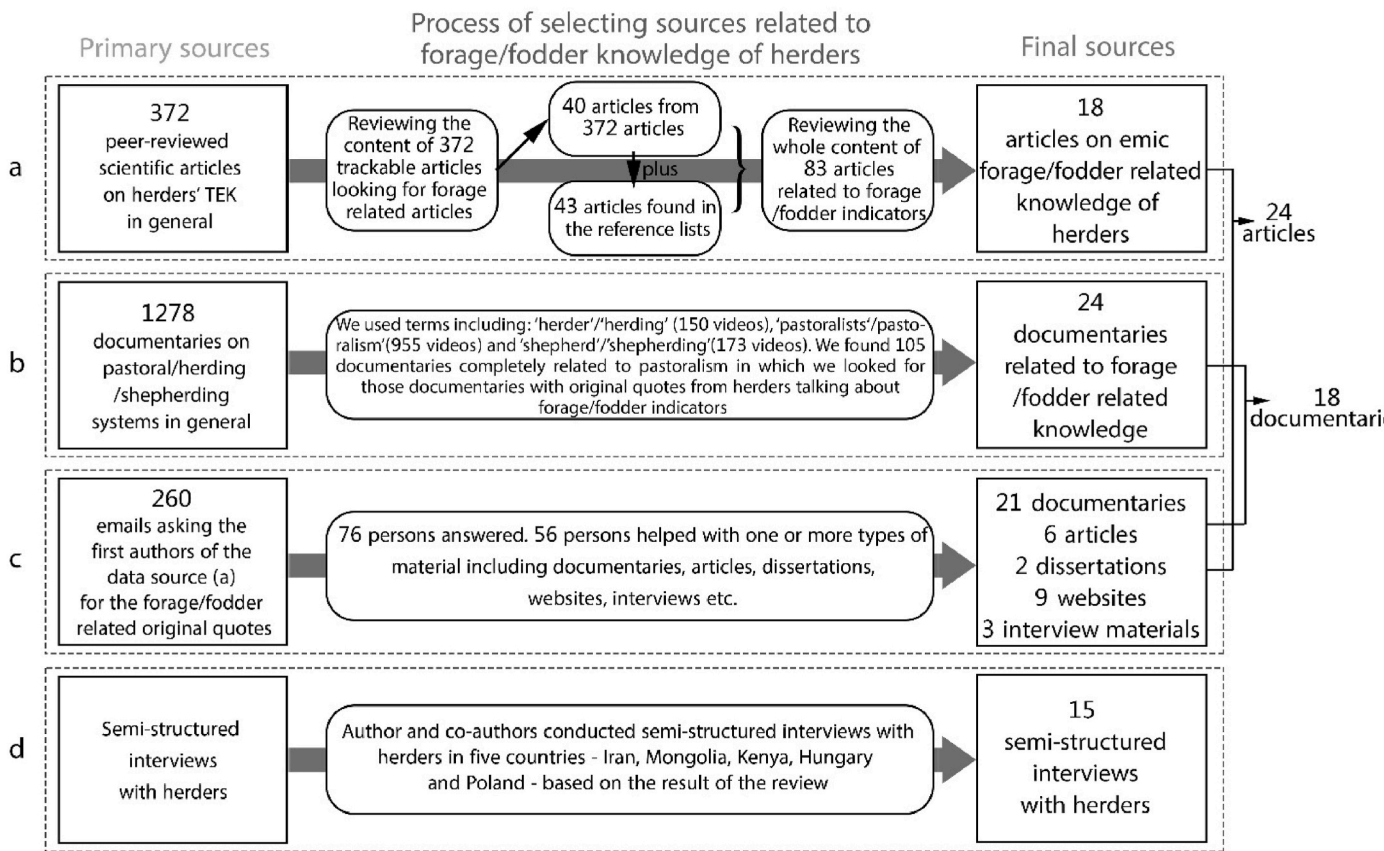

Fig. 1. Process of screening and selecting the sources for review.

and livestock, and 24 documented this knowledge in detail. Out of all the documentaries that we watched, eighteen provided us with information on the emic understanding of forages (Appendix B).

We found 716 forage plant species belonging to 102 families. Among all families, Poaceae (17.5%), Fabaceae (12.2%), Asteraceae (8.2%) and Amaranthaceae (4.1%) had the highest number of species. Regarding plant life cycle, 85.2% of the species were perennials and 14.8% were annuals. With respect to life form, mentions were made of forbs (non-legume forbs, 40.8%), woody species (30.5%), grasses (17.9%), herbaceous legumes (5.2%), sedges (2.8%), lichens (2.5%) and rushes (0.3%).

3.1. *Forage indicators in local traditional pastoral knowledge systems*

We found 35 indicators used by herders to describe forage species (2545 records, Table 1, see Appendix C, Table C1, Figure C1 for all data). Some of the indicators were related to the botanical features of plants (e.g. nutritional value, seasonal variation, size, smell), while others described livestock behavior during grazing (e.g. liked, avoided, grazed only in need). The third group focused on the effects and impacts of forage plants on livestock health (e.g. healthy, medicinal, toxic).

Similar indicators were used to describe and classify forage species by different pastoral systems in spite of the substantial differences in pastoral systems and foraged species globally (Manzano et al., 2021, Fig. 2). Eight indicators were mentioned in at least ten countries (Table 1), such as nutritional value (17 countries), types of livestock (which species eats/avoids it, 14), scarcity fodder (14), seasonal variation (12), animals like or dislike it (12), general valuation (12), only parts are eaten (10), and general impacts on health and status (10). Some indicators were found only in a few countries (e.g. plant gender, livestock posture during grazing/feeding behavior). In addition to the main indicators, sub-indicators used to describe and categorize forage plants were also regularly found to be similar among countries (e.g. fattens the animal, sweet, short grass).

Indicators were not only used at the species level but often referred to specific plant parts (leaves, flowers, fruits, roots) and their traits (size, shape, toughness, texture), which indicates the fine scale of resource use (Bahru et al., 2014; Luizza et al., 2016; Molnár Zs, 2017).

The perception of forages is relative, fuzzy, conditional and specific to context (cf. Knapp and Fernández-Giménez, 2009; Meuret and Provenza, 2015a,b; Molnár Zs, 2017). It is well known that the palatability of forage species changes profoundly within and between seasons, and even within a day following photosynthetic activity (Waudby et al., 2013; Molnár Zs, 2017). Furthermore, preference for a species may also depend on the local combination of co-occurring species, for example, an otherwise moderately preferred species can be highly preferred if surrounded by non-preferred species, or during droughts and cold winters (Ghorbani et al., 2013; Molnár Zs, 2017).

Palatability, which is a key scientific term often used in scientific discussion as a forage indicator (El Shaer, 1997; Ihsan et al., 2018), was not mentioned explicitly in any herder quotes reviewed in this study. This may be due to the fact that the palatability of almost all plant species is a matter of time and place in the view of traditional herders, and expresses a relationship between plants and livestock. Modern rangeland science often categorizes plant species into palatable, moderately palatable or non-palatable, with many plant species falling into the non-palatable category. It is also possible that scientists trained to think in terms of 'palatability' might have translated local descriptions that effectively referred to relationships between livestock and plants into plant attributes. Precise documentation of pastoralists' perceptions of forage plants is essential, as distorted descriptions of local forage knowledge may create conflicts in decision-making about the availability and quality of forage, and the proper ways of grazing management between traditional and modern knowledge systems (cf. Bedunah and Angerer, 2012).

Table 1
Indicators used by traditional herders and pastoralists to describe forage plants in different parts of the world, number of indicators found, and number of countries where the indicator was documented. Individual countries are indicated in upper index. Data are based on the global review of papers and video documentaries, and the interviews conducted by the authors in five countries (Iran, Mongolia, Hungary, Kenya and Poland).

