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INFORMING DECISION-MAKING WITH
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Knowledge co-production with traditional herders on cattle grazing behaviour for better management of species-rich grasslands

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Abstract

1. The research gap between rangeland/livestock science and conservation biology/vegetation ecology has led to a lack of evidence needed for grazing-related conservation management. Connecting scientific understanding with traditional ecological knowledge of local livestock keepers could help bridge this research and knowledge gap.
2. We studied the grazing behaviour (plant selection and avoidance) of beef cattle (*c*. 33,000 bites) on species-rich lowland pastures in Central Europe and traditional herding practices. We also did >450 outdoor interviews with traditional herders about livestock behaviour, herders' decisions to modify grazing behaviour and effects of modified grazing on pasture vegetation.
3. We found that cattle grazing on species-rich pastures displayed at least 10 different behavioural elements as they encountered 117 forage species from highly desired to rejected. The small discrimination error suggests that cattle recognize all listed plants 'by species'.
4. We also found that herders had broad knowledge of grazing desire and they consciously aimed to modify desire by slowing, stopping or redirecting the herd. Modifications were aimed at increasing grazing intensity in less-desired patches and decreasing grazing selectivity in heterogenous swards.
5. *Synthesis and applications*. The traditional herd management practices presented here have significant conservation benefits, such as avoiding under- and overgrazing, and targeted removal of pasture weeds, litter and encroaching bushes, tall competitive plants and invasive species. We argue that knowledge co-production with traditional herders who belong to another knowledge system could help

connect isolated scientific disciplines especially if ecologists and rangeland scientists work closely with traditional herders, co-designing research projects and working together in data collection, analysis and interpretation. Stronger links between these disciplines could help develop evidence-based, specific conservation management practices while herders could contribute with their practical experiences and with real-world testing of new management techniques.

KEYWORDS
adaptive management, conservation grazing, forage preference, knowledge systems, rangeland, traditional ecological knowledge

1 | INTRODUCTION

Efficient nature conservation requires well-supported, evidence-based decisions (Gillson, Biggs, Smit, Virah-Sawmy, & Rogers, 2019). However, quantitative analysis of multifaceted ecological and management situations is challenging. For example, complex multivariate models that describe real-world cause-effect relations, and thus provide useful evidence for conservation, are difficult and time-consuming to develop. Meanwhile, project expectations and publication policies motivate researchers to study relatively simple situtations. As a consequence, many complex situations remain unanalysed (IPBES, 2018; Öllerer et al., 2019). One example is the role of indigenous and traditional management practices in sustainable use of high conservation-value ecosystems (Mistry & Berardi, 2016).

The suitability of ecological models to complex systems has been disputed since the appearance of quantitative models. Most ecological models explain only *c*. half of the total variance, and the amount of unexplained variance is then attributed to 'random' factors (Peek, Leffler, Flint, & Ryel, 2003). Some explanatory variables are not included in these models even though their importance is well acknowledged in social sciences, for example the effect on ecosystems of local decisions of traditional land users (Newing, 2011).

Connecting scientific understanding with traditional ecological knowledge could help bridge the knowledge gaps related to complex situations by bringing in new perspectives and new types of evidence (Biró et al., 2019; Díaz et al., 2018; Mistry & Berardi, 2016). A key limitation to successful knowledge co-production between science and traditional knowledge is that ecologists are often underrepresented in participatory research of socio-ecological systems (Rissman & Gillon, 2017). Traditional ecological knowledge is the cumulative body of knowledge, practices and beliefs of often long-settled communities culturally transmitted across generations about the relationships of living beings (including humans) with one another and with their environment (Berkes, 2018; Raymond et al., 2010). Knowledge co-production is the collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem (Armitage, Berkes, Dale, Kocho-Schellenberg, & Patton, 2011).

Limited attention to traditional management practices may originate from a misunderstanding that conservation evidence can be delivered solely from scientific studies published in the peer-reviewed literature (Sutherland, Pullin, Dolman, & Knight, 2004). In fact, high conservation-value sites managed using traditional practices can be regarded as valid evidence for the appropriateness of those management systems for conservation (Babai & Molnár, 2014). Indeed, traditional knowledge and practices can help to more efficiently develop new sustainable solutions for natural resource management (Berkes, 2018; Biró et al., 2019).

In this paper we discuss the ecological and behavioural bases of a widespread conservation practice and the related traditional knowledge, namely, the behavioural elements of grazing by domestic herbivores. Many open habitats of temperate regions were naturally maintained by wild herbivores, which were later replaced by domestic livestock (Vera, 2000). Some contemporary conservation management to maintain open habitats uses domestic animals (Rook et al., 2004; Vera, 2000). Many grasslands and wetlands need regular grazing (considerable defoliation) to avoid either litter accumulation leading to decreased biodiversity or forest encroachment (Biró et al., 2019; Vadász, Máté, Kun, & Vadász-Besnyői, 2016). Nevertheless, grazing must be properly managed as overgrazing can result in unfavourable changes in species composition (Adler, Raff, & Lauenroth, 2001).

