FINAL REPORT

'Fine-scale landscape ecology: linking vegetation change with interacting indirect and direct drivers using traditional ecological knowledge and oral history' (2019-2024, NKFI K 131837)

MAIN ORIGINAL OBJECTIVES AND HYPOTHESES OF THE PROJECT (original from the project proposal, indicating relevant publications and submitted and under preparation manuscripts)

- indirect (e.g., social, economic) drivers acting at regional and national scales can be as significant as those acting locally in driving direct drivers and thus shaping fine-scale vegetation structure and composition, and the trajectory of successional changes (see Babai et al. 2021, Gantuya et al. 2021, Biró et al. 2022, Sharifian et al. submitted, Biró et al. 2024, Biró et al. submitted);
- local and traditional knowledge can be used effectively to assess the interaction of indirect and direct drivers at various spatial and temporal scales, and their impacts on past and recent vegetation changes, for example, on land abandonment and woody encroachment (see Gantuya et al. 2021, 2025, Sharifian et al. submitted, Demeter et al. b, before submission);
- to improve the methodology of oral history interviewing and adapt it for use by vegetation ecologists (see Molnár and Babai 2021, Biró et al. 2024, Molnár et al. 2024).

COMPARISON OF PLANS AND RESULTS

This project was my most difficult project ever regarding organization and managing the sequence of field studies and publications. The key challenges were: 1) Covid impacted two years of field work and travel to foreign countries (Iran, Mongolia and the Balkans); 2) health issues and other personal challenges of two key participants during 2023 and 2024; and 3) serious summer droughts in 2022 and 2024

However, inspite of these difficulties, we were able to accomplish most of our plans, and if not, we conducted related other research work as far as possible (analysing data from our previous related projects on drivers and land-use, specific reviews, and methodological reviews). Table 1 shows the detailed comparison of plans and results. We prepared a medium sized report (50 000 characters) as not all the project plans could be accomplished.

Original publication plans from the project proposal	**Published papers (10) and manuscript submitted (2) or before submission (2)**
vegetation changes and direct and indirect drivers in woody ecosystems, Forest Ecology and Management, D1	Biró et al. (2022, Landscape and Urban Planning, D1) on country-scale forest changes and their drivers, and a key drivers in oak forests (Demeter et al. Biological Conservation, D1) on the impact of the invasive alien fungus, oak powdery mildew, on the natural regeneration of *Q. robur*
oral history based fine-scale landscape history of forest steppes in Mongolia, Journal of Ethnobiology and Ethnomedicine, D1	Gantuya et al. (2021, Ecology & Society, D1) on fine-scale landscape changes perceived by locals, and additionally: Gantuya et al. (2025, People & Nature, D1) on historical changes of pasture management in Mongolia and its local perception
structural and compositional heterogeneity of woody encroachment under various direct and indirect drivers; Biological Conservation, D1	Demeter et al. (a) on the planned topic (manuscript under preparation for Forest Ecology and Management, D1, see results below)
interacting effects of pre- and post-abandonment land-use on forest encroachment, Forest Ecology and Management, D1	see the previous manuscript, additionally see Demeter et al. (b, under preparation for Biological Conservation, D1) on conservationists views on present and future management of these encroached areas
contrasting impact of interacting drivers on vegetation change in two neighbouring villages; Land Use Policy, D1	Biró et al. (2024, People & Nature, D1) on the legacies of land use in Kalotaszeg, and the use of the oral history approach in revealing these legacies
methodological manuscript on using the DPSIR framework in interviewing fine-scale vegetation changes; Biological Conservation, D1	see above in Biró et al. (2024), where the DPSIR framework was used to elicit oral history
vegetation changes and direct and indirect drivers in grasslands and wetlands, Agriculture, Ecosystems & Environment, D1	Biró et al. (2025, People & Nature, D1) on a comparative analysis of land-use changes in 21 grassland localities in Hungary and Romania and the interaction of indirect drivers acting at different spatial scales
drivers of changing grassland management in Hungary and Iran; Journal of Applied Ecology, D1	Sharifian et al. (submitted, Ecological Indicators, D1) on the direct and indirect drivers of change and their inextricable interactions in Iran

Additional publications (based on work during the covid period)	
instead of the Serbian/ Albanian field work we wrote a paper on a Romanian situation where field data were already available	Babai et al. (2021, Ecology & Sociey, D1) on how the increasingly complex interaction of direct and indirect drivers impede adaptation by locals to social-ecological changes
a global literature review on knowledge and decisions around land-use of pastures	Sharifian et al. (2023, Journal of Environmental Management, D1), a paper with a global perspective on how herders use traditional knowledge of their pastures in management decisions that influence landscape stability or change
a global methodological review paper using our own experience and global literature	Molnár and Babai (2021, Trends in Ecology and Evolution, Nature Indexed, D1) on how local traditional ecological knowledge can be used in ecology and by ecologists
a global methodological review paper using the experience of the IPBES author team and global literature	Molnár et al. (2024, Trends in Ecology and Evolution, Nature Indexed, D1) on how ecologists can build knowledge partnerships for better understanding of local ecologies, changes and drivers
a cross-knowledge system review based on the data of our previous OTKA project (land use through pig grazing, a special driver in forests and marshes)	Molnár et al. (2024, People & Nature, D1) on how local knowledge collected through interviews can be used in reviews that also use global scientific literature

Summary of key results

We studied micro-scale, national, sub-national, and regional scale drivers (both indirect and direct) of landscape change and their interactions, and searched for possible solutions.

In our Hungarian country-scale forest-focussed study we used the fine-scale site histories of 1,728 randomly selected sample localities to recostruct the main trajectories of regional and country-scale forest transformations and identified drivers at multiple scales since the 18th century. Drivers were highly intertwined and their effects were long lasting **(Biró et al. 2022)**.

In our cross-country (HU and RO) grassland study, we aimed to identify ecologically relevant interacting indirect drivers impacting the management of Natura 2000 grassland habitat types since the mid-20th century. Locals recalled mostly local and sub-national-scale drivers although experienced the effects of national and regional-scale drivers. These drivers have been endangering habitats with hardly recognisable, delayed processes that date back already to the collective farming period **(Biró et al. submitted)**.

Local farmers in Gyimes (RO) perceived a high number of direct and indirect drivers, as ecological, socio-cultural, economic, and political changes which affected our chosen target management practice the optimal and actual time of mowing and increased the number of trade-offs. The complexity of driver and trade-off interactions increased through time since the 1950s making adaptation more difficult. The cumulative effects of drivers and trade-offs decreased the economic and social viability of the system. We argue that the local community's adaptive capacity may have been drastically weakened **(Babai et al. 2021)**. In our other study (Kalotaszeg, RO) we showed that the indirect driver interactions led to the abandonment of traditional hay meadow management, resulting in a homogenising landscape with simplified land use dominated by sheep grazing and increasingly dependent on agricultural subsidies. Country-scale political and economic changes affected the landscape with crop outflow, resulting in labour outflow which reduced the time and attention devoted to haymaking and affected the ageing of the local human population **(Biró et al. 2024)**.

In the Mongolian forest steppe zone, we found 32 indicators on how herders perceived landscape and vegetation changes (long-term decadal trends, regenerative successions after disturbance, and recurrent fluctuations caused mainly by weather) for the 14 habitat types studied. Among herders there was variation in the perceived importance of droughts and increasing livestock numbers. To reverse adverse ecological changes, herders wished to cooperate especially with each other to increase mobility, stop overgrazing, and help nature to regenerate their worsening pastures **(Gantuya et a. 2021)**. The herding practices that were abandoned the most in the post-1990 era were those that required greater time investment by herders, were less compatible with modern lifestyles, or needed closer cooperation and better-functioning institutions. We concluded that the Mongolian semi-nomadic herding system exhibits adaptability to new conditions, but the development of proper new practices by herders or the government may take considerable time. We argued, that herders' traditional ecological knowledge, revealed through oral history analysis, has a vital role in developing locally adaptive solutions, while institutions have a critical role in formulating policy. Possible solutions to avoid maladaptation in traditional pastoral social-ecological systems may be reached by slowing down the potentially harmful social-ecological changes and speeding up adaptation **(Gantuya et al. 2025)**.

Herders in Iran explained that most landscape changes they perceived originated from the inextricable interactions of a sequence of drivers, and identified 176 connections between the 69 reported direct and indirect drivers. We argue that in the studied Turkmen Sahra, barriers to substantial natural regeneration of pastures and other habitats caused by highly interacting drivers have created a situation, where viable solutions may not exist. Future land-use planning programs need to take this into consideration **(Sharifian et al. submitted)**.

In our multi-sited study on shrub and forest enchroachment, we found that the most important variable determining the herb layer species composition of the enchroached areas was the time since abandonment, and to a lesser extent the vegetation type, and not the type of land use before abandonment **(Demeter et al. a)**. When we asked conservationists about their views of woody enchroachment, maintaining and enhancing the naturalness of grasslands was a priority in all landscapes studied. Conservationists' knowledge of the area and their professional interests (botanist, entomologist, ornithologist, etc.) were the key drivers how they wanted to develop and/or maintain grassland-shrub-forest ratios, and with this the character of the landscape. We argue that the diverse perception and understanding of woody enchroachment and its direct and indirect drivers may become a source of significant conservation conflict between conservationists and land users and even among conservationists **(Demeter et al. b)**.

By studying a key driver of forest dynamics, we proposed a novel hypothesis, the 'pathogen mildew hypothesis', to explain the failure of natural regeneration of pedunculate oak. We found that forest ecologists and conservationists often overlook the impacts of this 'recent' driver (an invasive alien fungi), while the 'closed-forest' and 'wood-pasture' hypotheses do not adequately help the management of pedunculate oak regeneration **(Demeter et al. 2021).**

Although pastoralists vary greatly across the globe, the character and use of their traditional forage-related knowledge do seem to follow strikingly similar principles. We identified ten global principles, how they manage their livestock and pastures (key drivers at landscape scale), including, among others, a livestock-centered perspective, close monitoring and targeted pasturing of various forages, and the use of well-planned spatial movements at multiple scales to optimize the utilization of available plant resources **(Sharifian et al. 2023)**.

