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RESEARCH

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Understanding nature's contributions to people in ancient biocultural systems through network and RLQ analysis

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ABSTRACT

This research delves into the emerging paradigm of biocultural systems, focusing on the intricate social-ecological dynamics which created and maintained an ancient farming system, the European wood-pastures. Innovatively conceptualizing wood-pastures as biocultural systems, this study employs a network approach to unravel the complex interactions between human activities and the natural particularities within these environments. By using field surveys and interviews conducted in Transylvania, Romania, this research reconstructs the traditional social-ecological drivers behind the preservation of ancient wood-pastures and their Nature's Contributions to People (NCP). It identifies key variables and their centrality within the biocultural network, emphasizing that the rich natural values of wood-pastures are inextricably linked to management features. We employ RLQ and fourth corner analyses to investigate the interconnections among biophysical context, biocultural features (i.e. human made and natural features), and NCP, revealing significant correlations and gradients between the broad biophysical setting and the wood-pasture NCP. The findings underscore the importance of maintaining traditional management practices and stewardship to conserve the biodiversity and cultural heritage of wood-pastures. We contribute to a deeper comprehension of biocultural systems and offer insights for effective management and governance of traditional farming landscapes in Europe and beyond.

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Introduction

The sustainability challenges of ancient biocultural farming systems

The concept of biocultural systems is gaining increasing attention in the field of sustainability sciences (Maffi 2001; Angoletti 2006; Hanspach et al. 2020). Biocultural systems emerge from the interplay between biological, ecological and cultural factors; these interplays result in special social-ecological system identities, which often have region-specific features (Maffi 2001; Angoletti 2006). The traditional farming systems of Europe are archetypical examples of biocultural systems; these systems evolved over centuries as tightly coupled yet highly dynamic social-ecological systems (Fischer et al. 2012). Some of the traditional farming systems of Europe are carriers of ancient biocultural features (e.g. ecosystem physiognomies, built structures, management activities, local ecological knowledge and stewardship forms). However, they also show an accelerated

rhythm of change, either towards abandonment or modernization (Mauerhofer et al. 2018), mainly driven by socio-cultural, technological and economic aspirations of the local communities (Hartel et al. 2023).

The social-ecological changes occurring on the traditional farming landscapes also threaten biodiversity (e.g. Oksuz and Correia 2023) and Nature's Contributions to People (NCP) (e.g. Quintas-Soriano et al. 2022). In this context, it is important to understand the NCP of the changing traditional biocultural farming systems. Biocultural approaches for understanding ancient farming systems, their changes and how these changes relate to their NCP are scarce in Europe and are restricted mostly to the Mediterranean part of the continent (Plieninger et al. 2023), while other regions such as Eastern Europe are not covered by such studies. Wood-pastures are archetypical examples of ancient landuse systems with high ecological and cultural identity values. First, wood-pasture-like ecosystem physiognomies

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(i.e. open landscapes with scattered trees and shrubs) were created in Europe by natural drivers such as large herbivores, wildfires and special bioclimatic conditions (Sandom et al. 2014; Pokorny et al. 2015), making these systems important ecological heritage elements. Then, when human activities started to shape the identity of the European terrestrial ecosystems, wood-pastures were created as a result of silvopastoral activities. Notably, wood-pasturing in Europe dates back till the Neolithic (Plieninger, Hartel, et al. 2015), therefore, the current ancient wood-pastures are also important cultural heritage elements. The Transylvanian region of Romania is especially rich in ancient wood-pastures. The ancient wood-pastures of Transylvania are still unique in Central and Eastern Europe because they have large size, contain high abundances of large old trees and are rich in biodiversity, which is primarily driven by traditional farming (or the legacy of this farming) (Hartel et al. 2023; Roellig et al. 2018). Furthermore, a unique feature of the Transylvanian wood-pastures is that they are frequently visited by the Brown Bear (*Ursus arctos*) (Roellig et al. 2014). The Traditional Ecological Knowledge (TEK) related to wood-pasture management is still rich but declining, as it is increasingly restricted to elderly persons (Hartel et al. 2017). The fast departure from the traditional communal stewardship and management (Hartel and Plieninger 2014), the dramatic erosion of the values assigned to scattered trees (Torralba et al. 2018), the changing cultural and economic aspirations which does not anymore support the rich TEK (Hartel et al. 2023) and the increasing accessibility and attractivity of modern farming technologies (Hanspach et al. 2014) are increasingly imminent. Besides these aspects, there are several governance issues around the access and use of the wood-pastures, conflicts emerging from corruption being reported (Horcea-Milcu et al. 2016). Given these social-ecological features it is particularly interesting (from knowledge development perspective) and important (from a policy perspective) to understand the NCP of the Transylvanian wood-pastures as biocultural systems.

Ancient wood-pasture's NCP through a network lens

It was recently proposed that Nature's Contributions to People (NCP) can be conceptualized as the outcomes of social-ecological interactions, which in turn can be understood through a network lens (Felipe-Lucia et al. 2022). More specifically, NCP can manifest as links representing flows between natural and social system components, as nodes representing natural capital stocks, as value attributes of specific nodes, or as emergent network properties (Felipe-Lucia et al. 2022).