Numerous ecological and conservation biological studies document *what* herbivores eat, and how species composition changes under various grazing regimes (Vera, 2000). Many studies also document the chemical characteristics (e.g. macro and micro nutrients) of the diets of herbivores grazing particular pastures at different times of the year (Provenza, Gregorini, & Carvalho, 2015). Less attention is given to the behavioural mechanisms of grazers (Cosyns, Degezelle, Demeulenaere, & Hoffmann, 2001; Ferreira et al., 2013; Hejcmanová, Stejskalová, Pavlů, & Hejcman, 2009; Pavlů, Hejcman, Pavlů, Gaisler, & Nežerková, 2006). *Why* and *how* plant individuals are eaten in species-rich grasslands has been even less studied (García, Celaya, García, & Osoro, 2012; Henning, Lorenz, von Oheimb, Härdtle, & Tischew, 2017), not to mention the effect of various herding practices. Thus, we lack evidence at this basic level for how to manage grazing for better conservation outcomes.

Some years ago a Hungarian herder described how feathergrass *Stipa borysthenica* is grazed by his cattle as follows: '*Let's see, they definitely like it in early spring, also in late autumn after the first frosts, and also after rain if you "press" them. But otherwise they do not eat it*'. This answer summarized his accumulated experience about the complex relationship between plants and livestock. Answers like this are common wherever you meet herders in the world. They know how much and when certain species are 'desired' by their livestock (Dabasso, Oba, & Roba, 2012; Molnár, 2017; Ouachinou, Dassou, Azihou, Adomou, & Yédomonhan, 2018).

Livestock grazing behaviour as a research topic has been neglected in the ecological and conservation biological literature. Feeding behaviour is studied mostly by rangeland scientists who work in simple intensively grazed grasslands (consisting of up to 2–5 dominant species) or extensive rangelands (Provenza et al., 2015; Rook et al., 2004; Soder, Gregorini, Scaglia, & Rook, 2009; Teague, Provenza, Kreuter, Steffens, & Barnes, 2013). We have a deep understanding of plant–livestock interactions, for example on spatial and temporal patterns of forage preference, effect of post-ingestive feedback on preferences and aversions and intake rates (Provenza & Villalba, 2006), how the availability of alternative forages influences choices in simple systems (Provenza et al., 2009), and the role of learning and memory, including transgenerational linkages to forages and locations across landscapes (Provenza et al., 2015 and references therein). Agreil, Fritz, and Meuret (2005) and Bonnet, Hagenah, Hebbelmann, Meuret, and Shrader (2011) emphasized the importance of bite types and bite mass diversity, but these studies rarely discuss conservation issues. Conservation biology/ecology and rangeland/livestock science would both benefit from working more closely together (see their isolation in Appendix S1). Rook et al. (2004) and Dumont, Prache, Carrère, and Boissy (2007) argue that 'we do not know how livestock exploit species-rich grasslands'.

Meanwhile, millions of herders possess knowledge of livestock grazing behaviour because their livelihood depends on it. However, very few ecologists and rangeland scientists work closely with herders (e.g. Meuret, 1997; Molnár et al., 2016; Tamou, De Boer, Ripoll-Bosch, & Oosting, 2018). Meuret and Provenza (2015) describe how herders use knowledge of behaviour to influence food and habitat selection by livestock and efficiently increase daily intake. Herders do so by moderating selectivity and regularly boosting appetite such that animals use diverse arrays of plants. In Africa sustainable livelihood and pasture degradation are the focus of studies of herders (e.g. Dabasso et al., 2012; Ouachinou et al., 2018; Schlecht, Hiernaux, Kadaouré, Hülsebusch, & Mahler, 2006; Tamou et al., 2018). These studies usually do not discuss biodiversity conservation in detail. Realizing the gap between science and herders' knowledge, Meuret and Provenza (2015) suggest focusing first on qualitative exploratory studies of herder-modified grazing behaviour, to be followed by more controlled quantitative experiments.

Central Europe—our study area—is a specific situation: traditional herding still exists, herders use species-rich grasslands located in protected areas (Kis et al., 2016), conservationists manage these grasslands using domestic grazers (Vadász et al., 2016) and knowledge co-production between scientists and herders is well established (Molnár et al., 2016).

Given this background, our objectives were: (a) to identify types of behavioural elements of grazing livestock in relation to plants, (b) to assess herders' understanding of cattle behaviour and the ways they modify behaviour during herding and (c) to explore the conservation benefits of these modifications. Finally we discuss the possible improvement of knowledge co-production between traditional knowledge holders and scientists to decrease knowledge gaps between isolated scientific disciplines and thus contribute to evidence-based conservation management.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area, which lies near Kunpeszér in the Kiskunság region of Hungary (see study area map in Appendix S2), is at 92–97 m a.s.l., and has an annual mean temperature of *c*. 10°C and an annual mean precipitation of *c*. 550 mm. It is one of the most species-rich lowland grassland regions in Europe composed mostly of meadow steppes, fen meadows, tussock sedge beds and marshes (8–14 species per 20 × 20 cm, see list of typical plant species of the studied pastures in Appendix S3). Biomass production has high interannual variability, with a maximum in May and a smaller second maximum in August-September after the summer drought (Molnár, 2017). Beef cattle (Charolais, Hereford, Hungarian Simenthal and hybrids) graze the area with 0.3–1.0 livestock units per ha from May until November. Herds are closely herded or tended by herders with dogs.