Indicator	No. of indica-tors	No. of coun-tries	Sub-indicators
General			
General valuation (GVa)	590	12	good[HUN1,UGA1,AUT1,GHA1,BFA1,MNG1,POL1,POLint]; weak[HUN1,ESP1]; bad[UGA1,AUT1,MNG1,MNGint,POL1,POLint]; thin[HUN, MNG,POL]; best[HUN1,HUND2,HUNint,POL1,POLint,KEN1,KENint,MNG2,MNGint]
Botanical features			
Nutritional value (NVa)	244	17	fattens the animal[HUN1,UGA1,MNG1,MNGint,BFA1,ESP1,KEN1]; sweet[KEN1,IND1,ETH1,MARD1,POLint], increases the milk[IRN1,HUN1,KEN1,GHA1]
Seasonal variation (SVa)	187	12	good in specific growth stage[AUS1,HUN1,ETH1,IRN1,MNG1,MNGint,SWE1,BFA2,POLint]; depends on precipitation[BFA2, HUN1,IRN1,IRN2,SWE1,KENint]
Availability (Ava)	115	8	high availability[KEN1,KEN2,GHA1,BFA1]; low availability[KEN1,KEN2,GHA1,UGA1,BFA1,AUS1]
Sensitivity (Sen)	35	6	drought resistant[UGA1,ETH1,ETH2]; resistant to repeated grazing[ETH1,KENint]; sensitive to trampling[HUN1,MNGint]
Morphological characteristics (MCh)	35	9	soft[UGA1,SWE1,KENint, POLint,MNGint]; sharp edges[UGA1,ETH1,HUND1]; good or bad if flowers, fruits, leaves are of a specific shape[IRN1]
Habitat (Hab)	32	9	grazed especially in the mountain areas[SWE1,SWED1,ETH1;INDD7,INDD11]; only good if appears in specific habitat[ESP1,SWE1,ETH1,KEN2,KENint,RUS1]
Population trends (PTr)	23	4	increasers[HUN1,KEN1,UGA1]; decreasers[HUN1,KEN1,UGA1]; out-competes other species[HUN1,UGA1,ETH1,ETH2]
Plant herbage yield (PYi)	13	2	high herbage yield[UGA1]; too small as forage for pigs[SRB1]
Method of preparation (MPr)	33	2	good when fed fresh, only good if harvested properly[AUT1,HUNint,SRB1]
Regrowth, resprouting (Reg)	8	5	sprouts very fast after rain[HUN1,ETH1,UGA1,KEN2]; grass sprouting early in the season[ETH1,HUN1,KEN2,MNGint]
Plant size (PSi)	8	5	short grass[MNG1,HUN1,HUND1,HUND2, KEN1,ESP1,KGZ1]; tall grass[MNG1,HUN1,HUND2, KEN1,ESP1,KGZ1]
Chemical content (CCo)	10	9	rich in salt[IRNint,IRN2,MNGint,MNG3,HUNint]; rich in vitamins[SRB1,INDD7,GHA1,BFA1,POLint]; iron[AUT1]
Colour (Col)	3	5	only green-colored leaves are good[IRN1,KEN1,KENint, MNGint,POLint]; black, brown[KEN1]; only good if fruits, flowers, leaves appear in a specific colour[IRN1]
Taste (Tas)	10	7	when it has lost its bitterness, only good if fruits, leaves have a specific taste[IRN1]; sweet[HUNint,KEN1,POLint, MARD1]; salty, bitter[HUNint, MNGint]; dirty[CMRD1,KEN1,KENint]
Smell (Sme)	4	2	good when the plant loses its bitter/acrid? smell[IRN1]; has a good aroma[KENint, HUNint]
Hay quality (HQu)	13	3	lowers quality of hay if there is too much of it[AUT1,HUN1]; when it is still green[POLint, HUNint]
Interannual variation (IVa)	2	3	does not grow every year[HUN1,MNGint,RUS1]; grows as long as it snows in the winter[MNG1]
Plant gender (PGe)	1	1	variation in palatability to sheep between sexes of plant species[AUS1]
Grazing behavior			
Animals like or dislike it (ALi)	102	12	all kinds of animals like it[IRN1,UGA1,MNG1,MNG3,ETH2,HUN1]; animals do not like it[HUN1,AUS1,MNG1,MNG3,SWE1,ETH2, KENint;ARGD2]
Types of livestock (TLi)	362	14	sheep like it[HUN1,HUND1,AUS1,IRN1,IRN2,KEN1,KEN2,MNG3,MNGint, POLint]; grazed by goats[KEN1,KEN2,IRN1,BFA2,ETH2, MNG1,MNG3]; grazed by cattle[BFA2,ETH2,KEN1,MNG1,MNG3,CMRD2]
Only parts are eaten (OPa)	174	10	only leaves are grazed[HUN1,IRN1,ETH1,ETH2,KENint,KEN2,MNGint]; fruits are appreciated[BFA2,ETH1,ETH2]
Grazing behavior (GBe)	5	5	grazed with tongue (good for grazing), grazed with teeth (not good any more)[KEN1,MNGint]; day-and-night variation in grazing behavior[IRN2]; preferences in grazing place (rocky lands for goats, etc.)[IRN2]
Livestock posture during grazing/ Feeding behavior (PBe)	2	1	'long' or 'short' time between bite and swallow[KEN1]
Scarcity fodder (SFo)	117	14	eaten in drought[AUS1,ETH1,ETH2,KEN2,KENint,HUN1,MNG1,ZAFD1,EGYD2]; as emergency forage[AUS1,MNG1,MNGint,IRN1, HUN1,HUN2,AUT1,SWE1,SWED6,POLint]
Impact on health and status			
General (Gen)	98	10	negative when used in large quantity[AUS1,MNG1,AUT1,IRN1,IRN2,POLint]; medicinal[AUT1,MNG1,IRN1]
Causes injury (LHe)	9	7	injures animal's body[HUN1,ETH2,UGA1,INDD12,IRND2,MNG1,MNG3,MNGint]; too much causes loss of teeth[IND1,UGA1]
Causes disease (SDi)	19	7	causes diarrhoea[UGA1,AUT1,MNGint, KENint,SRB1]; causes photosensitivity[UGA1]
Prevents/cures disease (SDi)	49	5	prevents diarrhoea[AUT1,SRB1,POLint, MNGD14,HUNint]; prevents bovine influenza[AUT1]
Appetite (Ape)	41	4	increases appetite[AUT1,FRA1,HUNint,IRN2]
Physiological stage (PSt)	37	5	especially for young stock[AUT1,HUNint, KENint,MNGint, CHED1]; after birth, nutritious for pregnant animals[AUT1]
Animal product quality (APr)	17	7	improves milk fat[AUT1,UGA1,KEN1,KENint, POLint,CHED1]; fur stiff and erect [or: fur flat and smooth [nutritious][KEN1]
Stress (Str)	15	1	calming, prevents irritation in animals, used to avoid stress after transport[AUT1]
Other			
Host to harmful species (HSp)	5	4	refuge for ticks[HUNint,UGA1,KENint, MNGint]; and tsetse flies[UGA1]; provides habitat for predators[ETH1]
Human factors (HFa)	127	6	blessed herbs given on certain days to protect the animal[AUT1]; beliefs[MNG1,HUN1,EGYD2]