From a methodologicial perspective, we found that oral history helped to identify and link local, sub-national and national scale drivers and to understand the slowly manifesting social processes that drive ecological processes **(Biró et al. submitted)**. We found that herders have a reliable and widely shared understanding of landscape and pasture changes and their direct and indirect drivers **(Gantuya et a. 2021, Sharifian et al. submitted)**. Local communities' ecological memory can play an important role in filling knowledge gaps by reconstructing the socio-ecologically relevant indirect drivers and their interactions, as well as identifying vegetation characteristics that are for example legacies of previous land-use practices. By creating knowledge partnerships, we can still learn about the past management and the functioning of such biodiversity-rich cultural landscapes from the people who actively maintained them up until recently **(Biró et al. 2024)**.

Knowledge partnerships between traditional local knowledge holders, and ecologists can produce richer and fairer understandings of nature. We identified key topical areas where such collaborations can positively transform science, policy, and practice **(Molnár et al. 2024)**. To conduct research on traditional ecological knowledge properly, ecologists need to familiarize themselves more deeply with the methodologies of social sciences, further develop their links with social scientists, and adopt new approaches, such as strengthening respect towards other knowledge systems and being inclusive in research and open to new types of validation **(Molnár & Babai 2021)**.

Another methodological development during our project was the identification of the benefits and challenges of cross knowledge system reviewing. We concluded that discrepancies between knowledge sources were rare, sources were often complementary, filling each other's knowledge gaps. Differences in the contributions of the knowledge sources to the enriched picture of our review topic (pig foraging as a driver) resulted from the diverging interests and methodologies of the knowledge generators. We argue that tross-knowledge system reviews can help overcome limitations in ecological understanding and may provide a shared understanding among collaborating partners, build trust and foster acceptance of each other's knowledge as legitimate **(Molnár et al. 2024)**.

Core papers (10 published, 2 submitted manuscripts, 2 manuscripts under preparation)

Babai D., Jánó B., Molnár Zs., (2021): In the trap of interacting indirect and direct drivers: the disintegration of extensive, traditional grassland management in Central and Eastern Europe. *Ecology and Society,* 26:6., **IF: 5.27**, **D1**, https://doi.org/10.5751/ES-12679-260406

Biró M., Molnár, Zs., Öllerer K., Demeter L., Bölöni J. (2022): Behind the general pattern of forest loss and gain: a long-term assessment of seminatural and secondary forest cover change at country level. *Landscape and Urban Planning*, 220: 104334, I**F: 9.1, D1,** doi.org/10.1016/j.landurbplan.2021.104334

Biró, M., Molnár, K., Öllerer, K., Szilágyi, R., Babai, D., Molnár, C., & Molnár, Z. (2024). Oral history methods can reveal drivers of landscape transformation: Understanding land-use legacies with local and traditional knowledge in Central Europe. *People and Nature*, **D1**, **IF: 4.2**, *6:* 2463-2479. https://doi.org/10.1002/pan3.10738

Biró, M., Öllerer, K., Molnár, K., Türke., I.J., Horváth, D., Juhász, M., Molnár Zs. (2025): The role of indirect drivers in shaping Natura 2000 habitats – a multi-site analysis in Hungary and Romania. *People & Nature*, submitted.

Demeter, L., Molnár, Á. P., Öllerer, K., Csóka, G., Kiš, A., Vadász, C. Horváth, F., & Molnár, Z. (2021). Rethinking the natural regeneration failure of pedunculate oak: The pathogen mildew hypothesis. *Biological Conservation*, **D1, IF: 7.5**, 253: 108928. https://doi.org/10.1016/j.biocon.2020.108928

Demeter, L., Molnár, Cs., Bede-Fazekas, Á., Molnár, Á.P., Watkins, C., Molnár, Zs. (a): Impact of land-use history and abandonment on species composition during forest enchroachment. Manuscript under preparation, target journal: Forest Ecology and Management.

Demeter, L., Molnár, Á.P., Watkins, C., Schmotzer, A., Molnár, Zs. (b): Drivers of conservation management in areas under spontaneous forest enchroachment in Hungary. Manuscript under preparation, target journal: Biological Conservation.

Gantuya, B., Biró, M., Molnár, Á., Avar, Á., Sharifian Bahraman, A., Babai, D., Molnár, Zs. (2021): How Mongolian herders perceive ecological change in a 'stable' landscape. *Ecology & Society*, 26:21. **IF 5.27, D1**, doi.org/10.5751/ES-12454-260221 https://www.ecologyandsociety.org/vol26/iss2/art21/

Gantuya, B., Oborny, B., Batjav, Batnuya, Molnár., Zs. (2025): The relevance of traditional knowledge for modern landscape management: Comparing past and current herding practices in Mongolia. *People & Nature*, http://doi.org/10.1002/pan3.10784 Online first.

Molnár Zs., Babai D. (2021): Inviting ecologists to delve deeper into traditional knowledge. *Trends in Ecology and Evolution*, 36: 679-690. **IF: 20.59**, **Nature Indexed, D1**, doi:10.1016/j.tree.2021.04.006, https://www.sciencedirect.com/science/article/pii/S0169534721001063

Molnár, Zs., Aumeeruddy-Thomas, Y., Babai, D., Díaz, S., Garnett, S.,T., Hill, R., Bates, P., Brondízio, E., Carino, J., Demeter, L., Fernández-Llamazares, Á., Guèze, M., McElwee, P., Öllerer, K., Purvis, A., Reyes-García, V., Samakov, A., Singh, R. (2024): Towards richer knowledge partnerships between ecology and ethnoecology. *Trends in Ecology and Evoltuion*, 39: 109-115. **IF: 16.7, Nature Indexed, D1**, https://doi.org/10.1016/j.tree.2023.10.010

Molnár, Z., Demeter, L., Szabados, K., Kiš, A., Ajvazović, M., Runjanin, B., Mandušić, V., Biró, M., Öllerer, K., Marinkov, J., Ulicsni, V. Babai, D., Katona, K. (2024). Benefits and challenges of reviewing across knowledge systems:'Gourmet omnivore'pigs foraging in the wild. *People and Nature*, 6: 2182-2199., **IF: 4.2**, **D1**, https://doi.org/10.1002/pan3.10717

Sharifian, A., Gantuya, B., Wario, H.T., Kotowski, M.A., Barani, H., Manzano, P., Krätli, S., Babai, D., Biró, M. Sáfián, L. Erdenetsogt, J., Qabel, Q.M., Molnár, Zs. (2023): Global principles in local traditional knowledge: a review of forage plant-livestock-herder interactions. *Journal of Environmental Management*, 328: 116966. **IF: 8.0, D1**, https://doi.org/10.1016/j.jenvman.2022.116966

Sharifian, A., Biró, M., Babai, D., Arjmandi, A.A., Qabel, Q.M., Molnár, Zs.: NO WAY OUT: Perceived ecological changes and the inextricable interaction of direct and indirect drivers by Turkmen pastoralists in Iran. Submitted to *Ecological Indicators*.

PUBLICATIONS AND MANUSCRIPTS (in the order of publication)

How Mongolian herders perceive ecological change in a 'stable' landscape (Gantuya et a. 2021)

Recently, climate change has had a considerable impact on rangelands, available forage, and shifting boundaries of ecological zones in Mongolia. Additionally, long-term studies in the forest-steppe zone show that increasing livestock pressure impacts vegetation composition and cover. Evidence shows that the traditional ecological knowledge of Mongolian herders can serve as a valuable body of information relevant to observations about these ongoing ecological processes. Among other things, a deeper understanding of how herders perceive ecological changes would be useful for improving pasture management and promoting natural regeneration processes. We conducted indoor and outdoor structured and semi-structured interviews, with additional landscape walks and participatory fieldwork. In total we interviewed 33 people, all full-time herders. We found 32 indicators on how herders perceived landscape and vegetation changes for the 14 habitat types studied. Herders had deep knowledge of their landscape, and they attributed various changes to diverse drivers on their grasslands, wetlands, and forests. Among herders there was variation in the perceived importance of droughts and increasing livestock numbers. The perceived changes and indicators could be grouped into three main categories, namely long-term (decadal) trends, regenerative successions after disturbance, and recurrent fluctuations caused mainly by weather. Some of the long-term trends reported by herders are well-known, e.g., worsening of rangeland production, others, like the blackening of tussocks, or the impact of oilskin on yurt site regeneration, are rarely mentioned in the scientific literature, if at all. South-facing mountain slopes and flat areas in valleys were reported as the locations where vegetation change takes place most rapidly. To reverse adverse changes, herders wish to cooperate especially with each other to increase mobility, stop overgrazing, and help nature to regenerate their worsening pastures. We conclude that herders have a reliable and widely shared understanding of landscape and pasture changes that could help with this cooperation.

Table 2. Indicators of landscape and vegetation changes (trends, regenerative successions, and fluctuations) with frequency of mentions by herders (****: mentioned by [almost] all herders, ***: by many herders, **: by several herders, *: by a few herders only), habitats where these changes were observed and reported, and drivers as understood and reported by Mongolian herders. Drivers: LI: livestock numbers increasing, DP: decrease in precipitation and droughts, CC: climate change in general, HU: human utilization, GHDR: goats and horses dig roots.