2.2 | Observing cattle behaviour on species-rich pastures

We observed ingestive bite selection and avoidance behaviour of cattle at and just above the feeding station level (bites without movement of animals' forelegs, Figure 1) in May, June, August, October 2014 and May, June, August, September, October 2015, altogether during 22 days, both during morning and afternoon meals (4–5 hr each) on three nearby pastures. Livestock were calm, individuals were selected randomly. We went as close as possible (0.8–2 m) keeping impact on cattle to the minimum while having a good view of plants near each animal's mouth. When plants were difficult to identify to the species level, we visited the feeding station just after the animal departed. We documented how and how often certain plant species were approached, eaten or avoided by cattle (see behavioural elements in Table 1). To avoid differences among observers, most observations were done by the first author who had a full knowledge of the local flora and was experienced using binoculars (Nikon, 8 × 40 mm).

We grouped bite-level observations (*c*. 33,000 bites) into frequency categories as our goal was to document behaviour towards as many plant species as possible instead of quantifying daily intake or forage preference (cf. Agreil et al., 2005). We did not study grazing preference (i.e. choice given alternatives, comparing intake and available biomass for each species separately) which would have been impossible in such species-rich pastures. Frequency category 3 (see Appendix S3) means more than six (usually <20) observations

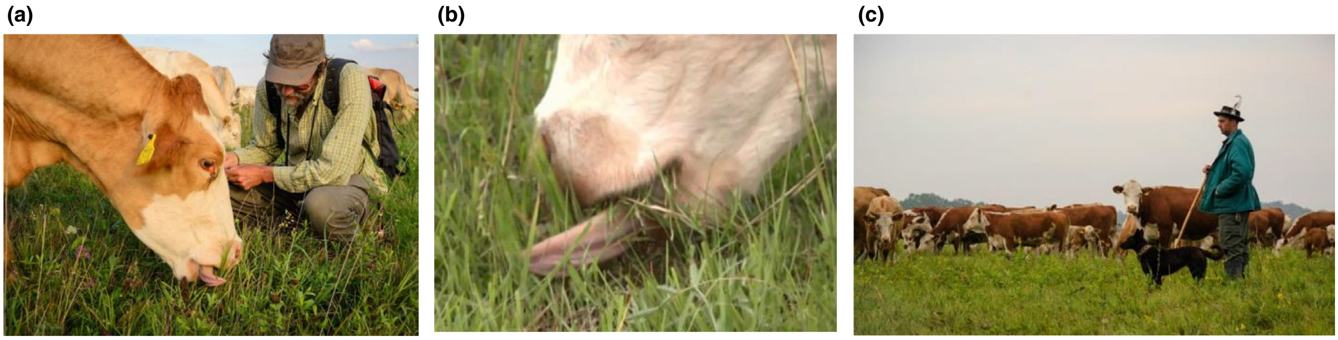

FIGURE 1 (a) Herders provided the motivation to start a study on the behaviour of cattle grazing in species-rich grasslands; (b) cattle can graze selectively even with their relatively large tongue (see videos in Appendix S4); (c) herders modify cattle behaviour, even daily intake rate, desirability of various plant species, and thus grazing selectivity, and by doing so they utilize their pastures sustainably (photos: Ábel Molnár, János Budai, Zsolt Molnár)

TABLE 1 Observed behavioural elements of herded cattle, their frequency and dominance on a species-rich pasture for 117 plant species

Behavioural element	Herders' description	Frequency of observation (%)	Proportion of species where the element was dominant[a]/ occured (%)	Comments and examples
Steps for it (leaves the feeding station to eat it)	*Likes it, runs for it because it is sweet*[b]	0.3	0.9/7.7	*Phragmites australis* (before flowering), *Calystegia*, *Molinia* and some other grasses and forbs
Turns head for it (eats without moving forelegs)	*They are stuck, do not move, just eat/ they are keen not to let it eat by the neighbouring animal*	5.3	6.0/34.2	Tussocky grasses (*Festuca*, *Chrysopogon*), *Phragmites*, *Frangula*, less often other grasses, and most legumes (*Trifolium*, *Lotus*, *Vicia*, *Medicago*)
Likes it (makes several bites before moving forward)	*Terribly likes it, eats to the ground/ only makes tiny steps, keen to eat as much as possible*	17.4	23.1/43.6	See species mentioned above, less often some others, rarely even some poisonous ones (e.g. *Asclepias*, *Iris*)
Eats together with another species (usually with some more desirable)	*Eats with the others, it may not have that bad taste to shake it out/ cattle eats mixed, a bunch with her tongue*	18.0	23.1/53.8	Grasses and legumes mentioned above, and many other small, moderately avoided forbs
Only picks (parts of the plant, e.g. a leaf or flower)	*Picks its leaf or flower/ only picks, does not like that much, though more if hungry*	20.5	33.3/77.8	Many species were picked, for one third this was the most common behavioural element
Touches but releases (takes into her mouth but releases eventually)	*One cattle only tries, the other eats it/ grows mixed with something undesired*	0.1	0/7.7	*Ononis spinosa* and *Genista tinctoria*, rarely some other thick-leaved, less-desired species
Smells only (after smelling cattle avoids the plant)	*Has strange smell or urine, smells it but doesn't eat it*	0.0	0/1.7	*Lysimachia vulgaris* and *Rorippa amphibia* but only rarely
Avoids (without touching the plant the animal makes a definite bypass)	*Bypasses, don't even try or step on it/they don't eat it, it is stinking/eats around, thorns hurt her nose*	37.9	66.7/98.3	Only *Frangula* and *Calystegia* were never avoided, some desired species were avoided during or after flowering (e.g. grasses, legumes)
Lets it fall out (from her mouth)	*Puts in the corner of her muzzle with tongue/it is mixed with some undesirable or earthy bit*	0.3	0/24.8	*Lysimachia vulgaris*, rarely with some other species
Shakes out (makes an extra effort to get rid of it from her mouth)	*Shakes out while moving foreward, turns out with her tongue (bad taste or dry piece)*	0.1	0/10.3	Rarely (e.g. *Potentilla anserina*), and some other less-desired species

[a]Either in spring or autumn.