A network representation of NCP can enhance understanding of the complexity and subtleties of social and ecological (or for biocultural systems, biological and cultural) system characteristics and interactions, thereby aiding in the identification of leverage points for sustainability interventions within the system (Manolache et al. 2020). Nevertheless, a network approach enables the understanding of how changes in one part of the system cascade through interconnected pathways, ultimately shaping the system's overall dynamics and resilience (Bodin and Tengö 2012; Barnes et al. 2022). Wood-pastures are ideal model systems for social-ecological network representation because their ecosystem features can be easily mapped (Hartel et al. 2013; Hanspach et al. 2014) and related to management practices, their management and stewardship can be understood, the NCP's can be assessed and related to ecosystem features and management (Hartel et al. 2017; Torralba et al. 2018). Furthermore, the key role of the herder in maintaining the wood-pasture social-ecological system (biophysical features, management and NCP) can also be understood (through social methods) (Molnár et al. 2016). (Re) Constructing ancient farming systems such as the ancient wood-pastures as social-ecological networks can act as an important baseline for social-ecological restoration, which was recently highlighted as being key for biodiversity conservation in human-shaped landscapes (Fischer et al. 2021).

Biocultural systems influenced by the topography and management

Traditional land management systems undergo continuous adaptation driven by the interplay of local community aspirations, available technologies, policies and the broad topographic and geomorphological features characterizing the landscape (Hartmann et al. 2022; Hanazaki 2024). These changes are measurable in the farming systems and specifically in wood-pastures through variables reflecting management practices, human-made structures and broad landscape variables (Stephenson 2008). In the European context, flat landscapes with fertile soils were areas where machine and agrochemical-based agriculture started to establish and spread in the past two centuries. This resulted in the disappearance of traditional farming systems, including wood-pastures (Plieninger, Levers, et al. 2015; Silva et al. 2020). Traditional rural communities and ancient wood-pasture systems mostly persisted in remote areas where industrial farming was economically unviable or technically challenging due to rugged terrain, harsh climates (Azcarate and Peco 2012; Culbert et al. 2016) or geopolitical instabilities (Hartel et al. 2016). The ancient wood-pastures of Transylvania (Romania) are ideal biocultural systems (Vijulie et al. 2024) to assess the relationship between

their physiognomy and biocultural features and NCP in the context of broad topographical and geomorphological contexts. The main reason for this is that ancient wood-pastures still occur from lowland areas up to the mountains. As Romania increasingly adopts modern farming practices, it is expected that the extent of wood-pastures will reduce, with trends indicating that wood-pastures in open, flat landscapes accessible to modern technologies face greater pressure for technologization compared to those in forested or remote areas (Feurdean et al. 2016). While topography and soil quality can influence the persistence of traditional farming systems, historical and socio-cultural factors also play a crucial role in conserving valuable landscapes, as exemplified by Mediterranean systems such as the Montado and Dehesa in Iberia. This underscores the social-ecological and historical contextual complexity of the drivers and processes involved, which vary across different contexts and scales (Antón and Gómez-Baggethun (2021), Bugalho and Ferreira (2019).

Research objectives and hypotheses

The overarching goal of this research was to provide an Eastern European perspective on the biocultural changes ongoing in the ancient wood-pastures.

First, a social-ecological network baseline will be constructed to understand ancient wood-pastures and their NCP. This will be done by linking management, biocultural features, and NCP while highlighting the crucial role of the herder in the various network components. Considering that the wood-pastures of Europe show high regional diversity in their key biocultural features (e.g. management, TEK, tree species, bioclimatic context) (Bergmeier et al. 2010), our study provides a strong biocultural study case which can inspire further research on other regions and other landuse systems, especially because we provide a social-ecological baseline for understanding the biodiversity of ancient wood-pastures and their restoration.

Second, our research provides a unique opportunity to understand the wood-pasture vulnerabilities to social and technological changes, drivers which resulted in the decline and loss of several wood-pastures in Western Europe in the past century. We will unravel the interconnections among biophysical contexts (at local and landscape levels, including topographical and landcover variables), local biocultural attributes characterizing each wood-pasture, and the NCP of wood-pastures. Our research hypothesis posits are: H1. wood-pastures exhibiting varied NCP occupy distinct positions along a biophysical gradient; H2. The biocultural features of the wood-

pastures mediate the relationship between NCP and the biophysical context.

Materials and methods

Study site and variables for statistical analysis

During 2023 and 2024, we surveyed 110 wood-pastures in distinct biocultural regions of Transylvania (Székely region in the Eastern Romanian Carpathians, the Saxon historical region in Central Romania, the region around Cluj-Napoca and western Romania) (Figure 1). Wood-pastures were identified from Google Earth satellite images and partly from our previous studies (Hartel et al. 2013, Hartel, Hanspach, et al. 2018). In all wood-pastures, we recorded several biocultural features by adopting the methodologies and concepts of Bieling and Plieninger (2013) and Stephenson (2008). We used three categories of variables for the characterization of the wood-pastures: biocultural features, biophysical context, and NCP, considering a slightly adapted version of the categories proposed by the IPBES approach on NCP (Pascual et al. 2017). These will be detailed below.

Firstly, biocultural features of the wood-pastures were recorded in the field and include 28 variables grouped into the following categories (adapted from Stephenson 2008; Bieling and Plieninger 2013): *'built structures'* (five variables: 'Abodes', 'Concrete watering', 'Fountain', 'Electric fence', 'Sheepfold'), *'practices'* (14 variables: 'Sheep extensive', 'Sheep intensive (overgrazing)', 'Sheepdogs', 'Coppice', 'Pollard', 'Cattle', 'Buffalo', 'Horse', 'Pig', 'Tree stump', 'Dirt road', 'Permanent pond', 'No mechanization', 'Electric fence', see Annex 1) and *'nature features'* (15 variables: 'Vera tree', 'Anthill whole surface (Anthill)', 'Scattered tree whole surface (Scattered tree)', 'Scattered shrubs', 'Large Old Trees (LOT)', 'Dead trees', 'Temporary ponds', 'Permanent pond', 'Spring', 'Reed patch', 'Wild boar activity (Wild boar)', 'Bear activity (Bear)', 'HNV grassland'). These variables were used as binary variables (see Table S1 in Annex 1).