Indicators of landscape change	Frequency of mentions	Habitats	Drivers
Trends			
1. Change in rangeland production	****	Almost all pastures	LI, DP
2. Decrease in hay quantity and quality	**	Hayfields	LI, DP
3. Change in haymaking time	***	Hayfields	CC
4. Decrease in vegetation cover	****	Almost all pastures	LI, DP
5. Change in plant height	****	Almost all pastures	LI, DP
6. Change in plant population sizes of useful plants	****	General	LI, DP, HU
7. Increase in weed and pest populations	**	Disturbed place by Brandt's vole (*Lasiopodomys brandtii*), along the road, near the dung	LI, DP, Brandt's vole
8. Increase in unknown, unfamiliar plants	***	Disturbed place by Brandt's vole, along the road, near the dung	DP, Brandt's vole
9. Shrinking of plant roots	***	South-facing slopes	LI, DP, GHDR, heavy rain (hail), spring

Fig. 4. Herders' observations of different types of recurrent regenerative successions in Khangai and Arbulag soums, Mongolia. Numbers of relevant indicators is shown in brackets. Photos: Ábel Péter Molnár.

Regeneration of abandoned animal rest places. *Sharil, hyag, and tsagaan huli mainly grow first on or near abandoned places. If it is not used for 3–4 years, good (=more ova) grasses will grow.* [25]

Regeneration of abandoned marmot burrows and Brandt's vole patches. *About 5 years after the marmots are gone and the holes are blocked, these plants (Sharil, hyag and tsaagana) are replaced by other pasture plants.* [26]

Regeneration of abandoned yurt sites. *When we use felt carpet in the yurt, the plants grow easily after 2 year.* [27]

Regeneration after forest fire. Larch (or other) trees start to regenerate after 2–3 years. *After many years, approx. 20–30 years, the larch forest will grow back naturally, but regeneration varies depending on how deep the fire was.* [28]

Fig. 5. Herders' observations of multi-year fluctuations in various habitats in Khangai and Arbulag soums, Mongolia. Numbers of relevant indicators is shown in brackets. Photos: Ábel Péter Molnár.

Allium altaicum, Ribes altissimum, and *Lonicera altaica* grow smaller and produce fewer fruits in drought years, and grow better in wetter years. Some weeds such as *sharil)* increase in the year after a drought. [29]

Some animal species also fluctuate with drought and rain. *If it rains a lot, the grass grows high and Ulin tsagaan ogotno (Brandt's vole) naturally reduces.* [30]

The shores of large rivers constantly change, collapse, and develop during major floods. *If a river floods, plants are taken away with their roots, water flows in different directions, and soyr develops* (or disappears). [31]

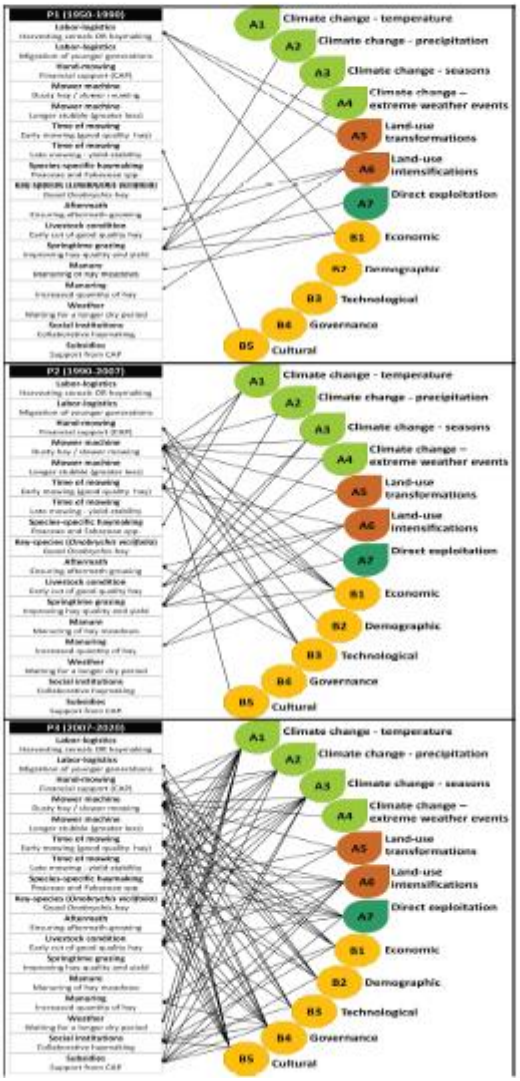
If there is wet snow in autumn (*mid-August to early September*), some trees or their branches (*even thick ones*) may break and fall. [32]

other (somehow) related changes; changes are interrelated, so general trends are often unclear. In both study areas, however, the

In the trap of interacting indirect and direct drivers: the disintegration of extensive, traditional grassland management in Central and Eastern Europe (Babai et al. 2021)

Micro-scale management of cultural landscapes with species-rich grasslands requires the operation of extensive, traditional land-use systems. These social-ecological systems are under increasing pressure of interacting drivers that impact on farmers' individual decisions and force them to make trade-offs. We aimed to reveal the local understanding of driver interactions and related trade-offs focusing on a key element of a traditional social-ecological system. We studied the time of hay-mowing using participatory observation (105 field days), semi-structured interviews (n = 85), and focus group discussions (n = 2), analyzing the interacting IPBES defined drivers that influence the choice of the time of mowing and related trade-offs in a small-scale community in a mountainous landscape (Gyimes, Transylvania, Romania) from the 1950s to the present. Local farmers perceived a number of direct and indirect drivers, as ecological, socio-cultural, economic, and political changes affected the optimal and actual time of mowing and increased the number of trade-offs. The most important factors were (1) the quality of the hay; (2) long-term yield stability by ensuring seed ripening, and (3) qualifying for financial support from agri-environment-climate schemes. Direct drivers influenced the phenology of vegetation and thus the time of mowing, while indirect social, cultural, and political drivers only impacted on the latter. The complexity of driver and trade-off interactions increased through time making adaptation more difficult. While farmers were navigating through the increased complexity, an informal social institution that previously optimized the work forces of farms gradually disappeared. The cumulative effects of drivers and trade-offs decreased the economic and social viability of the system. Our results suggest that the local community's adaptive capacity has been drastically weakened. We argue that more flexible and adaptive regulations are needed to assure the continuity and ongoing adaptation of this and other Eastern-Central-European, centuries-old but still existing traditional management systems, which created and maintain high nature-value cultural landscapes.

Fig. 7. Increasing number of direct and indirect drivers and trade-offs regarding the timing of mowing on hay meadows in the studied periods since the 1950s in Gyimes, Eastern Carpathians, Romania. Key: green: direct driver–climate change; brown: direct driver–land use change; blue: direct driver–direct exploitation; yellow: indirect drivers–economic, demographic, technological, governance, and cultural drivers



Inviting ecologists to delve deeper into traditional ecological knowledge (Molnár & Babai 2021)

Ecologists and conservationists increasingly acknowledge that traditional ecological knowledge (TEK) is vital for a better understanding and conservation of biodiversity; for example, for a more complex socioecological understanding of long-term processes, ecosystem resilience, the impacts of traditional management practices, and the worldviews underpinning these practices. To gain a deeper understanding of the ecological dimensions of TEK, ecologists and conservation biologists should conduct participatory long-term collaborative research on TEK. To conduct TEK research properly, however, ecologists need to familiarize themselves more deeply with the methodologies of social sciences, further develop their links with social scientists, and adopt new approaches, such as strengthening respect towards other knowledge systems and being inclusive in research and open to new types of validation.

Table 1. Potential advantages and challenges in the application of long-term, participatory, and collaborative TEK research methodologies by ecologists and conservation biologists[a]

Advantages of long-term TEK research	Challenges of long-term TEK research
• Sufficient time to build genuine trust and positive, enduring relationship with locals, partnering with Indigenous/traditional scholars, and to apply Free Prior Informed Consent in culturally appropriate ways	• Long-term research requires considerable time and it can be challenging and burdensome to adjust research methodologies, build trust, and embed into the local culture
• Time to adjust research plans and implementation to meet the needs of the local communities	• Time and patience are needed to understand local ecological and other terms, taxonomies, and biocultural indicators of species and ecosystems, specific behaviours, and customs
• Time for careful listening, observing, embedding, discussing diverse topics, connecting more closely with the place, and obtaining deep understanding and reliable and validated results	• Researchers require at least a rudimentary knowledge of the studied practices (farming, herding, forest use, fishing)
• With both partners having deep knowledge of the landscape, mutual respect for each other's ecological knowledge will enable more to be learned about the hundreds of species and tens of ecosystem types known locally	• The application of social science methods may pose unexpected challenges for ecologists (e.g., self-reflexivity, elicitation methods that respect local protocols and ethics); the unethical integration of 'distilled TEK artefacts' into science should be avoided
• Sufficient time to understand social-ecological contexts, elicit reflections on the appropriateness of the research methodology, and find out about local stories and beliefs	• Participatory fieldwork implies being present in all seasons and weather conditions
• Reciprocal understanding of vocabularies (including folk names, taxonomies, concepts, models) facilitates mutual explanation and understanding	• Researchers need to be 'prepared for the unexpected' regarding local interpretations of ecological patterns and processes (e.g., the role of ancestors and supernatural beings) and must dedicate patience and time to the elicitation of related TEK (including values and worldview)
• As compliance constraints disappear, this engenders a culturally safe environment for participants on both sides, fostering natural behaviour and honest exchanges of information, and helps the researcher to understand which research questions are really relevant to the local community	• Challenges for natural scientists may include participating appropriately in cultural and family events, respecting customs and taboos, and maintaining enduring relationships
• Long-term interactions lead to the development of a common reference collection of situations, experiences, and stories	• A small sample size may distort research results (individual specificities, knowledge that is empirically sound but not widely shared); comparative research and an overall understanding of the local social-ecological system are needed
	• Local political, social, and historical contexts must be understood, including power relation-

Behind the general pattern of forest loss and gain: A long-term assessment of semi-natural and secondary forest cover change at country level (Biró et al. 2022)

Despite deforestation taking place globally, forest cover is increasing in many European landscapes. This increase, however, resulting from plantations and spontaneous forest regrowth, may obscure the generally declining trend of semi-natural forests, though the latter are essential for local and landscape-level conservation strategies and sustainable forest management. We assessed changes in semi-natural and secondary forest cover since the 18th century in Hungary, focusing on the continuity of semi-natural forests. The main trajectories of regional and country-scale forest transformations were reconstructed from the fine-scale site histories of 1,728 randomly selected sample localities. Historical and recent datasets were complemented with field data to estimate forest cover change for seven time periods between the 1780s and the 2010s. Total forest cover changes over these 230 years showed a U-shape curve (from 25% to 24%), leading to a forest minimum in the first half of the 20th century. Semi-natural and secondary forests exhibited strikingly different trends. The proportion of semi-natural forests decreased to 36% of the total forest area by the 2010s, driven mainly by conversion to arable land, while 88% of the actual semi-natural forests have remained continuous forest since the 18th century. Our results showed that when reconstructing landscape-scale historical forest cover change and continuity, the loss of semi-natural forests remains hidden if the calculations are limited to 'total forest cover change'. It would therefore be immensely important to distinguish between semi-natural and secondary forests, and between types of continuity in the assessments used for conservation-oriented landscape planning and sustainable forest management.