ARGD2 = Argentina documentary; AUT1 = Vogl et al. (2016); AUS1 = Waudby et al. (2013); BFA1 = Naah (2018); BFA2 = Sanon et al. (2007); CHED1 = Switzerland documentary; CMRD1 = Cameroon documentary; CMRD2 = Cameroon documentary; DEUD1 = Germany documentary; EGYD2 = Egypt documentary; ESP1 = Fernández-Giménez and Estaque (2012); ESP2 = Fernández-Giménez (2015); ETH1 = Wario et al. (2015); ETH2 = Bahru et al. (2014); ETH3 = Luizza et al. (2016); FIND4 = Finland documentary; FIND9 = Finland documentary; FRA1= Meuret and Provenza (2015a,b); GHA1; Naah (2018); HUN1= Molnár Zs (2017); HUN2= Kis et al. (2017); HUND1 = Hungary documentary (Molnár Zs and Sütő, 2020); HUND2 = Hungary documentary (Molnár Zs and Karácsony, 2021); INDD2 = India documentary; INDD4 = India documentary; INDD7 = India documentary; INDD8 = India documentary; INDD12 = India documentary; IND1 = Duenn et al. (2017); IRN1 = Ghorbani et al. (2013); IRN2 = Barani (2003); IRND2 = Iran documentary; IRNint = interview with Iranian herders for this study; KEN1 = Jandreau and Berkes (2016); KEN2 = Vehrs (2016); KENint = interview with Kenyan herders for this study; KGZ1 = Levine et al. (2019); LSO1 = Pitikoe (2017); MAR1 = Mathau and Puri (2018); MAR2 = Toneu (2017); MARD1 = Morocco documentary; MNG1 = Fernandez-Gimenez (2000); MNG2: Gantuya et al. (2019); MNG3: Sambuu (1987); MNGint = interview with Mongolian herders for this study; MNGD14 = Mongolia documentary; POL1 = Kotowski et al. (2021); POLint = interview with Polish herders for this study; RUS1 = Dwyer and Istomin (2008); SRB1 = Molnár Zs et al. (2020); SWE1 = Inga (2007); SWED1 = Sweden documentary; SWED6 = Sweden documentary; UGA1 = Roschinsky et al. (2012); USA1: Knapp and Fernández-Giménez (2009); ZAF1 = Samuels et al. (2018); ZAFD1 = South Africa documentary.

Fig. 2. A) Hungarian herders point out "*I see the grass through the mouths of my animals*" (Molnár Zs, 2017) which is similar to the observation of a French shepherd as described by Despret and Meuret (2016), that "*his* [the shepherd's] *fingers know and anticipate what the sheep's mouths know*". Both statements, though from herders situated in different countries and herding regions, accentuate the fact that herders' knowledge is partially gained through the close monitoring of the relationship between their animals and the forage. B) Hungarian herders say "*Tippan* (small tussocky *Festuca pseudovina* grass) *is the soul of the Hortobágy steppe!*", which is very close to the observation made by Mongolian herders living 6000 km away who perceive that "*Botjul* (small tussocky *Festuca lenensis* grass) is the best grass that my livestock can find to feed on in Mongolia'' (Gantuya et al., 2019).

Not unexpectedly, the nutritional value of forage species was widely mentioned by herders as one of the main forage indicators. The main difference in the understanding of nutritional value within TEK, when compared to intensive livestock systems, is that traditional herders' perceptions of nutritional values were usually contextual and relative, as the resources they use are highly variable (cf. Smith et al., 2015). For example, a low-quality forage species can be considered as basic, moderately or even most nutritious in a drought period (Ghorbani et al., 2013; Kis et al., 2017; Molnár Zs, 2017). In intensive systems, however, a narrower range of highly nutritious forage plants, mostly cultivated, is constantly used in stall feed to raise the efficiency of the production system. Despite the existence of such a fundamental difference, pastoral production systems are often criticized for their low efficiency (Haghiyan and Nejatiyanpour, 2021). However, it should be taken into consideration that pastoralists use the growth and regrowth of almost all plant species at different times of the year. Through this, although pastoral systems may not be as productive in terms of yield per animal as intensive systems, they produce food on marginal land, support biodiversity, and prevent the encroachment of rangeland and grassland by species prone to dominancy (many of which are alien and/or invasively spreading), and thus are more sustainable in the long term. In addition, the ability to use such a wide array of species allows herders to utilize a broad spectrum of ecosystems that are otherwise too marginal for food or fodder production.

Traditional and modern knowledge systems have several forage indicators in common, including nutritional value, impact on livestock health, livestock performance and plant size (height) (Ball et al., 2001; Molnár Zs, 2017; Kotowski et al. unpubl.). There were also some indicators which were described with different words in the scientific and traditional knowledge systems. For example, anti-quality factors such as nitrates and alkaloids are often used as a forage indicator in science (Ball et al., 2001; Raufirad et al., 2016), while herders spoke about 'impacts on animal health' (e.g. describing a plant as poisonous). In forage, nutrients increase with biomass in the early stages of the plants' life cycle, and decrease in later stages as the plants' biomass continues to increase. Decreasing forage value with ageing is expressed in science with the concept of 'maturity stage' (Ball et al., 2001). Herders too understand this change, and sometimes refer to it as 'seasonal variation'. However, herders' assessment of the nutritional value of forage is contextual to their herds' feeding conditions. In this light, plants at a higher stage of maturity are not necessarily excluded from being grazed. In certain feeding conditions, "cattle [are herded to] eat the dry 'litter' together with the green regrowth"[HUN1, HUND1], as combining grazing on plants at maturity stage is used to 'prevent diarrhoea' when livestock are feeding on new grass after the rains or in spring.

Several of the reviewed papers argued explicitly that in local knowledge systems, a diverse set of indicators is used to describe various forage plants (Vogl et al., 2016; Molnár Zs, 2017). Unlike traditional knowledge systems, modern rangeland science focuses only on a lower number of indicators, and especially on indicators describing productivity of nutritious (usually sown) fodder grass and legume species (Kotowski et al. unpubl.). It seems that the dependence on and the close relationship with the livestock affect the number and importance of indicators upon which decision-making by herders is based. In rangeland science, the shorter forage species list (e.g. Szemán, 2006) and the looser connection with the livestock (e.g. Rogalski, 2004) may be responsible for the lower number of indicators and the different priorities. Adaptive management of natural resources requires innovative rangeland management practices, such as regenerative agriculture, which imply more adaptive decision-making on foraging with a more complex set of indicators, and which actually mirror traditional knowledge (Molnár et al., 2008; Manzano et al., 2021). The differences between the traditional and the rangeland science knowledge systems explained here may help to understand conflicting views around regenerative practices such as holistic management (Gosnell et al., 2020). This debate may have overseen the strong social component of learning complexity in adaptive management (Fernández-Giménez et al., 2019), of which forage indicators are a fundamental part.

The reviewed sources provided ample evidence that herders operate as part of nature (Forest Peoples Programme, 2020; Manzano et al., 2021), and the variability of natural conditions is reflected in the variability of the TEK sets of forage indicators. The constant presence of herders in nature and their monitoring of changes in forage quality and quantity give herders the privilege of knowledge about the temporal and spatial availability of different plant species with full or partial forage value (Fernandez-Gimenez, 2000; Vogl et al., 2016; Molnár Zs, 2017; Gantuya et al., 2021). This leads to the creation of several indicators, each of which acts as a precondition in the selection of plants by livestock and/or herders (Molnár Zs, 2017). For instance, a Turkmen herder in Iran said "the sheep nibble on the flowers of Cheratan [*Halocnemum strobilaceum*] in the middle of February as Cheratan has seven days of spring in the middle of winter" (it is not eaten in other seasons). Thus, we had several preconditions, including types of livestock, only parts are eaten and seasonal variation; when all these preconditions are met, the plant species can be grazed. (Note: *Halocnemum strobilaceum* is considered to be an unpalatable species in modern rangeland science, not only

Table 2
Use of forage indicators to achieve different objectives in various traditional pastoral systems. Data are based on the review of papers, video documentaries and the interviews conducted by the authors in five countries (Iran, Mongolia, Hungary, Kenya and Poland).