[b]Herders' descriptions are in italics, individual quotes are separated by a dash.

per meal, 2 means three to six observations per meal and 1 means one to two observations per meal (category boundaries were set arbitrarily). We analysed 117 species (from a total of 241) for which we had observations on at least 3 independent days in spring and autumn respectively. We developed a desirability index using the proportion of intake-positive elements (the first five in Table 1) divided by the total frequency of all 10 elements. Based on the frequencies of all 10 behavioural elements, we performed principal component analysis (PCA) ordination combined with Ward's Clustering to explore the disjunction patterns of species and to identify the most powerful behaviour types in forming this pattern. The analyses were carried out in R.3.5.3. Statistical Software (R Core Team, 2017).

2.3 | Documenting herding techniques and their effects on pasture vegetation

We studied traditional herding practices and their effects on pastures by participatory observation during 155 field days since 2010. We made altogether >450 outdoor interviews in Hungarian language (mother tongue) about livestock behaviour, herders' decisions to modify livestock behaviour and reported effects of grazing on the vegetation of their pastures (see details in Molnár, 2014, 2017). Key sentences from all interviews were transcribed and grouped into topics (main behavioural elements and herding practices). Some typical questions during outdoor interviews were: Why did your cattle stop grazing this patch; start to speed up/slow down/change grazing direction; under which circumstances do your cattle like/avoid species X; why did you send your dog now and to do that specific job? Three herders (age 35, 37, 48, all men) were visited more than 20 times, while 11 other herders were visited 5–10 times. In this study, a herder was a person who stays with livestock usually during the whole grazing period; possesses deep experience working with livestock, herding and pastures; and follows the main herder traditions of the region (Kunkovács, 2013). Two of the most knowledgeable herders (JM and LS) were invited as co-authors on this paper. All key results and discussion points were thoroughly discussed with the two conservationist (AM, CV) and the two herder co-authors. Prior informed consent was obtained from all herders before the first interview adhering to ethical guidelines suggested by the International Society of Ethnobiology. Original quotations of herders are shown in italics.

3 | RESULTS

3.1 | Types of behavioural elements of grazing

Altogether 10 behavioural elements were identified at the plant–cattle interface for 117 species during herded grazing (Table 1; Appendices S3 and S5). Five elements were intake-positive, i.e. the cattle ingested the plant or part(s) of it, while the other five were intake-negative (the plant was avoided or rejected). The most frequent elements were 'avoids', 'just picks', 'eats together' and 'likes'.

The 10 different elements co-occurred in particular combinations (99 combinations in total) at the species level (Figure 2). More than 50% of the species had at least four behavioural elements (by