Second, the biophysical context was characterized using five variables (terrain ruggedness, arable cover, grassland cover, forest cover, and built area cover) at two spatial scales: a radius of 600 m around the central point of the wood-pasture and a larger radius of 1500 m surrounding the local 600-m buffer. The land-cover variables were derived from the 2018 CORINE land cover database and were expressed in percentages (see Annex 1). Terrain Ruggedness was based on European Digital Elevation Model downloaded from the European Copernicus Database (2016). The data processing was made with GIS. Third, **wood-pasture NCP** was quantified using 10 variables related to the

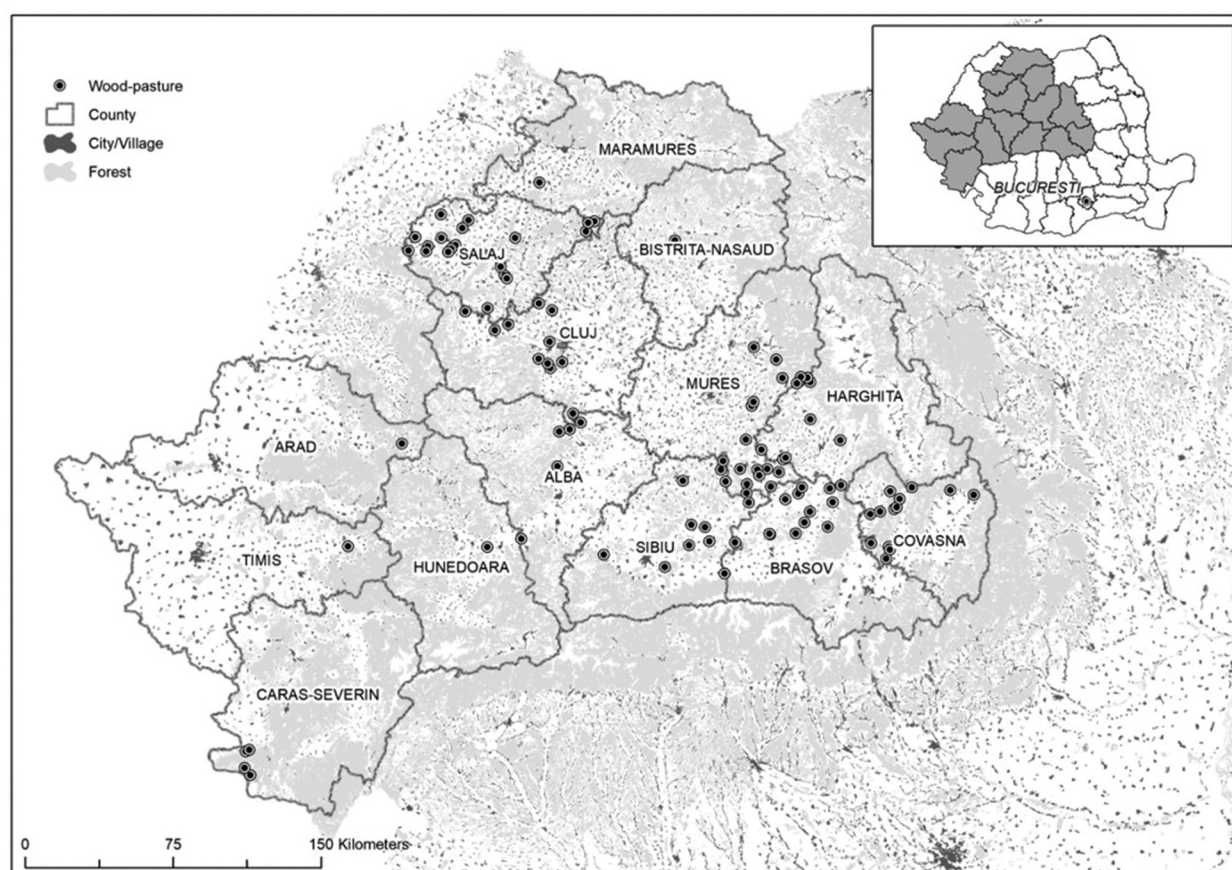


Figure 1. Map of the 110 wood-pastures surveyed for this research. Note that we studied wood-pastures formed by deciduous trees.

biocultural features of the wood-pastures (see above and Annex 1). The NCP of the wood-pastures from Transylvania were assessed through various studies (Hartel et al. 2014, 2017; Hartel, Hanspach, 2018; Torralba et al. 2018; Fagerholm et al. 2019). Since we approach wood-pastures of Transylvania as biocultural systems, we used NCP variables, which also mirror the biocultural contributions to people (and nature). The NCP variables used for our analysis were partly named and characterized using the recent IPBES framework ('Genetic and species diversity', 'Habitat creation', 'Ecological and evolutionary processes', 'Food, feed and materials', 'Interactions with nature' and 'Animal welfare', Pascual et al. (2017) and partly created to capture the biocultural features of the studied wood-pastures which were not present in the IPBES framework ('Erosion control', 'Danger', 'Vegetation erosion', 'Biocultural values', 'Meat and milk, livestock related'). The descriptions of the NCP and the way these relate to nature features and management are presented in Table S1 of Annex 1. The wood-pasture NCP were linked to the biocultural features (practices and nature features) using our previous research in the region (Dorresteijn et al. 2014; Hartel et al. 2017; Torralba et al. 2018), using recent literature reviews (e.g. highlighting NCPs related to livestock, Leroy et al. 2024) and also through our expert knowledge gathered from the embeddedness in

the system (e.g. the co-authors CsL, DG are farmers and communal wood-pasture association representants and/or farming was genuine part of their youthhood (including TH)). Table S1 (Annex 1) presents the links between NCP and the biocultural variables and the explanations of these links. We stress that further conceptual developments of the NCP can better encapsulate the biocultural features existing in the natural environment, such as the traditional management practices and structures, which, on one hand, contribute to biodiversity and, on the other hand, also can supply intangible contributions to people (the whole wood-pasture system can be perceived as such a biocultural system).