Pastoral management objectives	Aspect	Use of indicators (direct quotes in italic and interpretations in non-italic)
Arrange optimal grazing and increased intake	Temporal scale	Like it when flowers are open (not in the morning)[ZAF1]; "*For two months of the year, the pods are good so animals can eat something, if they eat too many pods, teeth fall out*"[IND1]; "*worthless, cattle ate it in winter*"[HUN1]; "*eat it in spring and autumn*"[MNGint]; dry steppe in the morning and wetlands in the afternoon/*without a herder cattle would seek the juicy bits, the worthless is left*/different pasture in the morning and afternoon[HUNint], "*We constantly figure out what the sheep should graze on when, and for how long, and we think about it every day*"[HUND2]
	Spatial scale	Thick woody cover causes physical challenge[ETH1]; grazed on stubble in summer[HUN1]; even palatable plants can become less preferred when they become dominant[ZAF1]; flocks divided, grazed in different pastures (lambs on fresh forbs/grasses)[IRN2]
	Sequencing the menu	"*In the mornings they like reed better, probably softer then*", "*Grazing starts with areas they don't like that much*"[HUND1], "*Or we could say, you have to establish a menu. And then every day I try to go through the menu. grazing them on everything*"[HUND2]; Sequencing forage types and patches that the livestock are allowed to graze during a day for higher intake[FRA1]; "*a good 'salad' after morning corn for pigs*"[SRB1]
	Scarcity periods	"*Animals like it if nothing else is available*"," *in winter they would eat the sour grass*"[HUN1]; "*When nothing else is green livestock will browse it*"[ETH3]
	Salt needs	Flocks taken to pastures with halophytes to meet livestock salt craving[IRN2,MNG3]
	Unpalatable/toxic species	It is poisonous but livestock eat it when dried[MNGint]; toxic and of very poor palatability, but animals graze it in November[IRN1]
Adjust availability and preference	Herd composition	"*It mostly depends on the breed. F1 is more choosy, Hereford eat many plants that the others won't have. That's why herds are of different breeds*"[HUND1]; "*The grass that is good for sheep is fino - it is small*"[ESP1]; "*cattle eat it when it's green, they also pick off its seeds; its tubers are eaten by pigs*"[HUN1]; "*It is the best for cows, opareshi, irikarro, and emunuwa, as well as empalakai*"; "*provides forage for livestock especially camels and goats*"[ETH3]
	Browser and grazer	Browsed by sheep and goats and grazed by cattle; grazed by goats in post-rainy season[BFA2]; browsed by goats when it [*Pulsatilla* sp.] starts to grow[MNGint]; *The pods* (sakaram) *are perceived as a favorite feed for goats*; "*camel graze it*"; *browsed by* goats[KEN1]
Migrate at the right time and to the right place	Time of migration	"*In Khoozestan province there is a species called Bahman* [*Stipa capensis*] *which, when it starts growing, we have two months' time to survive there, as this species* [when it passes its vegetative stage] *penetrates the sheeps' body like a needle and kills it*"[IRND2]; "*We see the cows are getting enough grass, but still not good milk. We must move from here because it's not a good place. This area is cold for our livestock; the species of grass growing right there is not good for cows. Maybe the grass is tall, but it's cold.*"[KEN1]
	Length of migration	"*Herders nomadized to the Khangai* [mountain-steppe] *region for two to three months. But when autumn begins, and the taana* [*Allium polyrhizum*] *is half dried, we nomadized back to the Gobi*"; "*for example, bagluur* [*Anabasis brevifolia*], *if this plant has only two or three joints, the herdsman will move to another place*"[MNG1]
	Spatial patterns of migration	"*Compared to here, high altitude grass is more nutritious*"[INDD11]; on elevation such as mountains and hills, early sprouting grass is considered important grazing forage during the early part of the rainy season[ETH1]; "*male grass* [mostly *Festuca lenensis*, *Koeleria* spp.] *is more nutritious and best for livestock, it usually grows on southern slopes of mountains. Borog* [*Carex duriuscula*, *Kobresia* spp. and other *Carex* spp.] *that grows near forest in the river and valley is less nutritious, so livestock graze such places mostly in the warm season*"[MNGint]
Prepare good hay	Timing	"*It makes good hay until it casts off its head*"; "*good hay if cut in time*"; "*sheep like the straw with Cirsium arvense, better than alfalfa if cut before it flowers*"[HUN1]; "*it makes good hay after its head turns brown*"[MNGint]
	Mixing	Could be harvested during the rainy season, and conserved as hay and fed to cattle as a supplement to *Hyparrhenia rufa* during the dry season[UGA1]; "*we mixed it* [*Melilotus*] *in the hay of poorer grass* [for better smell]"[HUN1]; "*some bad or toxic grass is mixed in our hay but it is fine for livestock in winter because it has dried*"[MNGint]
	Quantity	"*It is never cut for hay (because too low)*"[HUN1]
	Quality	"*It is important to make good quality hay when the grass turns brown, saturates and before the nutritional quality is lowered, so we mostly prepare hay from 10 to 20 August*"[MNG3,MNGint]; "*Proper hay should be thin and young. It has the biggest amount of vitamins then. It should be fresh and dry. Usually we collect hay quickly, when it is still green. Young, green, dry – cool*"[POLint]
Prevent or cure diseases with targeted grazing	Prevention	Gets nibbled on but is less preferred as it can cause *waterpens* (water belly) when consumed at certain times during the year[ZAF1]; There are Gowdonbal [*Verbascum thapsus*] and Tanges [*Rhamnus pallasii*] in spring that cause jaundice. Shepherds avoid the pastures with these species when they have the highest amount of toxin[IRN2]
	Healing	"*One of the most important abilities of an experienced pastoralist is to diagnose plants to cure animal diseases. It means that he should have enough knowledge about plants and if his livestock is sick, he takes them to the parts of the rangeland that have medicinal plants*"[IRN1]; herders in Mongolia use some medicinal plants like *Sausurea involucrata, Sanguisorba officinalis* and *Salix* spp. to treat livestock[MNGint]; *leaves are bitter, seeds (look like apple or sunflower seeds) are healthy for piglets* (driven to *Carpinus* forest if they have stomach or lung problems)[SRB1]
Increase mating	Ram readiness	"*Before putting the ram into the flock, the best grass and pasture should be available for the ram.* [The ram] *should be kept far from female sheep and its smell, so it can get strong enough*"[Iranint]
	Mating efficiency	"*Mating starts when we graze the flock on crop residue* (barley and wheat) *as it increases the success of mating*"[IranINT]
Help pregnancy	Maintenance condition	"*In the past vitamins and other supplements were not given* [to pregnant sheep] *because they could find everything that they needed on the pasture. Now it is different*"[POLint]
	Delivery	"*Closer parts* [with better grass] *are usually left for lambing, the ones around the shed. The best bits are left mainly for the pregnant ewes.*[HUNint]/"*For those cows which are weak and are not able to deliver their calves they use Mokhor* [*Viscum album*] *which grows on the Namdar tree* [*Tilia platyphyllos*]"[IRNint]
Help ewes/cows and lambs/calves	Ewe/cow recovery	"*After giving birth, the ewe is weak. Therefore, we give them Kodi (male ficus)* [*Ficus carica*] *leaves, Bane* [*Pistacia atlantica*] *leaves, or even Badoom* [*Amygdalus scoparia*] *seeds and flowers. You should not give too much Badoom though. It is not good for their health*"[IRNint]; "*This is 'Yumdujen'* [*Dianthus superbus*]. *We give it to cattle and sheep. We usually give it to animals after they give birth, if some of the placenta hasn't come out*"[MNG14]
	Pasture for lamb/calf	"*More thin and soft grasses are given only to lambs and kids in spring*"[MNGint]
Increase milking	Milk quality	"*The taste of milk has changed because native plants are gone and the animals eat many weyane* [*Prosopis juliflora*] *pods*"[ETHxx]; "*If livestock from the Khangai region graze in the Gobi pasture, the taste of their milk is changed by Gobi species like taana* [*Allium polyrhizum*]"[MNGint]
	Milk quantity	The quantity of milk increases when livestock move from pasture that has been grazed for a long time to ungrazed and fresh grass[MNGint]; "*I have been living in different areas, Olulunga, Mara, Naroksura; but the most suitable area for cattle is in Olkiyumbo. The grass is very warm for our livestock. The moment they graze there they get milk*"[KEN1]
Manage for better pasture	Timing	[Burn the species because] it is detrimental to grass growth; provides habitat for predators that prey on livestock[ETH1]; trample invading tall marsh plants not eaten by livestock [*Typha, Schoenoplectus*], browse and trample encroaching less palatable bushes [*Salix cinerea*], and weed out harmful plants [*Carduus, Verbascum, Rhinanthus*][HUNint]; "*I do not graze on tippan* [*Festuca pseudovina*] *in dry weather as livestock will only break it with their legs*"[HUNint]