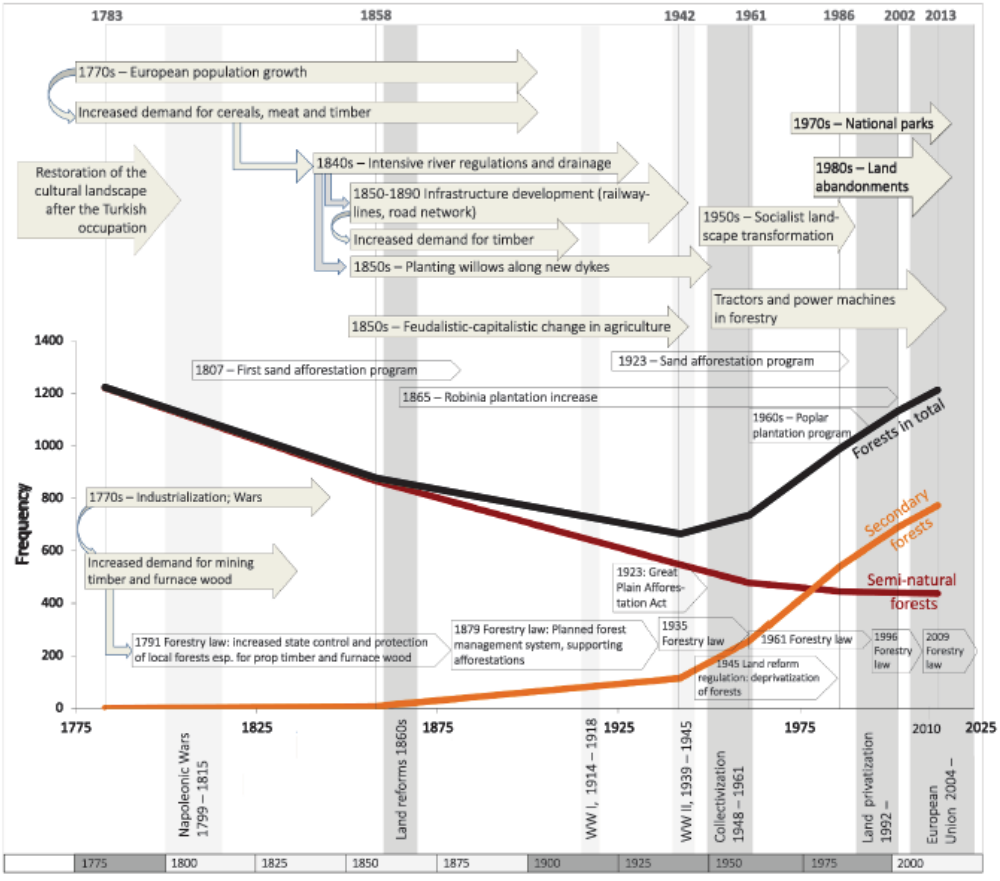


Fig. 5. Forest cover change in Hungary and its indirect drivers (boxes with arrows). Effects of multiple drivers resulted in a decrease in semi-natural forests and an increase in secondary forests. Note that the total forested area reached a minimum around the first half of the 20th century. Dates in top row: central dates of the time periods used in the study (Table 1.). Based on Andrásfalvy, 2007; Bartha & Oroszi, 2003; Jepsen et al., 2015 together with Appendix; Schindler et al., 2016; Varga, 2017; Mihók et al., 2017.

Rethinking the natural regeneration failure of pedunculate oak: The pathogen mildew hypothesis (Demeter et al. 2021)

Introduced pathogen microorganisms are important drivers of ecosystem change. This paper highlights the impact of the non-native pathogen mildew multi-species complex on the natural regeneration dynamics of pedunculate oak (*Quercus robur*). Pedunculate oak is a European keystone tree species, hosting a great amount of biodiversity, but its future role in (near-)natural forests is uncertain due to the lack of natural regeneration. We reviewed historical and recent ecological, pathological and forestry literature on topics related to the impact of mildew on the success of advanced natural regeneration of pedunculate oak in (near-)natural forests. We propose a novel hypothesis, the 'pathogen mildew hypothesis', to explain the failure of natural regeneration of pedunculate oak. Mildew reduces shade tolerance and vertical growth in seedlings and saplings, so sapling vitality and competitiveness have diminished considerably since it was unintentionally introduced to Europe in the early 20th century. Due to mildew infection, pedunculate oak in many cases no longer regenerates well naturally under its own canopy. We found that forest ecologists and conservationists often overlook the impacts of this 'recent' driver, while the 'closed-forest' and 'wood-pasture' hypotheses do not adequately help the management of pedunculate oak regeneration. Nature conservation and forest management plans should thus also consider the impact of mildew in order to improve natural regeneration, promote close-to-nature management of pedunculate oak forests, and support associated diversity. More generally, nature conservation, forest ecology and close-to-nature forestry should pay greater attention to the impact of introduced non-native microorganisms on the dynamics of natural ecosystems.

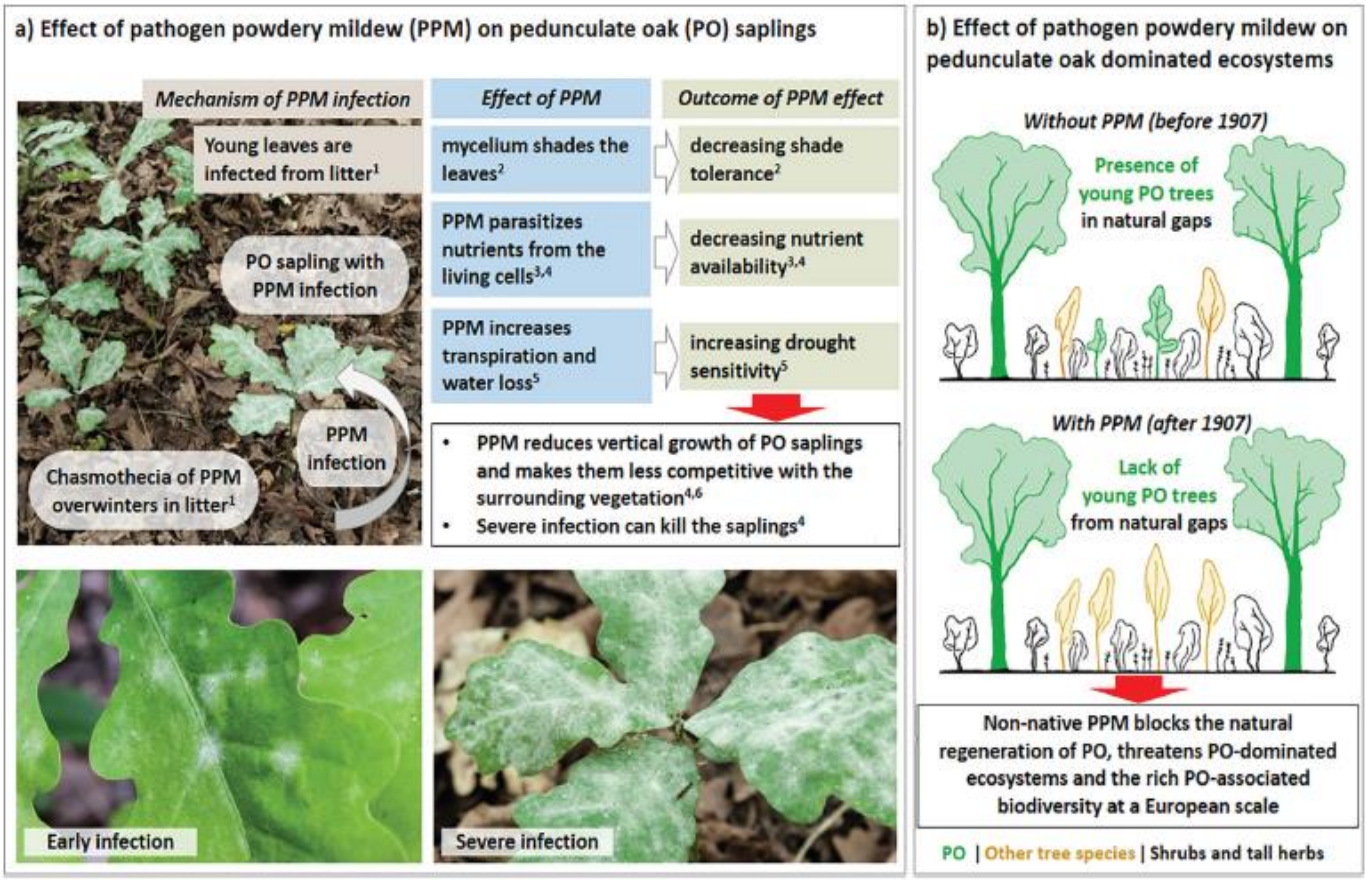


Fig. 1. The effects of pathogen powdery mildew (PPM) on pedunculate oak (PO) saplings (a) and on the dynamics and diversity of (near-)natural PO ecosystems (b). References: [1]Marçais et al., 2009; [2]Hajji et al., 2009; [3]Hewitt and Ayres, 1976; [4]Desprez-Loustau et al., 2014; [5]Hewitt and Ayres, 1975; [6]Igmándy, 1972.