The herder is a key component of the traditional pastoral systems (Ivaşcu and Biro 2020; Molnár et al. 2020). We were able to meet the herders in 80% of the wood-pastures assessed. However, only four herders were deeply committed to this activity as a lifestyle (and one of them left this work in the first part of the year 2024). In the remaining cases, herding was only a temporary activity. The lack of the availability of good herders is perceived a key challenge across Romania (authors, personal observations). With the help of two presidents of farmer associations who also own wood-pastures and employ high-quality herders (CsL and DG, co-authors of this work) we were able to connect with three authentic

herders who practice herding as an inherited lifestyle and take pride in their herder identity. We personally approached the herders and had several discussions with them in the wood-pasture, around their sheep-folds. We provided them with a list of wood-pasture natural features (see above) and asked them to complete the value of the nature features of the wood-pastures (see above). Using a simplified form of the IPBES framework ('living from-, with-, and in nature') (Pasqual et al. 2017) we asked the herders to complete their relation to the nature components as mentioned above. We asked the following questions: 'The component provides food or other indispensable raw materials' (for the 'living from' component). 'The component is the manifestation of nature's beauty and is valuable as such' ('living with'), and finally, 'The component is an important part of the shepherd's lifestyle' ('living in'). The results were validated by them and are presented in a simple figure.

Analysis and interpretations

Figure 2 synthesizes the logic and reproducibility of the research process outlined in the paper. We employed Social Network Analysis (SNA) to visualize and understand network characteristics of the traditional wood-pasture management system (linking practices, nature features and NCP). SNA, widely utilized in recent studies exploring environmental management and governance collaboration processes (Berardo and Scholz 2010; Guerrero et al. 2023; Manolache and Nita 2018), provided insights into how the social-ecological features of the wood-pastures contribute to societal benefits. Using the

variables describing the biocultural features of the wood-pastures (see practices and nature features above) as well as the wood-pasture NCP (see above), we constructed a tripartite network. Each variable represents a node in the network, and the edges between the nodes show the relatedness of the variables. The links (edges) were created based on published literature for the study region (Hartel et al. 2017; Torralba et al. 2018; Plieninger et al. 2019) as well as our own experience either as researchers grown up in Transylvania with farming being a genuine part of the lifestyle (TH, LCs, DG) and as livestock owners and wood-pasture custodians (LCs, DG). We used normalized degree centrality as a centrality metric in our analysis to indicate the strength of anchoring a specific node within the network. Understanding and harnessing degree centrality becomes imperative, as it reveals the robustness of certain elements in sustaining the wood-pasture network. Through the lens of centrality metrics, we discerned patterns of connectivity and influence, discerning the pivotal nodes that drive the resilience and functionality of these ecosystems. The integration of degree, betweenness, and eigenvector measures (Brandes et al. 2016) facilitated a holistic understanding of the socio-ecological drivers shaping Nature's Contributions to People (NCP) within these environments. By grounding our analysis in this comprehensive approach, we positioned ourselves to unearth valuable insights into the intrinsic value of ancient biocultural systems and their role in sustaining biodiversity and cultural heritage.

To explore the association between NCP and the biocultural features of the wood-pastures as well as

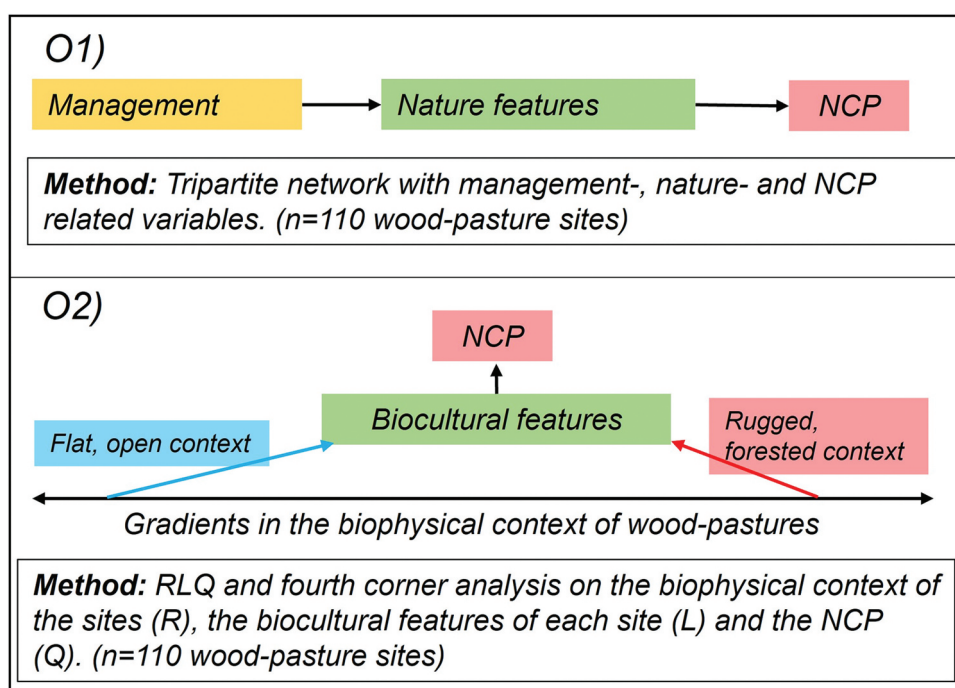


Figure 2. Synthesis of the logic and reproducibility of the research process outlined in the paper.