in Iran (Fayaz et al., 2014), but also in other countries (El-Morsy, 2010)).

3.2. Use of forage indicators in pastoral management

Herders regularly used the various forage indicators when deciding on livestock grazing movements and rangeland management (Table 2, see Appendix C Table C2 for all quotes). Detailed knowledge of the forage condition and distribution over space and time, as well as of livestock preference and behavior, enabled them to find the right time and place for grazing under the prevailing conditions (Inga, 2007; Meuret and Provenza, 2015a,b; Molnár Zs, 2017). The objectives of using forage indicators were often very similar among mutually distant pastoral groups (Table 2).

Herders used a wide range of forage indicators in their daily, weekly, monthly and seasonal herding and grazing management. For example, to modify livestock desire, herders sequence 'appetizers', 'main courses' and 'desserts' along daily grazing routes (Meuret and Provenza, 2015a, b; Molnár Zs et al., 2020); considering the phenology of forages (time of flowering, fruiting) to plan monthly-scale grazing movements (Fernandez-Gimenez, 2000); and relative palatability (the best available …) to design seasonal migrations (Wario et al., 2015; Gantuya et al., 2019).

Herders move livestock at diverse spatial and temporal scales to utilize forage resources in the most productive period possible (e.g. Behnke and Scoones, 1993; Krätli and Schareika, 2010). Among other reasons, this is to ensure optimal weight gain of their livestock and successful reproduction (improved mating, strengthened mothers and young animals, increased milk provision) by utilizing the transient forage nutrients while portioning the pastures to last for the whole season/year (Molnár Zs and Karácsony, 2021; Molnár Zs and Sütő, 2020). Movements are applied 1) because there is not enough pasture locally (e.g. Dwyer and Istomin, 2008; Sambuu, 1987); 2) to reach the optimal utilization stage of diverse forages ('To be at the right place at the right moment', Linstädter et al., 2013); and 3) for long-term maintenance of pasture resources (e.g. Linstädter et al., 2013; Liao et al., 2014; Fernandez-Gimenez, 2000). For example, to match actual grazing patterns to the present and future predicted availability of forages, herders graze the same area with different livestock species, or move livestock to different habitats (Sambuu, 1987; Sanon et al., 2007; Varga et al., 2016; Gantuya et al., 2019). For traditional herders, grazing also means healing at the same time, as forage and medicine are not necessarily distinct categories (using forage plants for medicine) (Provenza and Cincotta, 1993; Provenza, 2003; Villalba and Provenza, 2007; Maiti et al., 2013; Aziz et al., 2018).

Herders benefit from the diversity of forage plants (e.g. grasses, forbs, sedges, trees and shrubs, herbaceous legumes, lichens, crop-field weeds) by keeping variable herds (sheep, goat, camel, cattle etc. in divided or mixed herds) (Molnár Zs, 2012; Gantuya et al., 2019) or even a variety of lineages within a given breed, with different feeding habits and performances (Kaufmann, 2007; Krätli, 2008). The basis of these decisions is the knowledge of specific plant-livestock interactions (Bartolomé et al., 1998; Samuels et al., 2016), preference for certain places (e.g. rocky places for goats, plain areas for sheep, Sanon et al., 2007; Animut and Goetsch, 2008), temporal variation in grazing behavior (e.g. being less selective during the night, Barani, 2003), and scarcity periods (Molnár Zs, 2017; Schroeder et al., 2019). The Wodaabe pastoralists talk of a 'calming effect and companionship' between certain livestock species, which they think help with herd management and animals' feeding performance, not just in view of an optimal use of forage (Krätli, 2008).

Dividing the flock into dried vs. drop/wet/lactating, young vs. adult, male vs. female, weak vs. non-weak and pregnant vs. non-pregnant bands in order to provide each category with specific pasture is another practice in managing forage resources (Eugene Ensminger and Parker, 1986; Sambuu, 1987; Barani, 2003; Meuret and Provenza, 2014; Motamedi et al., 2018). For example, the sedentarized Borana herders of Southern Ethiopia and northern Kenya divide their herds into *haawicha* (kept near settlements for milk supply) and *foora* (dry herds taken to distant grazing lands), as a strategy to access various pastures (Helland, 1980; Wario et al., 2016).

In the mainly heterogenous grazing environments, herders associate certain plant species with specific rangeland units. They also select different habitats for grazing with specific objectives. For instance, marshlands or forests are often pastured in winter and drought periods in Central Europe (Varga et al., 2016; Biró et al., 2019) to avoid or overcome forage scarcity. The selection of different rangeland units or habitats with specific forage properties influences the herders' grazing decisions and spatio-temporal livestock movement over the rangelands (Wario et al., 2016). The differences in the spatial distribution of forage species and the varied properties over time (e.g. gradual drying out, gradual change in nutrients in the course of plants' life cycle) provide an opportunity for herders to time their mobility to access the desired forage over a longer period during the season (Kiptot, 2007; Krätli and Schareika, 2010). This is an attempt to stretch the rainy season and the period of abundance in a highly variable environment such as the African savanna. With an understanding of the grazing potential of a range unit and that of specific forage species, where spaces allow, herders regulate the time spent in any particular area in order to optimize animal nutrition and decrease the possibility of degradation (Sambuu, 1987; Oba, 2012; Ghorbani et al., 2013; Molnár Zs, 2017) and help avoid undesirable situations such as biting insects, ticks and poisonous plants (Ghorbani et al., 2013; Gantuya et al., 2021). In some cases herders manage the species composition of their pastures by protecting plants that have certain properties while inhibiting others (Molnár Zs, 2017; Molnár Zs and Sütő, 2020).

3.3. Sources and transfer of knowledge of forage plants and their indicators

In fourteen sources there was explicit information about where the knowledge of forage plant species comes from (see Appendix C Table C3 for all quotes). The classical model of knowledge transmission includes three types of transmission: vertical (e.g. parents to children), horizontal (among individuals of the same generation) and oblique (between unrelated generations) (Cavalli-Sforza and Feldman, 1981). The main source of forage-related knowledge that was mentioned explicitly in the reviewed sources was knowledge transmitted by family members and elders. Both empirical and abstract pathways of knowledge transmission and imitation are important mechanisms of TEK acquisition.