Global principles in local traditional knowledge: A review of forage plant-livestock-herder interactions (Sharifian et al. 2023)

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.

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.

Oral history methods can reveal drivers of landscape transformation: Understanding land-use legacies with local and traditional knowledge in Central Europe (Biró et al. 2024)

1. Ecosystems and landscapes shaped by the intricate relationship between people and their natural environment embody the impact of many different past land-use practices and historical events. However, in some regions, classical historical records of landscape change do not exist or are insufficiently detailed. Local communities' ecological memory can play an important role in filling this gap by reconstructing the socio-ecologically relevant indirect drivers and their interactions, as well as identifying vegetation characteristics that are legacies of previous land-use practices.
2. We studied a rapidly transforming cultural landscape in Transylvania (Romania) by conducting 144 oral history interviews covering the last 70 years (before, during and after collective farming).
3. The interviews revealed complex interactions of indirect drivers. Country-scale political and economic changes affected the landscape with crop outflow during the collective system (1962–1989), resulting in labour outflow to cities from the 1960s. The latter reduced the time and attention devoted to haymaking and affected population ageing. Together with other drivers, this demographic change led to a major transformation of the traditional landscape by the 2010s. We identified 47 vegetation characteristics as land-use legacies related to grasslands and classified them into general legacy types.
4. Our results support that there was an opportunity to innovatively revive the traditional cultural landscape after the fall of communism, when local knowledge, and willingness to manage the landscape were still present, but financial assets and government support were lacking. The indirect driver interactions led to the abandonment of traditional hay meadow management, resulting in a homogenising landscape with simplified land use dominated by sheep grazing and increasingly dependent on agricultural subsidies.
5. We found that many vegetation characteristics of the studied species-rich grasslands are only legacies of former land-use activities, still known by locals but no longer applied. By creating knowledge partnerships, we can still learn about the past management and the functioning of such biodiversity-rich cultural landscapes from the people who actively maintained them. We argue that this type of knowledge is essential to revive and adapt practices for protecting and managing species-rich habitats across European cultural landscapes and for supporting the planning of appropriate conservation management and subsidy schemes.

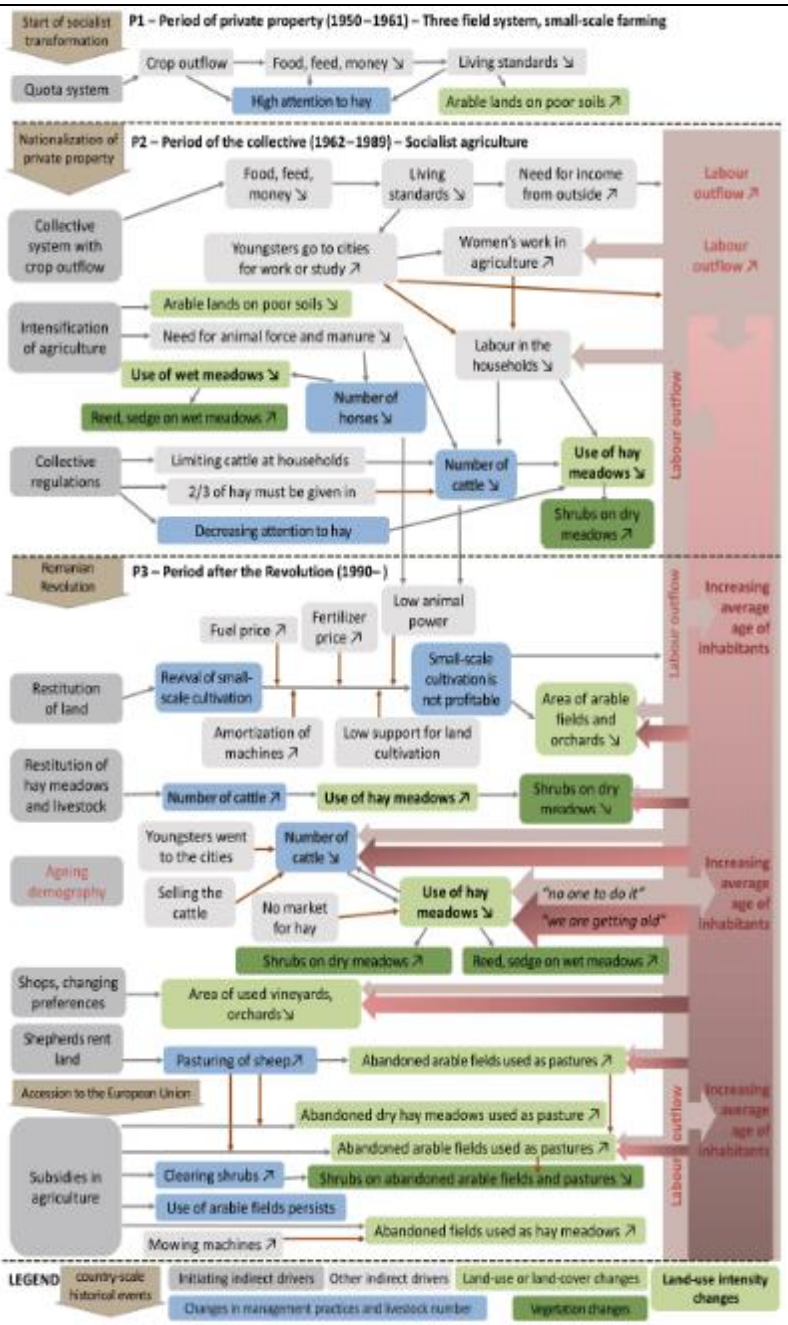


FIGURE 3 Ecologically relevant indirect driver interactions and their impacts mentioned in the oral history interviews. Demographic consequences of indirect driver interactions are shown on the right with vertical arrows highlighting delayed effects of the two mutually reinforcing demographic drivers (labour outflow and population ageing). Ageing demography was initiated by local internal demographic processes. Brown arrows show exacerbating effects of drivers (see legend). Arrows in boxes indicate direction of change. Italicised texts show exact quotations from interviewees.

Towards richer knowledge partnerships between ecology and ethnoecology (Molnár et al. 2024)

Indigenous and traditional practices based on ethnoecological knowledge are fundamental to biodiversity stewardship and sustainable use. Knowledge partnerships between Indigenous Peoples, traditional local communities, and ecologists can produce richer and fairer understandings of nature. We identify key topical areas where such collaborations can positively transform science, policy, and practice.

Table 1. Some key subject areas of ethnoecological and scientific knowledge of socio-ecological systems to help design knowledge partnerships (see related references in Appendix IV in supplemental information online).

Ethnoecological knowledge domains	Ethnoecological subject areas	Corresponding scientific ecological subject areas
Land/seascapes, ecosystems, plant and animal species	• Local categories, folk names, characteristics, taxonomy and uses of wild and domestic plants, animals and fungi, soil, rock, water, snow, ice, wind etc.; distinguishing parts of a landscape into macro-, meso-, and microscale habitats • Local categories and knowledge of ecological needs and modes of interactions of species and wider ecosystems and/or landscapes; spatial distribution, patchiness, dynamics (incl. trends and fluctuations) of elements of biodiversity at different spatial and temporal scales • Trends over time in the local environment, conceptualisation regarding direct and indirect drivers of change or status, including climate; local knowledge of extinct and new arriving (potentially invasive) species	• Categories and classifications of biotic and abiotic elements of nature • Physiology, molecular ecology, phylogenetics, phenotypic and genetic diversity • Spatial and temporal patterns and dynamics of populations, ecosystems and landscapes, coexistence of various elements of nature • Functional ecology: traits, flows of resources, productivity, ecosystem health (biological, chemical, physical characteristics) • Landscape ecology, maps (vegetation, edaphic, topographic) and types of partitioning proposed, changes of species pools • Flora, fauna, ecosystem, and landscape histories, history of land-use, and of internal and external drivers of change
Land and biodiversity management practices and related ethnoecological knowledge	• Categories of NCPs related to biodiversity, practices that modify patterns and processes in the environment to enrich NCP provisioning • Trends and changes in various management practices and their short- and long-term perceived impacts on biodiversity and interactions between species • Monitoring processes related to degradation or regeneration of biodiversity under various management practices and intensities; practices to mitigate adverse impacts or restore damaged populations/ecosystems • Locally developed indicators and their use to monitor impacts of practices • Management decisions, linked to ethnoecological understanding of changes and their drivers for the management of biodiversity	• Identifying formal categories of NCPs and ecosystem services • Short and long-term impacts on ecosystem structure and function, biogeochemical and physical flows, productive capacity at fine and coarse scales in relation to changes and adaptation of the local management system to internal and external drivers etc. • Local management processes applied to regeneration or active restoration, or protection of individuals, selected species, life history stages or entire habitats, and the ecological impacts of these • Species, ecosystem and landscape-level indicators and monitoring of ecological change • Landscape mosaics and complexities: biodiversity flows between agroecosystems, forests and other habitats • Developing experimental set ups in field (or in labs) simulating local practices and monitoring with ecological approaches
Social institutions underpinned by ethnoecological knowledge	• Explanations of indirect (social, economic, political) drivers of ecological change at multiple scales, and actors driving these changes • Assessment of the impact of rules, social taboos, norms, social structures, power relationship on management decisions, and their ecological consequences • Ways of learning from and about nature and its changes, and pathways of inter- and intragenerational knowledge transmission • Ways of coping with and adaptation to the ecological and social consequences of environmental changes, such as maintaining the resilience of the socio-ecological system	• Drivers of change which affect customary rules, e.g., access to spaces, where, when, and what amount to hunt, collect, where to cultivate or bring herds, and ecological monitoring of impacts (spatial/temporal changes in spaces and associated biodiversity) • Norms of social behaviour (not elaborated rules): limiting overuse at the expense of others within a community, sharing, giving and receiving (e.g., seeds, propagules), and the ecological consequences of these on reshuffling (mixing) of biodiversity and agrobiodiversity and on the potential resilience to climate and yield stability • Exchanges and mobility of humans and biodiversity