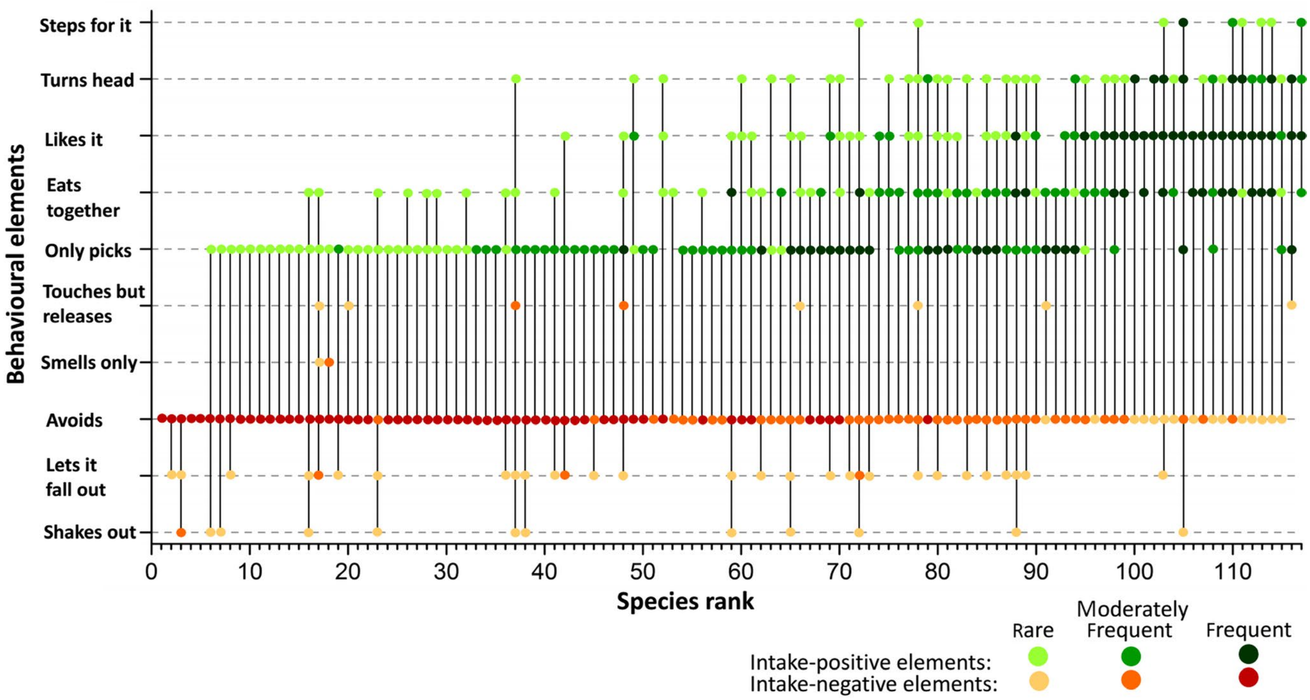

FIGURE 2 Frequency of behavioural elements toward 117 plant species. Species were ordered from left to right according to their ranks based on their desirability index (proportion of intake-positive types, in %; see data in Appendix S3). Coloured dots indicate frequency of behavioural elements. Dots of the same plant species are connected with a thin vertical line

different cows, or the same cow sometimes 'liked' and sometimes 'avoided' the same species; see Appendix S6). Most species were both eaten and avoided (Figure 2). 'Sweet' grasses and legumes were the most desired species, but even these had cases where they were avoided (e.g. during or after flowering). Only two species, *Calystegia sepium* and *Frangula alnus* were never avoided. Species that were most often only picked were mostly dicotyledons, but also some grasses and legumes, as well as medicinal plants such as *Sanguisorba officinalis*, *Symphytum officinale* and *Plantago lanceolata*. The species most often avoided were poisonous, thorny and/or medicinal species, but most of these were also regularly 'tested' (picked). Only five out of 117 species were never eaten: *Prunella vulgaris*, *Potentilla reptans*, *P. anserina*, *Eryngium campestre* and *Carlina vulgaris*.

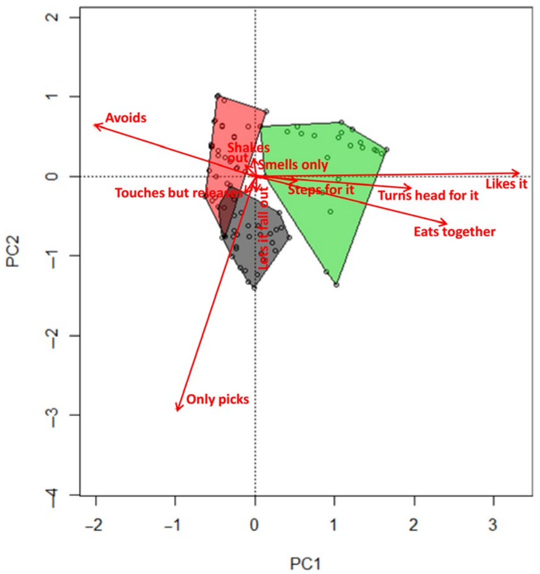

FIGURE 3 Principal component analysis (PCA) of the 117 plant species based on the 10 behavioural elements. Eigenvalues for first and second axis: 10.37 and 3.81, respectively; explained variance: 52.95% and 19.47% respectively. Green: desired species, grey: eaten together with others and picked, red: avoided but sometimes picked

Desirability changed seasonally for about one-third of the species (see Appendix S7). Desire for *Achillea* spp., *Asclepias syriaca* and *Bothriochloa ischaemum* changed the most between spring and autumn. Four of the five intake-negative behavioural elements were rare, and the frequency of 'mistakes' by cattle was low (<0.5%). Herders argued: *The livestock do not make mistakes. They were born here, they know all the plants! Maybe, when they are greedy, they pick a plant they will not eventually eat*. The PCA clustering resulted in three groups ordered along a desirability gradient (Figure 3).

3.2 | Herders' practices to change cattle behaviour and their relevance for conservation management

Herders argued that they can modify the frequencies of behavioural elements by inducing cattle to feed longer on less-desired species (upward curved arrows, Figure 4) and move less rapidly (downward