However, forage knowledge in pastoral systems is not limited to 'human knowledge'. There is important 'animal knowledge' at work too in different forms, including epigenetic transmission (Krätli, 2008; Jablonka and Lamb, 2006). Furthermore, animals not only 'know' as part of their nature (knowledge coded in genes), they too need to learn (Provenza and Cincotta, 1993; Provenza and Launchbaugh, 1999; Krätli and Schareika, 2010; David et al., 2019). Pastoralists' livestock carry knowledge that is relevant to pastoralism because they have learned it over generations in pastoralist herds. The knowledge cycle in pastoralism includes both herders and livestock over both human and animal generations (Meuret and Provenza, 2015a,b; Krätli, 2008).

Often herders gain their knowledge from older family members: "*All good herders have herder ancestors. You have to be born into it, it can't be learned from books*"[HUND1]/"*from older generations, it has been explained to us since our childhood*"[POLint]/"*Our parents taught us, so we do the same*"[IND1]/"*My grandmother was like an 'engine'. She was pushing us all.*"[ARGD1]/"*We gained this knowledge by learning from our parents*"[MNGint]/ "*we could observe their work*"[POLint]/"*We weren't taught* [directly] *but we just picked up knowledge. Although my grandfather never explained, I knew instinctively why he did a certain thing*"[HUND1].

Herders also learn from their peers as they interact during livestock herding, and knowledge exchange occurs horizontally. A Rabari shepherd in India mentioned that "*Other people migrating in the area also teach us, we share our knowledge. So we always know what to use in new* *areas.*''[IND1]/"*I have neighbors who say my granddaddy did it this way and I am doing it this way.*''[USA1]

Herders' own experiences and observations are also often reported as a basic source of knowledge of forage. "*I have really learnt a lot from my herding experience*"[LSO1]/"*It's much more than forest, snow, reindeer and lichen, you have to understand the whole circle as well. It's so hard to document, but above all you have to experience it to understand*"[SWED1]/"*A herder tastes the grass that his livestock eat* [i.e. is interested in what livestock eat]. *Goats eat a lot of succulent and bitter herbs.*"[MNGint]/"*You have to see your animals every day, otherwise you are lost*"[HUNint]. A Sami woman reindeer herder criticized scientific methodology in measuring forage production, as follows: "*The wind and snow burden makes bread moss fall down from the canopy, which provides plenty of food for the reindeer. Research on reindeer grazing has solely focused on the layer that is easily accessible to them. I think this is an oversimplified view, and the reality is much more complicated.*"[FIND9] Learning by doing and practicing is an important process in acquiring TEK, where Indigenous peoples and local communities (e.g. pastoralists) learn about their environment and the elements of their nature-oriented subsistence on their own, through trial and error (Simpson, 1999).

Based on their experiences, herders are sometimes proud of their innovations. "*A shepherd has to invent*"[ESP2]/"*A herder's duty is to think!*"[MNG2]. The dynamic nature of a pastoral livelihood, as well as pastoralists' TEK, which follows the dynamic changes of their environment, forces pastoralists out of a stable zone, where they have to adapt to new sociocultural, economic, political or ecological surprises (Fernández-Giménez, 2015). To increase their resilience, pastoralists not only act based on their experiences, but also apply practices which are formed innovatively.

Learning about plants from the livestock is reported as crucial in learning about forage species. *"I see the grass through the mouths of my animals", "I keep watching what the cattle eat"*, "*Now I look at it from the sheep's point of view*"[HUN1,HUND1,HUND2]/"*You can see it through sheep's physical condition, its milk and the quality of 'oscypki' [local cheese]*"[POLint]/ *"As a Maasai, we look to the fur to see if it is standing upright, to know if the area we are grazing is not good for cows", "We can see if the grass is enough depending on if they graze with their teeth, or with their tongue.*"[KEN1] (grazing with the teeth is a sign of forage shortage), "*Herders should observe every day the grazing livestock's belly, colour and fattening, and change the pasture immediately if there are any shortages of grasses, water or salt*"[MNG3]. "*I looked at the sheep and saw that the wool was not erect and shiny. I asked the shepherd: what has happened to the sheep?*"[IRNint]. The relationship between pastoralists and forage depends on whether a plant species is used by the livestock or not (cf. Hunn, 1982). Proper herding and grazing are possible when pastoralists and their animals practice reciprocal learning, where pastoralists improve their skill and art in herd management and livestock production through constant and close monitoring of livestock feeding and the condition of their body and products (Meuret and Provenza, 2014; Molnár Zs, 2017). To unravel the complexity of relations between pasture elements (e.g. forage plants) and livestock, pastoralists try to understand the situation through the lens of the livestock and even try to put themselves in the position of the animals (Fernández-Giménez, 2015).

Sometimes herders refer to certain beliefs or worldviews that were connected to forages. [After speaking about good and bad forage plants he continued] "*Everything created by God is good, there is no bad that comes from him*"[KEN1]/"*We don't cut acacia when the southern winds are blowing but it is OK to pollard the Balanita tree*". [The narrator:] "*before* [cutting the branches of acacia] *they* [pray and] *ask* [the tree] *to forgive them*"[EGYD2,SUDD1]. In Gyimes (Eastern Carpathians, Romania) some people know a story about the inheritance of knowledge on medicinal plants: plants could speak until the death of Jesus. When Jesus died, the plants fell silent. What the local community knows today about medicinal plants is what has not been forgotten since the death of Jesus. Therefore, the parents' knowledge of medicinal plants needs to be learned (Babai unpubl.).

The future of traditional forage-related knowledge depends on the future of traditional pastoral systems. As long as pastoral systems and their practices remain alive, the knowledge will also survive (Spoon, 2011).

3.4. Global principles of forage-related knowledge

The review of forage indicators and their use in herding management (Tables 1 and 2) showed that despite the specificity of pastoral TEK, which highlights the space-based and context-based features of such knowledge, there were many indicators and management objectives and practices used by pastoral communities in different countries that shared similarities. We were able to identify several common features, which we grouped into ten general principles of forage-related pastoralist TEK (Fig. 3, Table 3).

Herders 1) have a livestock-centered perspective of forages (see e.g. Kiptot, 2007; Molnár Zs, 2017; Roturier and Roué, 2009), 2) closely monitor and predict forage quantity and quality, and 3) utilize targeted grazing of plants with medicinal and good nutritional properties to improve livestock condition and health (e.g. Fernandez-Gimenez, 2000; Ghorbani et al., 2013; Vogl et al., 2016). 4) Traditional herders have an internalized responsibility to optimize livestock's forage selection and intake both in space and time (Meuret and Provenza, 2015a,b; Molnár Zs, 2017; Molnár Zs et al., 2020). 5) The livestock is herded (driven, redirected or stopped as is appropriate), but has some freedom in the choice of the forage and the place to graze (e.g. Meuret and Provenza, 2015a,b; Molnár Zs and Sütő, 2020; Molnár Zs and Karácsony, 2021). 6) Herders use livestock types with different feeding requirements and knowledge 7) to manage and utilize pastures properly (as tested e.g., in Cuchillo-Hilario et al., 2017, 2018), through understanding relative and changing palatabilities, and for better sustainability outcomes (Martin et al., 2020), 8) adapting to changing forage availability and quality by spatial movements, and 9) with proper timing of spatial movements (e.g. Fernandez-Gimenez, 2000; Kiptot, 2007; Meuret and Provenza, 2015a, b), while 10) they keep their focus on context-specific changes in forage preference and forage intake (e.g. Inga, 2007; Waudby et al., 2013; Meuret and Provenza, 2015a,b, Molnár Zs and Karácsony, 2021).

We can only hypothesize the main drivers behind these general, common features. Plants, livestock and humans all possess several general features, which could lead to these similarities.