Benefits and challenges of reviewing across knowledge systems: 'Gourmet omnivore' pigs foraging in the wild (Molnár et al. 2024)

1. Evidence-based conservation can benefit substantially from multiple knowledge sources and different knowledge systems. While traditional ecological knowledge (TEK) and collaborative research are increasingly acknowledged, detailed cross-knowledge system reviews are scarce and their methodology underdeveloped. We have two objectives: to prepare such a review and to discuss the benefits and challenges of such reviews.
2. We review pig keeping in forests and marshes, a historically widespread but nowadays almost extinct practice in Europe, but one with high potential for organic farming, conservation and restoration. We focus on what, when and how free-ranging pigs forage in the wild. We review five knowledge sources: living and archived TEK, pig and wild boar scientific literature, and the authors' observations of foraging.
3. Unexpectedly, given the amount of available information, archived TEK differed considerably from living TEK of *svinjars* (Serbian: traditional pig keepers), and scientific knowledge on pig and boar foraging from TEK. *Svinjars* deeply understood the consumption and avoidance behaviour of pigs towards 98 and 56 plant taxa, and 42 and 17 animal taxa, respectively. Our review showed that pigs are *gourmet omnivores*, optimizing and switching between foraging on earthworms, acorns, grasses and corn. Discrepancies between knowledge sources were rare, for example on the consumption of woody roots, earthworms, mushrooms and snakes/ lizards. Sources were also complementary, filling each other's knowledge gaps.
4. Topics where the cross-knowledge system review was most fruitful were acorn foraging, browsing, earthworm and mushroom consumption. Differences in the contributions of the knowledge sources to the enriched picture resulted from the diverging interests and methodologies of the knowledge generators.
5. We identified and discussed both the benefits (different approaches of knowledge generation; expanded time scales; complementarity; novel cause–effect explanations; identification of knowledge gaps; and biases) and the challenges (how to identify relevant publications and knowledgeable TEK holders; how to collate knowledge and verify its reliability; and how to conduct a culturally respectful synthesis) of cross-knowledge system reviewing.
6. *Synthesis and applications*. Cross-knowledge system reviews help overcome limitations in ecological understanding and may provide a shared understanding among collaborating partners, build trust and foster acceptance of each other's knowledge as legitimate.

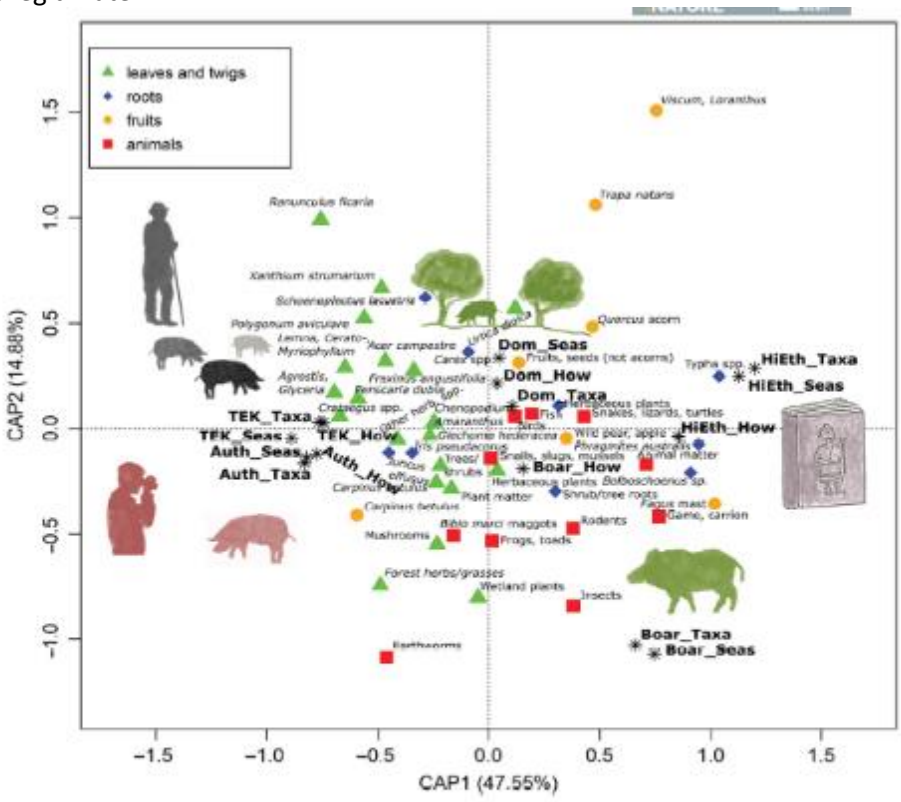


FIGURE 2 Comparison of the five knowledge sources and the 47 forage types based on the quantity of available information. Distance-based redundancy analysis of all 47 forage types regarding the three knowledge areas (Taxa = what taxa, Seas = in which season and How = how pigs/wild boar forage) coming from the five knowledge sources (HiEth and TEK = archived and living TEK, Dom and Boar = domestic pig and wild boar literature, and Auth = authors' observations) of the two knowledge systems (traditional knowledge and science). Historical–ethnographic sources (archived TEK) correlated positively while living TEK of *svinjars* correlated negatively with the first axis, suggesting unexpected, wide-ranging differences in their content. *Svinjars'* TEK and our own observations overlapped the most (cf. the same study area). Animal forages were richly documented in the wild boar literature, herbaceous species by *svinjars'* TEK and authors' visual observations. Some of the differences between sources were caused by the non-overlapping sets of species (e.g. reed and cattails did not occur in the *svinjars'* places) or study sites (wetlands were underrepresented in wild boar studies).

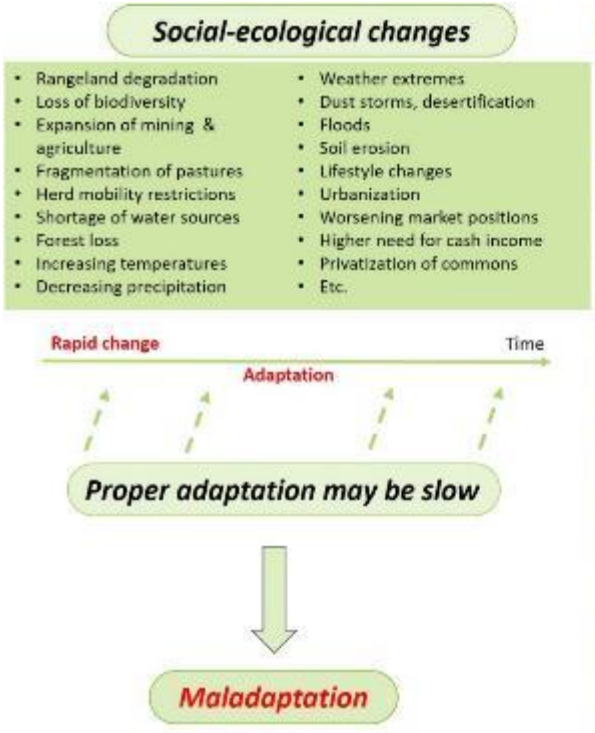
The relevance of traditional knowledge for modern landscape management: comparing past and current herding practices in Mongolia (Gantuya et al. 2025)

Traditional ecological knowledge (TEK) is increasingly acknowledged as key to sustainability, and to the successful adaptation of local communities to rapid changes. However, implementing TEK is a major challenge in most parts of the world. A book published 80 years ago by Sambuu Jamsran, a Mongolian agricultural minister in the 1930s, provides a unique opportunity to compare the past versus present knowledge and practices of semi-nomadic herders. Sambuu collected information from highly respected herders during a dialogue workshop about the proper management of herds and pastures. This cooperation between a politician and the herders yielded a valuable collection of 'best practices'. We aimed to assess the relevance of this traditional knowledge for the successful adaptation of local communities in present Mongolia.

We interviewed 31 middle-aged or older herders about 69 pieces of advice extracted from Sambuu's book. Two questions guided our inquiries: 1) Do you agree with the advice? 2) Do people in your region adhere to it? If so, why, if not, why?

Most recommendations were still accepted as valid (77%) by herders; however, only a smaller proportion was followed (49% of all). The interviews revealed some key reasons for the abandonment of certain traditional practices in the post-1990 era, driven by fast social-economic changes, even though the herders were aware that the traditional practices were more proper and sustainable. The practices that were abandoned the most were those that required greater time investment, were less compatible with modern lifestyles, or needed closer cooperation and better-functioning institutions.

In conclusion, the Mongolian semi-nomadic herding system exhibits adaptability to new conditions, but the development of proper new practices by herders or the government may take considerable time. As in many cases around the world, there is a time lag between the changes and the herders' responses to these changes. Herders' traditional ecological knowledge has a vital role in developing locally adaptive solutions, while institutions have a critical role in formulating policy that can mitigate the negative impacts of rapid changes while fostering tradition-based, sustainable, and innovative practices for the future.