the biophysical context within which the wood-pastures are situated, we used two complementary analyses: the RLQ and the fourth corner analyses. These analytical tools were developed by ecologists to explore the nexus of environmental conditions, species composition, and species traits and to understand how the environmental condition selects species traits through the species established in the analyzed sites (Dray et al. 2014). RLQ analysis utilizes three datasets: one containing the environmental features of each site (R), one with the species (abundance or presence-absence) at each site (L), and one with the traits of each species (Q) (Dray et al. 2014). The RLQ ordination positions sites with similar species traits close to each other, and species that co-occur with similar environmental variables are also placed close together. In this way, the covariance between species traits and environmental conditions across different sites can be understood. While the RLQ summarizes multivariate structures, it does not provide significance tests (Dray et al. 2014). The fourth corner analysis, on the other hand, allows for testing the significance of bivariate associations between individual traits and environmental variables, making it a valuable complementary analysis to the RLQ (Dray et al. 2014). The RLQ and fourth corner analyses provide valuable

To apply the RLQ and fourth corner analyses to understand the NCP in ancient wood-pastures, we made some interpretative adjustments of the statistical results relative to traditional ecological interpretations. In our conceptualization, the biophysical context of the wood-pasture determines its biocultural features, which in turn influences the NCP supply of the wood-pastures. Given that wood-pastures are social-ecological systems and have evolved as such (see Introduction), we expect the biocultural features of the wood-pastures to vary according to their broader biophysical context. For example, the most remote wood-pastures which are difficult to be accessed by people (being in rugged and forested landscapes) may contain more large old trees than the wood-pastures situated in plain areas close to cities where human access is easier (Hartel et al. 2018). The NCP supply of these different wood-pastures can also vary according to their broad biophysical properties and their biocultural features.

In this study, we treat NCP as analogous to species traits (Q), the biophysical context of wood-pastures as analogous to site-specific environmental features (R), and the biocultural features of the wood-pastures as analogous to species composition (L), which mediates the link between R and Q. In the original ecological interpretation, Q is key for understanding the co-variation between R and L, the species traits being intrinsic features of the species (i.e. we cannot imagine a species without any traits). In our case, NCP emerges

as supply from the biocultural features while the link between this trait (NCP, Q) and the biocultural features (L) is assumed and subject to interpretation. The social demand for several NCPs remains unknown (i.e. a biocultural feature can exist without a socially recognized NCP trait due to potential NCP mismatches). We can assume that for several NCPs (especially those related to the intangible NCP), there is no expressed social demand in the study region, and assessing the demand side of NCP and, therefore, quantifying the potential mismatches in NCP can provide additional strengths to this analytical and interpretative framework.

Due to the lack of an intrinsic link between L and Q in our research (unlike traditional ecological interpretations where the species traits are intrinsically linked to the species and Q helps explain the covariance between L and R), we cannot use NCP (Q) to provide a straightforward social-ecological interpretation of the covariance between biocultural features (L) and biophysical features (R) of wood-pastures. However, since RLQ analysis addresses patterns of co-variation between datasets and allows for flexible interpretations, we utilized this flexibility to adapt the statistical tool to our novel context. Specifically, we employed RLQ analysis to understand the joint role of biocultural features and biophysical properties of wood-pastures in supplying NCP.

As a first step, we calculated the variances of the separate ordination of each of the three datasets: using Principal Components Analysis (PCA) for R, Correspondence Analysis for L, and Hill-Smith PCA for Q (Hanspach et al. 2012). Subsequently, we explored the joint structure of the three data matrices via RLQ analysis (Doledek et al. 1996). Total inertia values for the R and Q data matrices were also calculated. Inertia is an index indicating the co-relationships between two or more datasets that contain the same samples. High inertia values suggest strong links between the R and Q data matrices through the L matrix (Doledek et al. 1996). The significance of relationships between environmental variables and traits was tested using fourth corner analysis (Dray et al. 2014). Specifically, the fourth corner analysis evaluates the links between all possible combinations of environmental variables and traits and then tests if those links are significantly stronger than expected by chance. All analyses were conducted in R (version 4.2.2 – 31 October 2022) using the following packages: *network*, *sna*, *bipartite*, *igraph*, *vegan*, *ade4*.

Results

Traditional wood-pastures as biocultural networks

The complex management and natural network contributing to co-creation of various NCP, is presented in a tripartite graph with three partitions:

management variables, the natural features of the wood-pasture (as maintained by management), and the NCP of the wood-pasture (as supplied by the natural features) (Figure 3a). At the level of the management variables, high degree centrality (i.e. connected to many features in their partition, in this case, management, Figure 3) had the variables 'non timber values of trees', 'buffalo' and 'cattle' (Figure 4). From the perspective of nature features, the variables with the highest degree centrality (Figure 4) were 'scattered trees', 'HNV grass', 'LOT', 'tree regeneration', and 'Vera tree' (Figure 4). Finally, at the level of NCP variables, the highest degree centrality (Figure 4) had the variables 'Genetic diversity and species diversity', 'Habitat creation and maintenance', 'Erosion

control', 'Ecological and evolutionary processes', and 'HNC diversification' (Figure 4). The variables with high relative values of degree centrality also had relatively high eigenvector and betweenness (Figure 4), acting as hubs (high network centralities, with influential role (high eigenvector centralities) and with bridging disconnected parts of the network capabilities (high betweenness centrality).