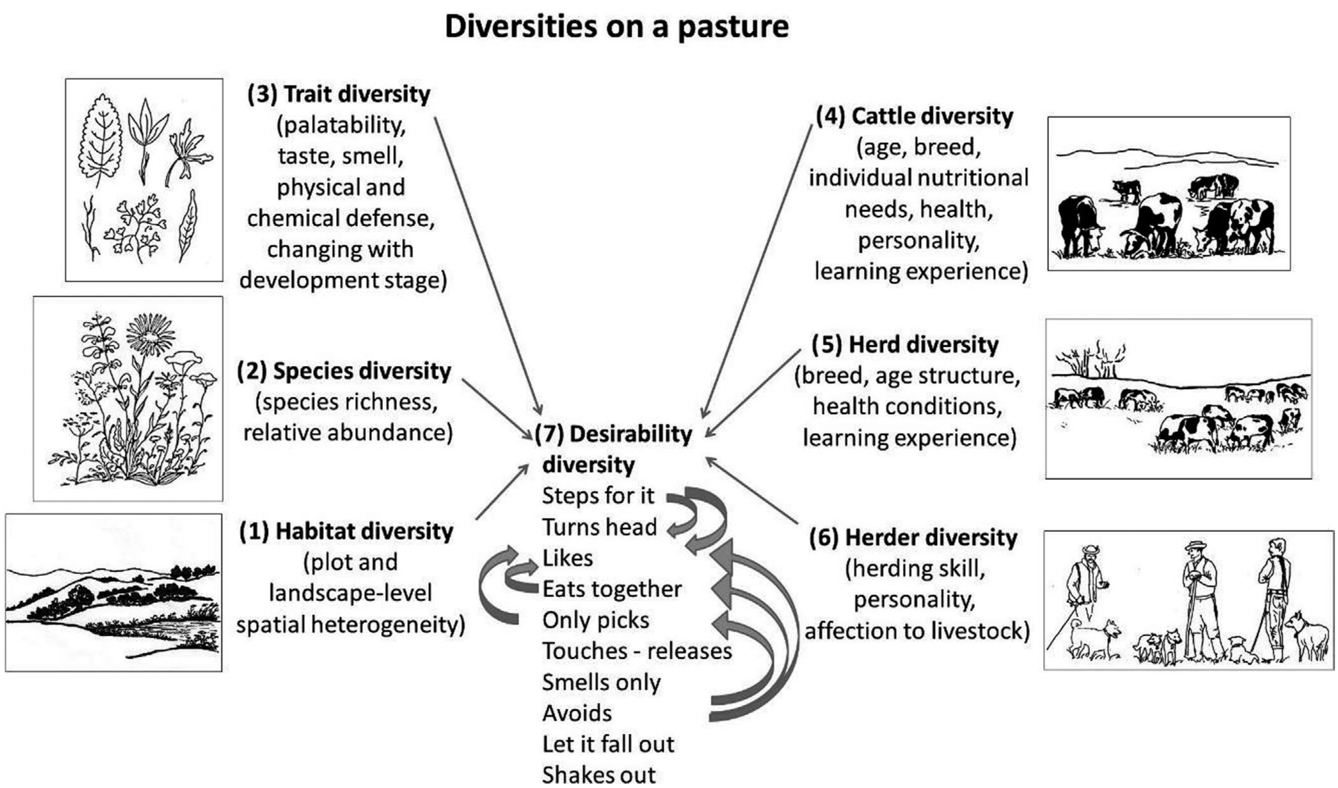

FIGURE 4 Conceptual framework of 'diversities' related to plant–livestock interactions on species-rich pastures grazed by herded livestock. Straight arrows indicate factors affecting livestock desire. Curved arrows indicate the directions in which herders modify behaviour of the livestock (mostly increase desire and intake, or motivate calm grazing by slowing herd movement). Drawings: © Marianna Biró

TABLE 2 Conservation relevant herding techniques of traditional herders regularly used to control grazing behaviour, animal distribution, modify intake of livestock, change selectivity of grazing and protect the forage resources on their pastures

Traditional herding techniques to control grazing behaviour	Original quotes of traditional herders about their herding techniques and herders' opinions of the effect of these techniques on livestock behaviour and pasture vegetation	Conservation relevance of traditional herding techniques
Attention to livestock, **keep monitoring them** for prompt and proper interventions with the least possible stress	*A herder's job is to observe livestock*[a]*./You have to learn how to feel with the livestock. All have a distinct personality./A herder can keep the livestock well also on a poorer pasture because he guides them* (=make them graze well)	Fine-tuned livestock–herder–pasture relation is the basis for proper management
Protecting the pasture **from unnecessary disturbance** and **promoting regeneration** after a grazing period	*You have to walk at the front of the herd to prevent trampling./We did not go to the pasture in early spring, they would trample the young grass./We pastured Festuca 'in dew' on warm dry days to avoid the break of leaves./If you rotate pastures, you give a chance for renewal*	Herders consciously protect pasture vegetation according to their indicators
Designing **daily 'menu'** (sensu Meuret, 1997) along the grazing route (sequence of foods to maintain and boost apetite, and increase desirability of less preferred forage species)	*Livestock have their order of meals to graze a lot everywhere. The menu is needed to prevent them to go first where they want to./Cattle of a good herder will eat up 80 species from 100, 90 on drier lands, less in marshes. But you have to 'stand by'./If we came here in the morning, they would not eat. Half-satiated they eat, even like it./They wish for better but first we finish with this poorer one*	Designed menus help utilize the pasture evenly, smaller pasture is enough for the same amount of livestock, animals move less and fatten better (cf. profit)
Letting them **spread** and graze calm	*We let them go where the place 'catches' them. They graze individually, they are happy./They move like a clock, graze around themselves, making small steps*	Movement and trampling is decreased, smaller disturbance to breeding birds
Selecting an area to be grazed **during its highest desirability status**, depending on season and weather	*We break the reed now. You can graze it down only in bad times. If the base of Agrostis gets light, its base, its 'soul' can grow./We only graze sedge in dry season./They don't like here, only 'in dew'.* (see also the quote on *Stipa* in the introduction)	Utilizes less preferred parts of pasture, often improving its forage quality
Block movement of the herd, or just slow them to **get them satisfied with the less preferred forage** of the patch, eat mixed forage	*"Step one, bite six", old herders said. They don't eat with the legs./You have to stand at the front, and stop them, many times a day. This is 'real' herding./We slowed them to eat mixed, not only Trifolium* (to prevent bloating)*./If we slow them down, they eat the dry grass, too and 'drink on it'* (=fatten)	Less selective grazing results in more homogenous utilization and can prevent spread of pasture weeds
Targeted grazing of less-desired forage species, improving pasture by grazing	*If spread they eat selectively, 'sweet' grass is eaten up. I change the daily route, and start grazing this area intensively. They will eat up the rest as if it were mown./In the morning, they are looking for better, and trample down Typha if you 'press' them. In the evening they want to get satiated. If I drive them into a marsh, they utilize previously avoided grass*	Prevents accumulation of litter, and suppresses bushes and tall plants (like *Phragmites*, *Typha*)
Increasing willingness to **graze less selectively and more intensively** by shortening a meal from 4–5 to 1–1.5 hr	*If they keep running, I give them a lent* (pen them). *In the next meal they are so 'grateful', they graze so well, you cannot imagine./After this penning, I visit places they don't like. They eat as they were glued there. They graze where I want them to graze*	Less selective grazing (more homogenous utilization, and management of pasture weeds)
Move them faster (towards watering/resting places) to prevent excessive **grazing trails**	*I move the back side slowly, they eat like a grasshopper in the evening./The grass looks like it were mown, cattle 'shaved it', but did not overgraze*	Too many grazing trails could cause degradation (spread of weeds)