Possible solutions to overcoming the maladaptation

Adaptations for better management of pastures and livestock, improved regulations and knowledge management	Potential for slowing down changes	Potential for speeding up adaptation
Ecosystem, pasture and herd management		
Pasture management plans, rotation and resting	**	***
Ecological restoration, control of invasive species	**	*
Prevention of forest loss, reforestation	**	*
Prevention of conversion to other land uses	***	*
Rehabilitation of water supplies	***	***
Change herd daily routes, mobility	**	**
Diversify or simplify livestock	*	**
Change herd composition/restocking	**	**
Supplementary fodder	***	***
Reorganization of labor around grazing	**	***
Regulations and policies		
Improve governance and local policies	***	***
Develop locally more appropriate regulations	***	***
Improve access to markets, increase market value	**	***
Revitalization, innovation of customary governance	**	**
Insurance systems to reduce vulnerability	*	**
Infrastructure improvement	*	**
Diversification of income sources	**	***
Knowledge generation and knowledge sharing		
Support local knowledge generation	**	***
Knowledge co-production with diverse partners	**	***
Collaborative research on adaptation options	**	***
Education, training	**	***
Sharing of best practices (e.g. modern technologies)	**	***
Early warning systems (e.g. weather forecast)	*	**

Fig. 5 Possible solutions to avoid maladaptation in traditional pastoral social-ecological systems by slowing down the potentially harmful social-ecological changes and speeding up adaptation. Asterisks indicate roughly the potential impact of different actions based on Fernández-Giménez 1999; Adger et al., 2003; Opiyo et al., 2015; Fernández-Llamazares et al., 2015; Shackleton et al., 2015; Li et al., 2017, Ahearn, 2019; FAO, 2021, Gantuya et al., 2021, Tugjamba et al., 2021 and Sharifian et al., 2023.

No way out: Perceived ecological changes and the inextricable interaction of direct and indirect drivers by Turkmen pastoralists in Iran (Sharifian et al. submitted to Ecological Indicators)

Traditional local communities have a deep and reliable understanding of complex landscape changes and the role of interacting drivers in these changes. This study aimed to identify the key landscape elements of the Turkmen Sahra landscape in Iran, reconstruct their changes over time, and understand the drivers behind these changes using the ecological memory of Turkmen herders.

Semi-structured interviews were conducted with 26 knowledgeable herders. Subsequently, a questionnaire was completed with 48 herders to quantify the perceived magnitude of changes. The results were thoroughly discussed with three highly knowledgeable locals.

Herders identified 30 key landscape elements that had mostly undergone negative changes. Key reported drivers were declining rainfall, increased drought periods, farmland and industrial expansion, the construction of dams and drainage channels, and changes of worldview. They also identified 65 plant species and reported observations of population changes over short and long terms. Most species were reported to have declined in the long term except *Tamarix kotschyi*, *Cuscuta campestris*, *Atriplex lentiformis*, *A. canescens*, *Halocnemum strobilaceum*, and *Aeluropus littoralis*. Some species were reported as showing high abundance difference in dry and wet years (e.g. *Medicago polymorpha*, *Phragmites australis*), other reacted less pronouncedly (e.g. *Halocnemum strobilaceum*, *Tamarix kotschyi*). Herders explained that most changes in key landscape elements originate from the inextricable interactions of a sequence of drivers, identifying 176 connections between 69 direct and indirect drivers.

We argue that in the Turkmen Sahra, barriers to substantial natural regeneration of pastures and other habitats have created a situation, where viable solutions may not exist. Future land-use planning programs needs to take this into consideration.

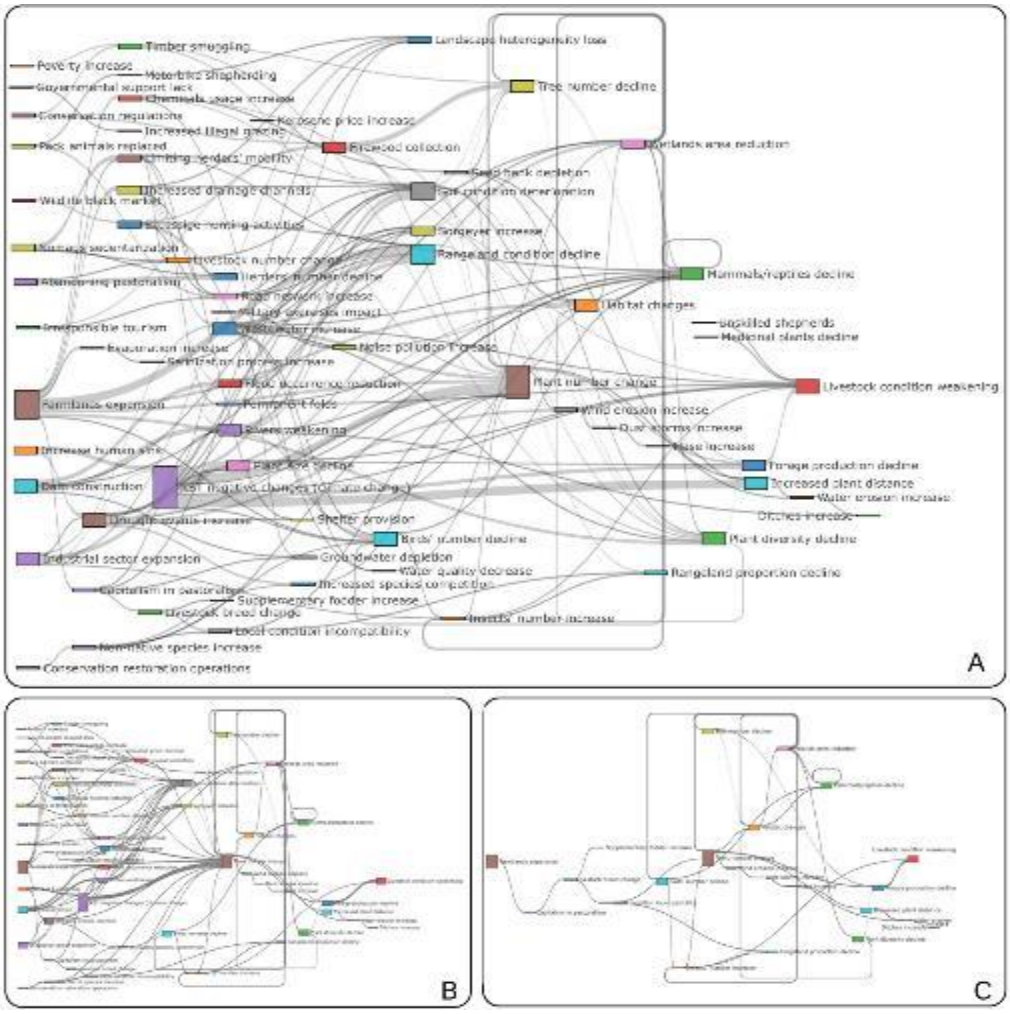


Figure 4. A: Sources, targets and links of changes in all elements of Turkmen Sahra landscape based on herders' ecological memory. B: sources, targets and links of changes for the key landscape element plant number. C: source, targets and links for change in livestock breed

The role of indirect drivers in shaping Natura 2000 habitats – a multi-site analysis in Hungary and Romania (Biró et al. submitted to People & Nature)

Traditional management practices have proved essential for maintaining biodiversity in many semi-natural grassland habitats of high conservation value. Abandonment of these practices may lead to shrub encroachment, decrease in biodiversity, and habitat loss. It is often overlooked in ecological studies, that these declines are generally the consequences of long-lasting, slowly manifesting social processes. We aimed to identify ecologically relevant interacting indirect drivers impacting the management of Natura 2000 grassland habitats since the mid-20th century.

We conducted 60 oral history interviews about 21 semi-natural grassland localities in Hungary and Romania (alluvial meadows, saline and dry semi-natural grasslands). Ecological memory was interviewed from knowledgeable locals by botanists about three time periods (before, during, and after socialist collective farming). We identified 211 mentions of indirect drivers and categorized them into five classes (demographic, economic, institutional, cultural, and technological).

When asked about the causes of grassland management changes, locals recalled mostly local and sub-national-scale drivers although experienced the effects of national and regional-scale drivers. Economic drivers were the most often mentioned indirect drivers in both countries for alluvial and saline habitats. Demographic drivers, such as ageing, labour shortage, and rural-to-urban migration were highly intertwined and the most pronounced for dry semi-natural grasslands. Changing lifestyles and young people's values were often emphasised cultural drivers.

Oral history helped to identify and link local, sub-national and national scale drivers and to understand the slowly manifesting social processes that drive ecological processes. We highlight that migration to cities, amplified by changing livelihood demands together with technological innovations has been endangering habitats with hardly recognisable, delayed processes that date back already to the collective farming period.

The multi-site approach revealed that social-ecological processes affected habitat management in various, locally specific ways. Differences between the two neighbouring countries were mainly due to the two different ways of land reform after the collapse of communism and the previous dictatorial repression in Romania (1970s-1980s). We argue that more attention should be paid to depopulating rural areas in subsidy schemes, conservation and landscape planning, with greater consideration of local landscape and demographic specificities, in particular supporting the surviving small-scale traditional farming practices, combining biodiversity conservation, sustainable food production and the maintenance of transitioning rural communities in Europe's marginalising agricultural landscapes.