The herder as a keystone through management and care in traditional wood-pastures

Our assessment shows the importance of the herder for several key features of the traditional wood-pastures (Figure 3b). The great majority of the wood-pasture natural features were considered as being

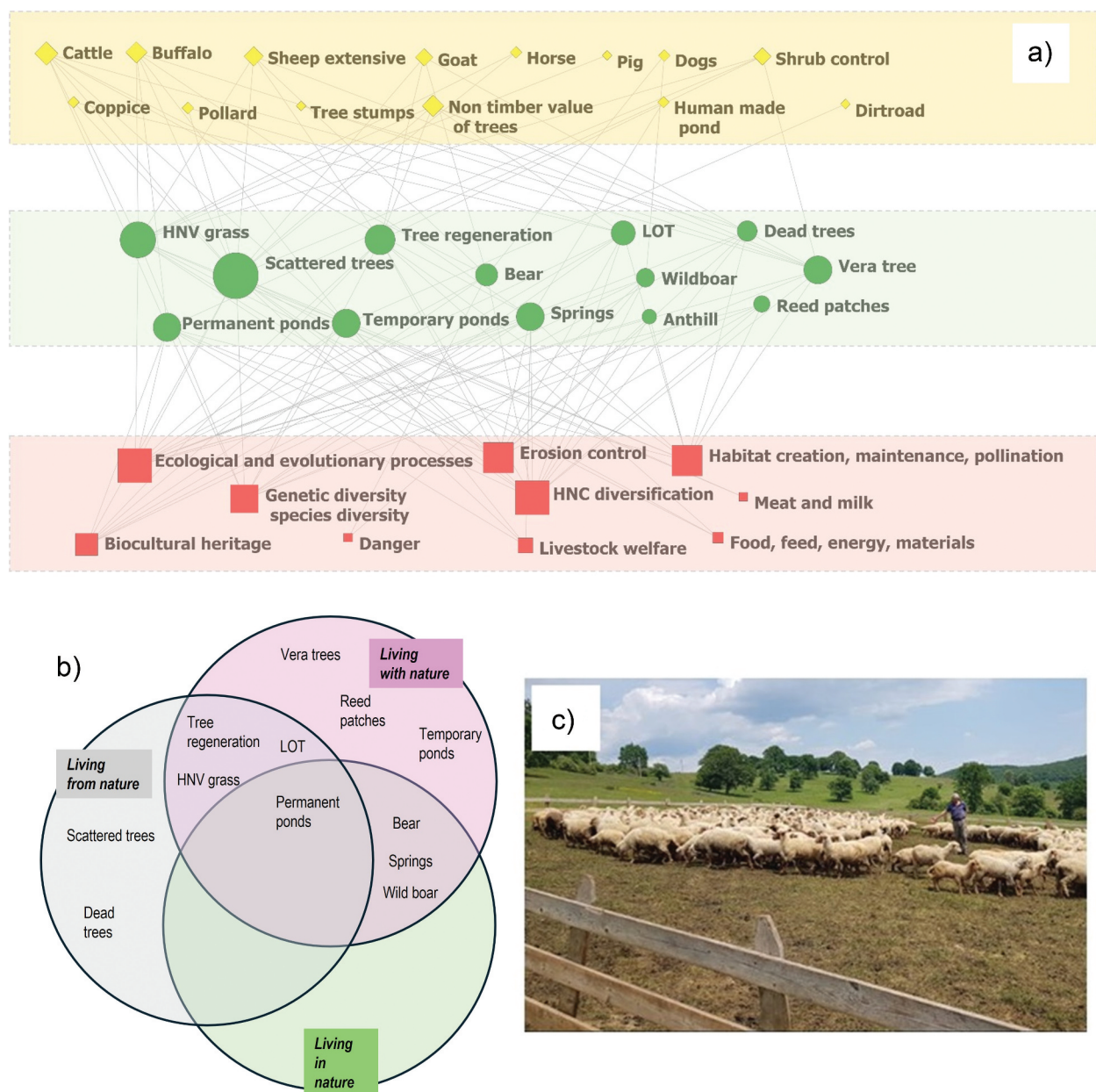


Figure 3. Tripartite network highlighting the complexity of the biocultural links with three partitions: management features, nature features, NCP (a). The natural features of the wood-pasture arranged in the three categories of nature values (b). A traditional shepherd contributing to the implementation of nature values that are presented in (b) (c).