[a]Original quotes of herders are given in italics, dash separates individual quotes.

curved arrows). But they cannot make an extreme negative element become an extreme positive one (or vice versa). They used at least nine different herding techniques to achieve their goals (Table 2). They argued: *Livestock must eat where I want them to eat. I let them go through a patch, or slow or stop them. This is what I call 'herding'. Otherwise you cannot make a living, both the livestock and the pasture deteriorate*.

Many elements of these herd management practices have conservation benefits, for example, by avoiding under- and over-grazing, and targeted removal of pasture weeds, reed, bushes and litter. Herders were conscious about most of these effects (Table 2).

4 | DISCUSSION

4.1 | Cattle grazing behaviour and its modification by herders

We documented 10 different behavioural elements of cattle grazing on species-rich grasslands (Table 1). We found a high number of combinations of behavioural elements at the species level (Figure 2), which can be regarded as *desirability diversity* (cf. Provenza et al., 2009). Species were grouped by PCA into three major categories: desired; eaten together with others and picked; and avoided but rarely picked (Figure 3). Season affected the behavioural element spectrum of many species (see Appendix S7). Some pasture weeds were only grazed in spring (*Asclepias*, *Bothriochloa*). Cattle foraged on *c*. 70–80 species on these species-, trait- and habitat-diverse areas (see Appendix S3, cf. Mladek et al., 2013; Vadász et al., 2016). Desirability was more diverse than could have been inferred from a forage preference study (cf. Soder et al., 2009). Discrimination error was small (<0.5%, Figure 2), which suggests that cattle recognized the 117 plants 'by species'. Further studies are needed to understand interactions among plant trait diversity (e.g. primary and secondary compound contents), neighbourhood (e.g. neighbouring individuals belonging to species with distinct desirability) and interannual variation of desirability (e.g. caused by changing forage quality) in species-rich pastures. Cattle feeding preferences may also change based upon, among other factors, plant physical and chemical characteristics and the age, gender and physiological state of the animal (Provenza et al., 2015; Soder et al., 2009).

Herders consciously modified grazing behaviour of livestock (Table 2). For them, the 'science of herding' meant controlling livestock movement, distribution and even desire. To do that effectively, herders recognize most of the 'not too rare, not too small' plant species on their pastures (Molnár, 2017). They also know circumstances that cause livestock to like or avoid these species (e.g. palatability, need for nutrients and fibre, taste, texture, Meuret & Provenza, 2015; Molnár, 2014, 2017), and what post-ingestive impacts these plants have (*makes them fatten well*, *poor forage*, *cause diarrhoea*, *bloats them*; Molnár, 2017). A key technique was planning the daily grazing route, as described first for science by Meuret (1997) in cooperation with French herders. By moving, slowing and stopping livestock, herders affected behaviour at the 'bite level'. Keeping in mind the diverse desirability of plants (Figure 2) and herders' intention to modify desire (Table 2), we conclude that herding techniques can strongly affect which plant species livestock eat. Consequently herding shapes the plant species composition of a pasture (*without proper herding weeds would spread and bushes would overgrow pastures*, cf. Kis et al., 2016). Species composition may have significant economic and conservation consequences by affecting carrying capacity and nature conservation value (Kis et al., 2016; Meuret & Provenza, 2015; Molnár et al., 2016). Furthermore, we hypothesize that the level of explained variance in multivariate explanatory models incorporating more herding-related variables will be much higher than in those that neglect these aspects of grazing. This hypothesis is based on the premise that the mode of grazing (e.g. free grazing, grazing in electric fence, herded grazing) heavily influences the composition of grasslands. Evidently, the main difference between free grazing and herded grazing originates from whether specific herding techniques (e.g. those that are used to modify the bite-level behaviour) are applied or not. Therefore, if we consider certain herding techniques as explanatory variables in multivariate models that describe the effect of grazing on composition (and diversity) of grasslands, we will be able to explain higher level of variance.