First, most plants are sedentary and good survivors, yet with a limited capacity to disperse, so in the long term, pastures (even annual-dominated ones) have a relatively stable species composition in most of the pastured areas. The intensity of plant growth and the richness in nutrients usually greatly depend on precipitation, while most plants prefer 'intermediate, moderate' temperatures (Khishigbayar et al., 2015). Absolute and relative palatability of forages usually change with the season and always have a spectrum in a landscape from 'low' to 'high' (Molnár Zs et al., 2020). Furthermore, there is limited manageability of species composition and nutrient availability in most extensively pastured areas, and this again fosters adaptation and resilience (Lambert and Litherland, 2000).

Second, there are only a few dominant livestock species (cattle, sheep, goat + camel, horse, reindeer) used widely in extensive pastoral systems (LPP, 2021). All these livestock species are social mammals, most are ruminants, and all have established but modifiable forage preferences (Meuret and Provenza, 2014).

Third, people share many common features all over the world. For example, people's dependence on livestock (livelihood, income, provision of food), and biophilia may lead to herders being deeply committed to taking responsibility for and caring for their animals. Herders all over the world use their knowledge of forages to maneuver through gradual and sudden, predictable and unpredictable social-ecological changes (Fernandez-Gimenez, 2000; Duenn et al., 2017; Nori, 2019; FAO, 2021). Herders tend to have a strong desire to utilize the available nutrients optimally, while also considering the long term (cf. rotation, regeneration, reserve pastures, otor [Murphy, 2011] movements [Genin et al., 2018; Gantuya et al., 2021]). An acceptance of unpredictability as 'normal' is widespread among herders using multigenerational experience of coping with unpredictability (Krätli and Schareika, 2010). And finally, an inner wish, a well-conceived interest exists among them to know the environment well and to adapt to it in the long term, for example, by selecting the best suited breeds and individuals, as well as optimizing herding practices for long-term profitability and ecological integrity (Roba and Oba, 2009; Gantuya et al., 2021).

Knowledge acquisition and transmission pathways in traditional knowledge systems also have similar elements, as does the character of ethnobiological knowledge regarding the range of locally known plant species (Berlin, 1992). The main pathways of knowledge transmission (vertical, horizontal and oblique) and imitation are also generally important (Cavalli-Sforza and Feldman, 1981). Personal experience and observation complement and update the ecological knowledge transmitted. Furthermore, there seems to be a definite correlation between livelihood type and range of known species (Bruyere et al., 2016).

In summary, the generality of these principles is likely to be a consequence of working with livestock with a nature-positive approach and learning from the animals' relationships with forage plants. Ruminants and natural forage plants are ruminants and natural forage plants at all latitudes. Therefore, to an extent, their relationships are inevitably similar.

Despite these general principles, the lexical details of pastoral knowledge of forages and livestock is diverse, as are pastoral management systems (Manzano et al., 2021). Again, there may exist several potential drivers of these local and regional specificities. For example, the differences between biomes, and landscapes within a biome (spatial heterogeneity, contrast and scale of patchiness of soil and geomorphology), differences in species composition of pastured areas (e.g., plant trait compositions, proportion of nutritional, thorny, toxic etc. species), and differences in forage unpredictabilities (e.g., of fluctuations, contrasts between seasons, amplitudes and trends of changes) (Animut and Goetsch, 2008; Liao et al., 2014; Gantuya et al., 2021). Furthermore, differences exist between and within livestock breeds (e.g., forage preferences, tolerances, behaviors, social organization, skills and animal knowledge), in herding strategies (e.g. free, tended, herded; sedentary, transhumant, nomadic), and in cultural norms, values, institutions and worldviews related to herding (Krätli, 2008; Tamou et al., 2018; Stolton et al., 2019). Complex decision-making of pastoralists regarding forage plants through using a mixture of indicators may explain why, for example, regenerative grazing methods have been difficult to systematize.

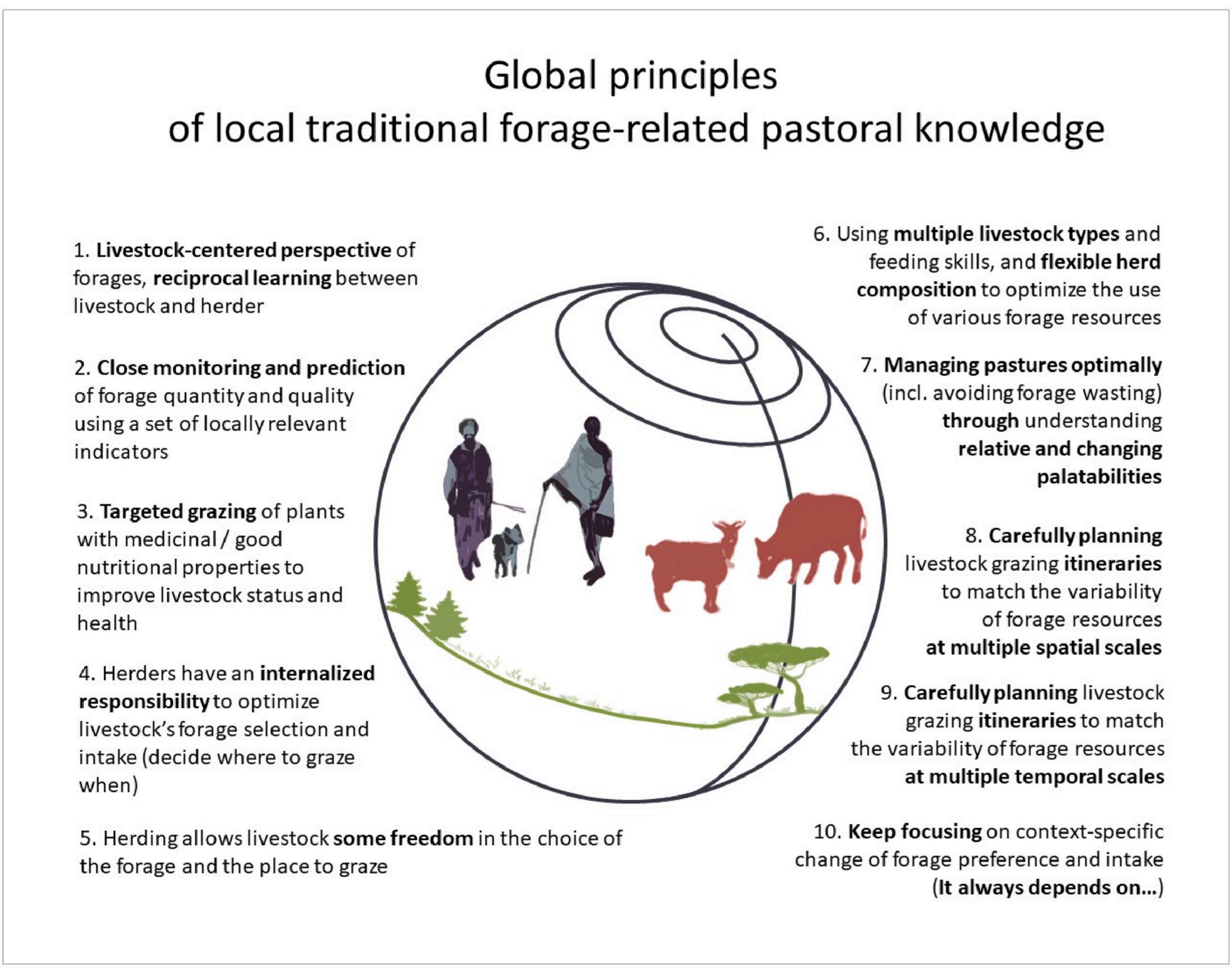

Fig. 3. The 10 global principles of traditional forage-related knowledge based on a global review of forage indicators and their use in herd and pasture management.