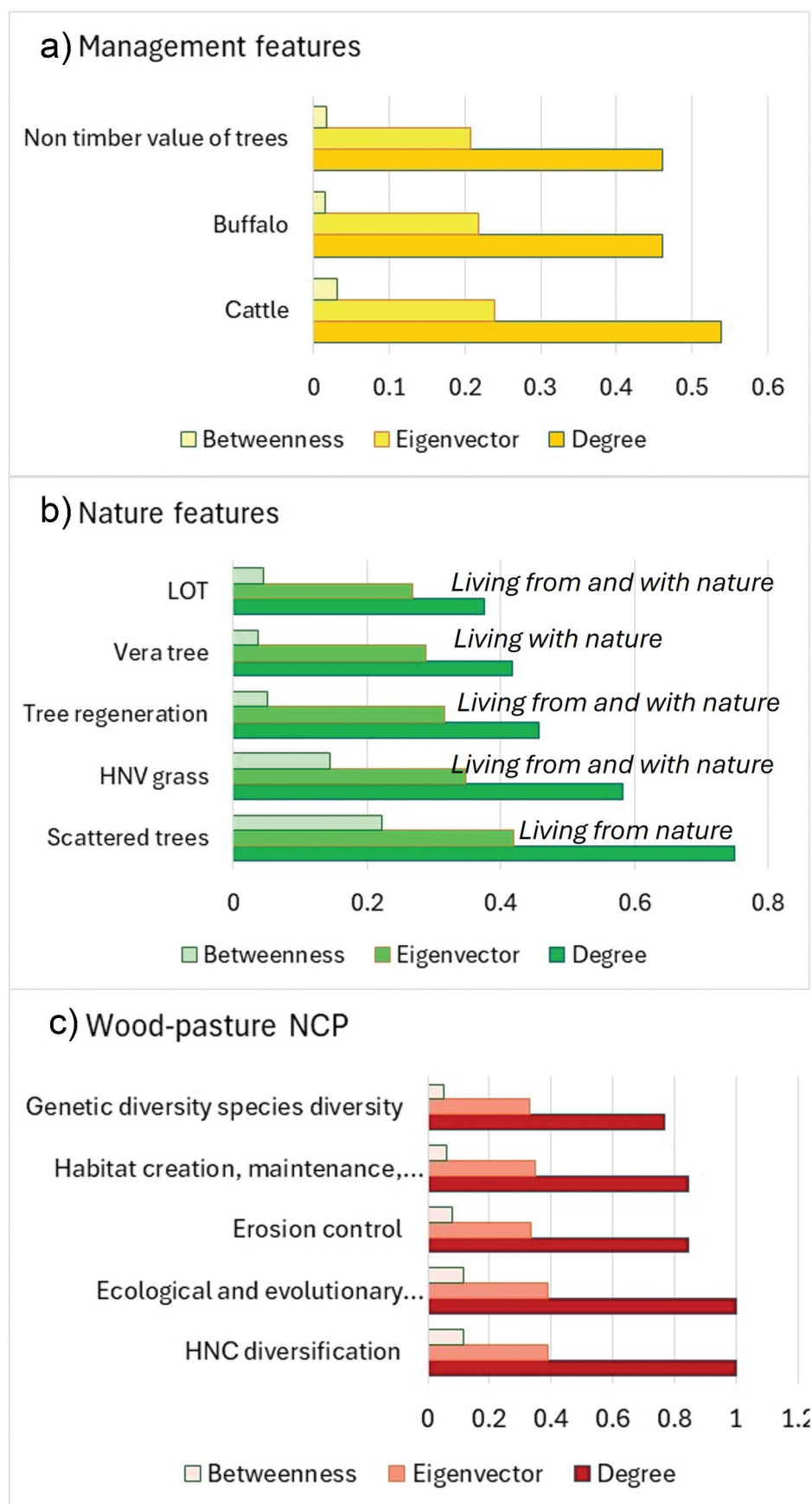


Figure 4. Network characteristics describing the social-ecological network presented in Figure 3a. Bar colour from dark towards light in the case of every colour: *Betweenness*, *Eigenvector*, *Degree*. In B the italics refers to the value of each node for the shepherds (see Figure 3b).

important as provisioning contributions (living from nature) as well as intrinsic values (living with nature) (with variables such as ‘Tree regeneration’, ‘HNV grass’, ‘LOT’, ‘Vera trees’, ‘Bear’, ‘Wild boars’, Figure 3b). The variables ‘Permanent pond’ and ‘Unfenced pasture’ were important from all three value domain perspective (Figure 3b). An outstanding illustration of ‘living with nature’ and ‘living in nature’ was the attitude of an elderly herder towards the Brown Bear in a region with high bear density: ‘The bear is the creation of God and has the right to exist. But for me, it is also part of the herder’s life. To know that the bear is around, and your dogs pay attention to it is a special feeling, and I feel fulfilment in such a lifestyle’. (male herder, 60 years, he is the fourth generation of herder in his family, Figure 3c). Another herder warned us not to approach the wood-pasture-forest margin because ‘there is a female bear with three cubs there’. When one of us (TH) asked him how he feels about that, he responded, ‘I have nothing with them, they have nothing with us. We avoid each other.’ (Male, 62 years). They also expressed that it is increasingly hard to find good

shepherds nowadays; the young generations are not interested in this lifestyle due to socio-cultural and economic challenges associated with it.

Exploring the nexus of biophysical context, biocultural features, and the NCP

The first axis of co-inertia (RLQ1) accounts for 93.05% of covariance Table 1, thus, the interpretations and the visualizations (Figure 5) focus on scores of this axis. RLQ axis 1 delineates a NCP continuum, from ‘Ecological and evolutionary processes’, ‘Interactions with nature’ and ‘Genetic and species diversity’ (referred in Figure 5 as Ecosystem related NCP) on the positive side to ‘Vegetation erosion’, ‘Livestock welfare’, and ‘Meat and milk’ (referred in Figure 5 as Production related NCP) on the negative side (Figure 5). In terms of biophysical context, RLQ axis 1 illustrates a continuum from forested and rugged biophysical setting surrounding the wood-pastures (positive side, Figure 5) to open farmland and built area setting within which the wood-pastures are situated (negative side, Figure 5). Biocultural features like ‘Electric fence’,