Many of the techniques herders used can offer conservation benefits by managing over- and undergrazing, and pasture weeds. *I try to fit in with both sides, so that it's good for me and for the conservation ranger. I did what I heard at home from my father. They grazed on the hay meadow in early spring. It's good for me, because the grass I cut* [in late June] *is not too old, but the grass is still there for their* [the rangers'] *wildlife until June* (Molnár et al., 2017). Herders' and conservationists' management objectives are not necessarily in common, but they may result in similar management decisions (Biró et al., 2019; Molnár et al., 2016). We agree with Meuret and Provenza (2015) who call herders 'ecological doctors' for their contribution to the 'health' (good ecological functioning) of pasture ecosystems through careful management of grazing lands. Beyond the above-mentioned conservation benefits, a true collaboration between herders and conservationists can also support the management of some of the protected, rare and invasive species if herders and conservationists would work together to co-design and test new management practices (García et al., 2012; Henning et al., 2017; Molnár et al., 2016; Vadász et al., 2016). A well-established example is the diversified grazing management regime in the Kiskunság National Park where cattle grazing at low or medium intensity (<0.5 animal unit/ha), with an annually varying rotation sequence of pasture units led to the highest level of plant species richness in Pannonian meadow steppes (Vadász et al., 2016).

Different types of diversity exist on a species-rich pasture (Figure 4): habitat diversity, species and trait diversity (Díaz, 2002), cattle and herd diversity and if cattle are herded, then diversity of herding techniques and skills (Meuret & Provenza, 2015; Molnár, 2014). Collectively, they finally all lead to: desirability diversity. These diversities are interdependent, such that a decrease in one type of diversity may have a negative effect on another type of diversity (e.g. lower trait diversity if species diversity is lower, lower herd diversity if individual cattle diversity is lower, Mason & Mouillot, 2013). Our results suggest that more complex and more targeted conservation management is feasible with herders than without them, potentially reaching (and maintaining) higher alpha, beta and gamma diversity on well-managed pastures (cf. diversifying potential, Vadász et al., 2016). This argument seems to be missing from the conservation biological and ecological literatures (e.g. Primack, 2008). More research will enable us to better understand differences in behaviour of individual herds caused by differences in past experiences and social learning, and effect of herders with different skills and experience on grazing selectivity and effect of their livestock on vegetation.

4.2 | Implications for research and conservation management

Traditional herding systems are changing (e.g. grazing regimes, Reid, Fernández-Giménez, & Galvin, 2014), as are societal perceptions of what we expect from pastures (e.g. forage vs. other ecosystem services, human and environmental health, Sayre, Bestelmeyer, & Havstad, 2012; Torralba, Fagerholm, Hartel, Moreno, & Plieninger, 2018). New ways of grazing management (e.g. management of livestock spatial distribution or cooperation between herders and conservationists) foster adaptive solutions (e.g. better management of forage resources and biodiversity; Biró et al., 2019; Provenza et al., 2013; Teague et al., 2013; Török et al., 2016). However, more attention should be paid to prevent the erosion of valuable traditional herding knowledge, and to help traditional knowledge holders maintain their ability to manage their local pasture resources sustainably (Ban et al., 2018; Barani, 2007; Fernández-Giménez, 2000; Kis et al., 2016; Ulambayar, Fernández-Giménez, Baival, & Batjav, 2017). *If people respected us a bit more, that would mean a lot*—a herder explained (Molnár et al., 2017). Research agencies should better support knowledge co-production with traditional knowledge holders (like they support scientists' cooperation with private companies), while, for example, European agri-environmental schemes could better support the employment of well-trained herders (Molnár et al., 2016; Parolo, Abeli, Gusmeroli, & Rossi, 2011). *In fact, for them* [researchers] *to know something, or to write a book or make a film* [about herding management], *they need us very much!/Conservation rangers wouldn't talk to us 20 years ago. Now they stop and we can talk about pasturing. We agree on about 90% of things* (Molnár et al., 2017).

In summary, we showed that knowledge co-production, participatory field work and joint analysis of data with herders, conservationists and ecologists could decrease knowledge gaps, connect scientific disciplines that so far have been isolated, and by this, increase the evidence base of conservation management by grazing domestic livestock. However, we argue that for efficient knowledge co-production we need not only the methodology of the social sciences but also a stronger participation of ecologists who can dig deeper into complex ecological issues (cf. Mistry & Berardi, 2016; Rissman & Gillon, 2017). We believe that through better knowledge co-production we will be able to understand yet understudied complex human-nature relations with important practical implications (Díaz et al., 2018; Provenza et al., 2013). Knowledge co-production similar to ours could be made not only among other herders, ranchers and pastoralists around the world, but in many other human-controlled species-rich ecosystems, for example, in tropical forest gardens, and managed forests, grasslands and marshes in cultural landscapes.

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AUTHORS' CONTRIBUTIONS

Z.M. and C.V. designed the study; Z.M., A.K. and R.K. collected the field data; A.K. made the statistical analysis, all authors analysed and interpreted the data and wrote the manuscript.

DATA AVAILABILITY STATEMENT

Data available via the Dryad Digital Repository: https://doi.org/10.5061/dryad.gqnk98sjn (Molnár, Kelemen, Kun, & Vadász, 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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