Table 3
Globally general principles in herders' forage-related traditional knowledge (forage indicators and their use in management).

Livestock-centered perspective of forages (forage needs and desires, health, reproduction), reciprocal learning between livestock and herder about each other's forage-related decisions (accumulation of multi-generational knowledge, often born into it)	"*We have an association with the cattle. We love and look after the calves like our children*"[INDD4]/"*When the herd is happy then so am I. A herder sacrifices himself for his herd and the herd sacrifices itself for its herder*"[DEUD1]/"*I need to be a man adapted to the mountains. A little more than the sheep. But not much*"[ESP2]/"*sheep need as much love as a child; anyone who doesn't love animals shouldn't watch over them, these animals expect things from us*"[HUN1]; "*I am the servant of my sheep, the sheep is the boss, I am its servant*"[HUNint]
Close monitoring and prediction of forage quantity and quality (and their patchiness) using a set of locally relevant indicators	[It is] "only palatable at the end of June, palatability is very low in November, they are particularly palatable during their growing cycle—especially in spring and summer, but after about 22 July the leaves are usually dry enough"[IRN1]/"*if only it rains in the next two weeks* (August) *we will have a good autumn pasture, otherwise we will go home early this year*"[HUNint]/"when the plant has completely grown it has a big yellow flower, an excellent forage for livestock, when autumn begins, and the taana [*Allium polyrhizum*] is half dried, if this plant has only two or three joints, the herdsman will move to another place"[MNG1]
Use (targeted grazing) of plants with medicinal and good nutritional properties to improve livestock status and health	"*Listen to me. There are two types of plants in general. Summer plants* [annuals] *and winter plants* [perennials]. *Winter plants are those which dry up in winter and summer plants are those which dry up in summer. The sheep in this area graze on winter plants all year round. It needs to graze on summer plants to be healthy. Otherwise, it gets sick and doesn't do well*" [IRNint]/"*before mating I bring them here to graze on tippan (Festuca), to make them strong and healthy*" [HUNint]
Inner need for responsibility of the herder in modifying livestock's forage selection and intake (e.g. conscious sequencing of forages by herding)	"*There are a lot of grasses the cattle don't like. Like children … But I make them eat everything …* [at the right time]/*If it was up to them they would eat what they like but not much else. And the grasslands would be spoiled*"[HUND1]/"*The main thing is to organize the animals' encounter with different mixtures of forages to boost their appetite*"[FRA1]/"*I can't rest under a tree to watch the cows, I must be in with the cows, watching how they are grazing, seeing if they are grazing in a good manner, to see if they are getting enough grass. If not, I drive them to another area*"[KEN1]; "*we want to have the cattle want to go where we need them to go*[USA1]; "*reindeer pastoralism rests on successful deciphering of herd behavior by the herders*"[RUS1]
The livestock is herded but to a certain degree it is allowed to play a decisive role in forage selection, place of grazing	"*So cattle know they are bound to graze here … Yes, but whenever they see a chance to get out of here they would try to take it*"[HUND1]/"*Because it's always the reindeer who decides if he will eat here, there, or not at all. And then goes somewhere else*"[SWED1]/"*Pigs know better where to forage, they like freedom as we do*"[SRB1]/"[We want] *to let each of our sheep select what it prefers to eat at this moment in the grazing circuit*"[FRA1]/"If they are spread out and are calm, we let them graze, they know how to fill their bellies"[SRBint]
Using different livestock types (incl. adjusting herd species composition) to make use of various forage resources	"*The sheep usually like to graze on the flat low lying areas. The goats prefer grazing on steeper ground amidst rocks*"[INDD8]/"*You send people to research the hills to see if there is enough grass for cows, and send others to research the plains for sheep. This is called lale'nok*". "*There are fewer options to graze cattle*"[KEN1]/"*Goats are good climbers in mountainous and difficult regions and can graze steep slopes. But lambs are less active and more delicate than goats and need fresh and sufficient fodder*"[IRN1]
Making use of 'all' plant resources, through understanding and utilizing relative and changing palatabilities (which species when and how)	"*They are picking some out, some are avoided, some just partly eaten. When there is nothing to choose they eat what there is*"[POLint]/"*With a herder around they are grazing. No grass is wasted.*"[HUND1]/"*You can only graze this grass (Festuca arundinacea) after the first frost, it becomes tasty and soft*"[HUNint]/"*Pastures are wasted because there are not enough cattle and sheep. We waste what nature gives us*"; "*If we cut the hay on the wet meadows in time, by the time the upper pastures dry out, we can move to the second growth*"[SRBint]
Adapting to changing forage availability by proper timing of grazing at multiple temporal scales	"*No day is the same as another. You always have to be thinking. Because the days change even in the same place.*"[ESP2]/"*Every plant has a distinct suitable time for grazing. The shepherds should not conduct herds to the rangelands until this time comes; like marriage has its suitable time*"[IRN1]/*Each season has its own grass, which is the best and useful at that time*"[HUNint]
Adapting to changing forage availability by spatial movements at multiple spatial scales	"*When I could see they were bored, I herded them up and took them to another area*"[HUNint]/"*if we stay in the same place, the livestock stops getting fat*" [MNG1]/"*We migrate into the upper regions of the forests in these mountains. These regions are rich in herbs and plants that are nutritious and help fight diseases*"[INDD2]
Keep focusing on context- influenced change of forage preference and intake (it depends on …)	If you ask herders: "*Do your sheep like that plant?*" most of them answer: "*It depends on context.*"[FRA1]/[is that plant good for your animal?] "*it depends* (on season, weather, breed, age, health status and how full their stomachs are)"; "*They are animals, not machines* (i.e. moods and needs change)"[HUNint]/"*livestock don't like to eat bread and honey all day long, they like some desserts and other stuff as well*"[ZAF1]; "*livestock do not like to eat one plant all day and nor do people* [eat always the same food]"[MNGint]

3.5. *Conclusions: using general principles of pastoral knowledge to improve research and policies*

In our review we identified 35 forage indicators and 10 main principles of forage-related knowledge that seem to be present globally. We found that herders' knowledge of forages and plant-livestock interactions reflected both context-specificity and general features (cf. local versions of a universal knowledge, Posey, 2002). Rangelands, whether grasslands, savannas, shrublands, woodlands, steppes, tundra or alpine, are the main source of forage and fodder provision for herders. In order to optimize use of the available resources, herders adjust their knowledge and grazing practices to local variabilities. The similarity among the local forage indicators used by different pastoral systems may indicate similar challenges encountered by herders in implementing their local knowledge.

Participatory and collaborative research between herders, scientists and conservationists has the potential to provide a better understanding of the challenges faced by pastoralists and herders. The 10 global general principles identified in the present study could be used by researchers to analyze these challenges in comparative studies of pastoral socio-ecological systems. Improved understanding of pastoral knowledge of forages and grazing management could help avoid harmful top-down policies and regulations and provide a basis for increased support for bottom-up initiatives. Understanding local knowledge on landscapes, forage species and their significance in livestock production may also help to safeguard the precarious livelihoods of traditional herding communities.

We hope that the general principles documented in this paper may facilitate a global-level synthesis without losing the essence of local traditional pastoral knowledge systems. A better understanding of how forage information is used by pastoralists can also help to disentangle questions about adaptive rangeland management. The International Year of Rangelands and Pastoralists (International Year of Rangelands and Pastoralists, 2020) provides an ideal opportunity to discuss globally relevant aspects of the otherwise highly diverse pastoral and herder communities. Herders' traditional knowledge may appear in many respects to be local, but our review has unveiled some of its main common general principles.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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