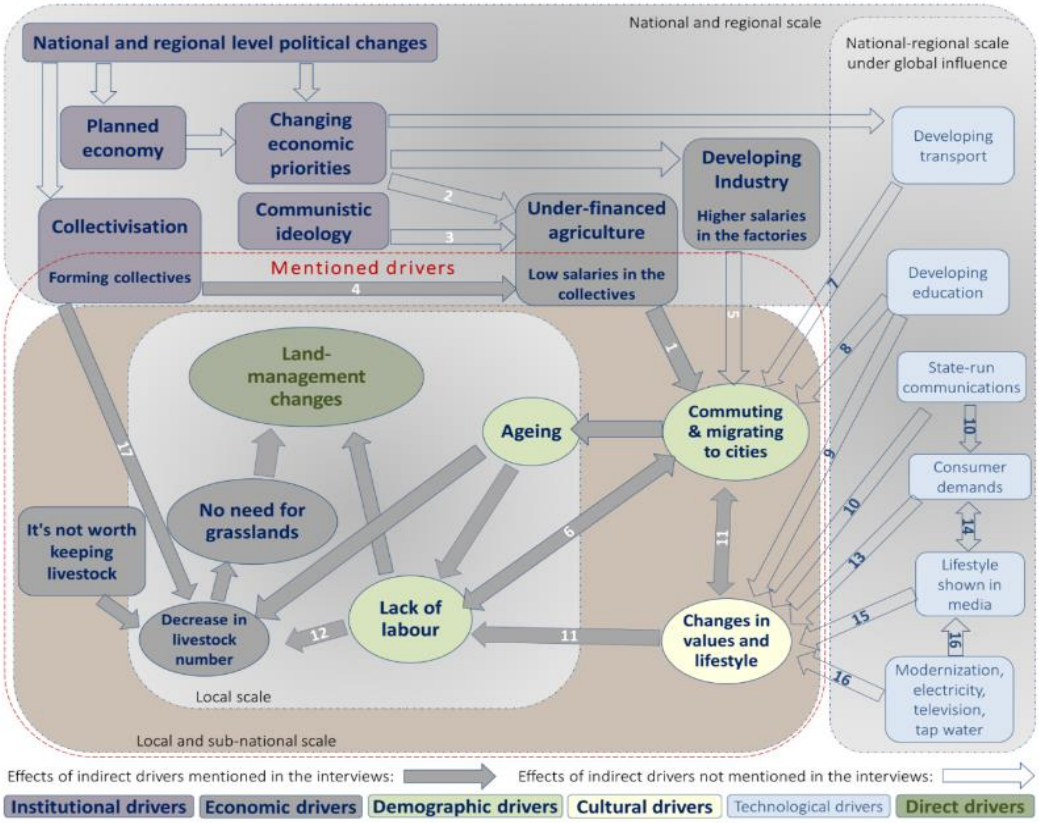


Figure 4. Multi-scale interactions of indirect drivers behind grassland management changes generalised from the oral histories of 21 studied grassland localities on the collective farming period in Hungary and Romania. Local and sub-national scale drivers mentioned in the interviews are inside the bottom-left box, bordered by the red dashed line. Literature on agricultural history helped us to identify non-verbalised drivers and to clarify the ecologically relevant multiple driver interactions and casual chains. Numbers refer to sections of main text explanations marked with the same number.

Impact of land-use history and abandonment on species composition during forest enchroachment (Demeter et al. (a) manuscript under preparation for Forest Ecology and Management, D1)

We investigated the impact of spontaneous woody enchroachment on the species composition of herbaceous, shrub and canopy layers in abandoned agricultural fields in Hungary. Vegetation surveys were made in 358 sampling points in three vegetation types (floodplain hardwood forests, hornbeam-sessile oak and Turkey oak-sessile oak forests), four land-use types (treeless pasture, wood pasture, hay meadow, vineyard) and three groups of different time since abandonment, reference grasslands and reference forests. At each sampling point, we estimated the species cover of all species for all vegetation layers. The number of woody species individuals was assessed at the shrub and canopy level. Field surveys were carried out in 2022 and 2023. Our objectives were to answer the following questions: 1) to what extent does the time since abandonment and the type of land-use history determine the species composition of the three vegetation layers; 2) do spontaneous enchroachments of the three vegetation types show marked differences as a function of time since abandonment and land-use history; 3) what implications might the differences detected have for the management of spontaneous forested areas for conservation and forest management? Variance analysis and partitioning were performed based on the cover values of the species assessed in the herbaceous layer. The most important variable determining the herb layer species composition is the time since abandonment, and to a lesser extent the vegetation type. Reference grasslands separated clearly from abandoned areas and reference forests. Only a minority of the sample points abandoned not more than 25 years ago (more open forest-grasslands mosaics) show a higher similarity to the reference grasslands. The lack of differentiation of the herb layer species composition of the abandoned areas and their high similarity to the herb layer species composition of the reference forests is an unexpected result, suggesting degradation of the reference forests rather than regeneration of the forest species composition of the abandoned enchroached areas. The evaluation of the shrub and canopy layer data is ongoing.

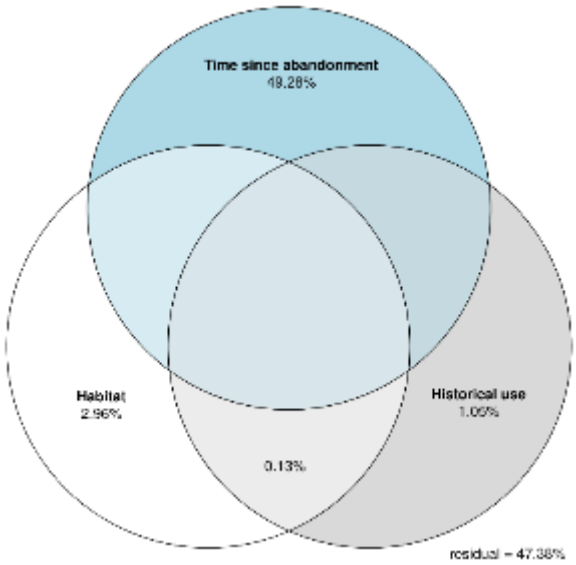


Figure 2. Impact of habitat types, land-use history and time since abandonment on herb layer species composition (Venn diagram with partitioned variance)

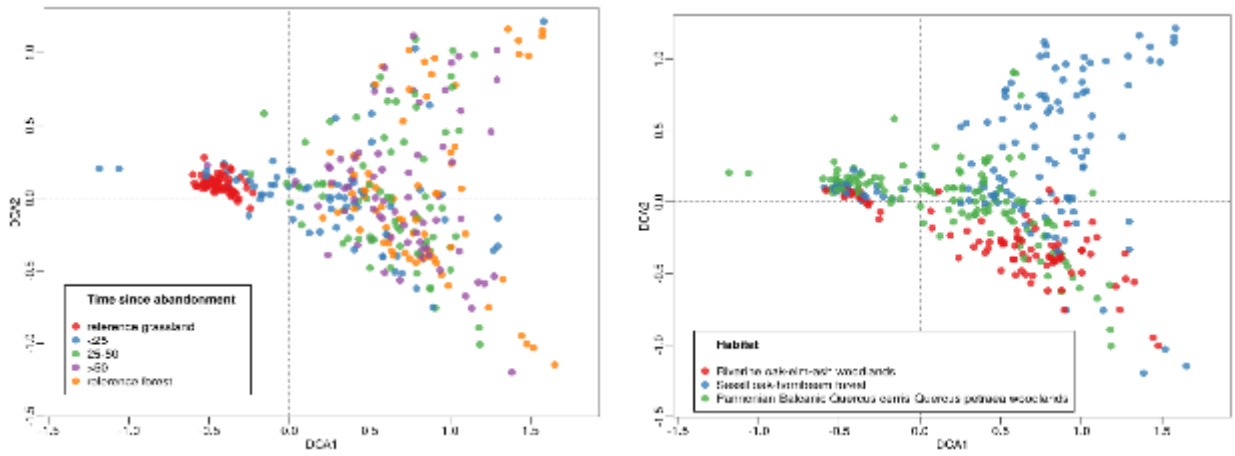


Figure 3. Impact of time since abandonment and habitat type on herb layer species composition based on DCA analysis of species-specific cover data

Drivers of conservation management of areas under spontaneous forest enchroachment in Hungary (Demeter et al. (b) manuscript under preparation for Biologiucal Conservation, D1)

The diverse perception and understanding of woody enchroachment can be a source of significant conservation conflict. Understanding the drivers and motivations behind management at different scales is essential for the conservation management of these dynamically and often rapidly changing areas.

We conducted field interviews with 30 conservation rangers and/or botanists from 9 national parks at 169 local sites in Hungary on the drivers influencing the spontaneous woody enchroachment process and the conservation management of grassland-shrub-forest mosaics and the management concepts of these areas. In our research, we collected local and practical knowledge on spontaneous forest succession with native woody species leading to riverine and swamp woodlands, mesic deciduous woodlands, dry decidious woodland and forest-grassland mosaics.

Maintaining and enhancing the naturalness of grasslands was a priority in all landscapes studied. Conservationists' knowledge of the area and their professional interests (botanist, entomologist, ornithologist, etc.) were the key drivers how they wanted to develop and/or maintain grassland-shrub-forest ratios, and with this the character of the landscape.

Over the last 20-30 years, there has been an increasing emphasis on a kind of wood-pasture landscape reconstruction and the retention of shrub patches of varying sizes, increasing the amount of grassland-woodland edge. In areas under the management of national park directorates, the main driver is the grant resource, while in privately owned areas it is the agricultural policy subsidy system. In the majority of the areas surveyed, the lack or decline of grazing livestock is hampering grassland management efforts. In the operation area of all national parks, there are extensive areas where spontaneous closed forest patches have developed on abandoned agricultural fields, though these areas are often still registered as grassland in the national land registry. In many cases, these areas have a diverse shrub and tree species composition, and are rich in native species and have a high conservation potential. Conservationists argue that their conversion back to grassland is pointless, but that the inadequate legal environment could lead to significant degradation if management changes. Such stands may be converted to forest for timber production, or, because of the regulators of the subsidy system, clear-cutting and replanting may be applied, which could seriously damage natural processes. However, these enchroached areas can play an important role in meeting the requirements of the recently adopted Nature Restoration Law of the European Union. The practical knowledge of nature conservation rangers and local foresters will be key to the development of adequate management plans of these areas.