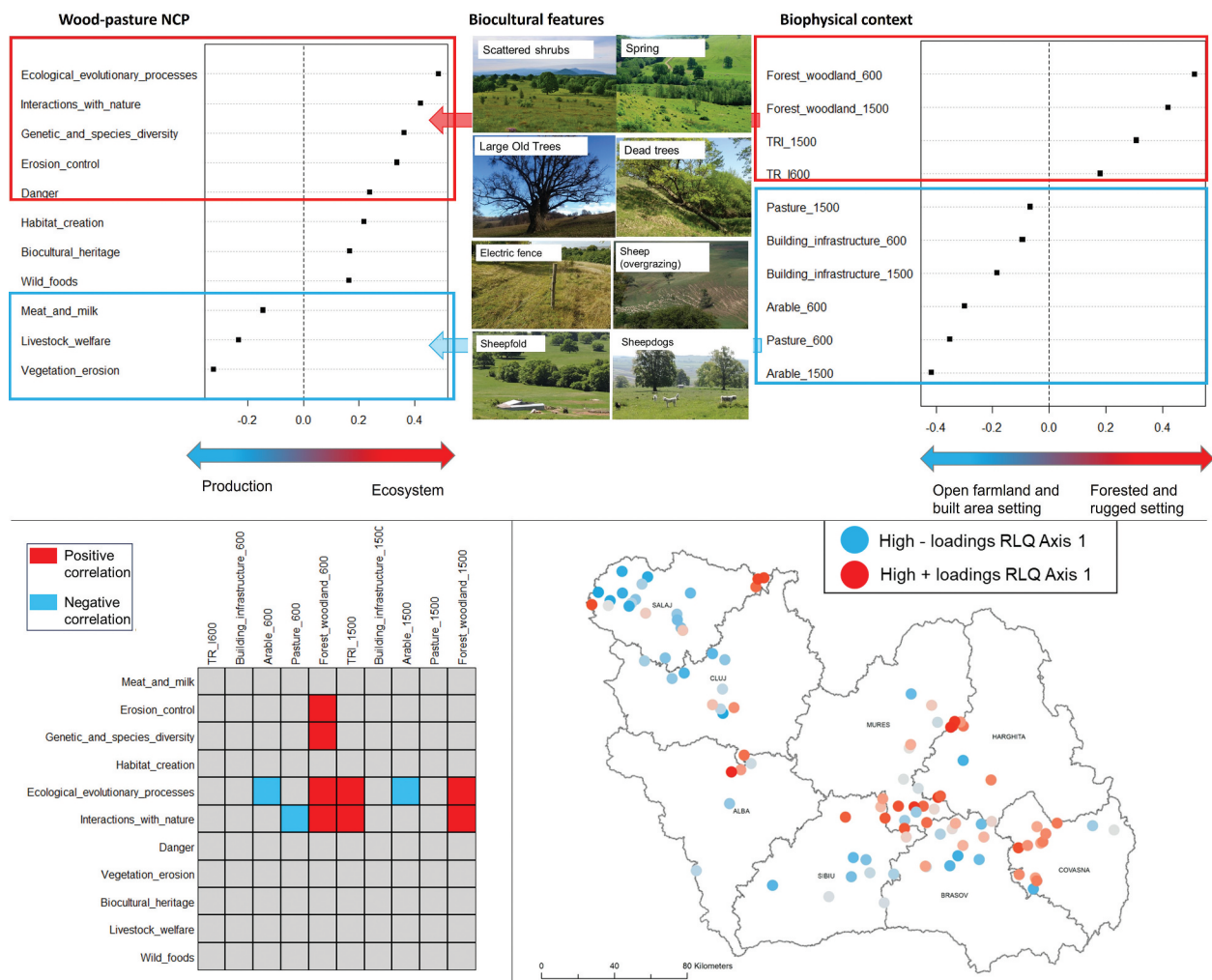


Figure 5. Graphical collage representing the results of the RLQ analysis (upper row), the fourth corner statistics down-left side (positive correlations with red, negative ones with blue) and a map with wood-pasture sites projected according to the RLQ axis 1 loadings (down-right).

Table 1. Results of the RLQ analysis of the wood-pasture's biophysical context (R), biocultural profile (L) and NCP (Q). Separate ordinations represented by the principal component analysis (PCA), correspondence analysis (CA) and the Hill-Smith PCA are also presented. Values for the separate ordinations and the RLQ analysis represent the eigenvalues (% inertia) of the first two axes.

	Axis 1 (%)	Axis 2 (%)
Separate ordinations		
R (PCA)	3.54 (35.49)	2.15 (21.58)
L (CA)	0.15 (18.52)	0.11 (13.23)
Q (Hill-Smith PCA)	6.63 (47.39)	1.89 (13.55)
RLQ analysis		
RLQ axis eigenvalues (Total inertia: 0.19)	0.17 (93.05)	0.006 (3.57)
Covariance	0.42	0.08
Correlation: L	0.11	0.07
Inertia: R	3.25	5.20
Inertia: Q	4.04	4.60

'Sheep (overgrazing)', 'Sheepfold' and 'Sheepdogs' mediate the link between the open farmland and built area setting and the production-related NCP of the wood-pastures (Figure 5). Conversely, biocultural variables such as 'Scattered shrubs', 'Spring', 'LOT' and 'Dead trees' mediate the link between the forested and rugged setting and the ecosystem-related NCP of the wood-pastures (Figure 5). The fourth corner analysis revealed significant positive correlations between 'Forest_woodland_600' and four NCP ('Erosion_control', 'Genetic and species diversity', 'Ecological and evolutionary processes' and 'Interactions with nature') (Figure 5) as well as the variables 'TRI_1500' and 'Forest and woodland 1500' and two NCP ('Ecological and evolutionary processes' and 'Interactions with nature') (Figure 5). Significant negative correlations were found between 'Arable_600' and 'Arable_1500' and 'Ecological and evolutionary processes', and between 'Pasture_600' and 'Interactions with nature' (Figure 5, Table 1).

Discussion

Our case study on ancient wood-pastures of Transylvania shows that a network approach can help in revealing the structural complexity and subtleties of the management-nature interactions which result in natural and ecological features that are valuable for nature conservation (e.g. protected species) and wood-pasture NCP. The analysis revealed that management and variables with high importance within the network (measured through the degree centrality) are closely associated with the variables reflecting high natural characteristics of the wood-pasture. The traditional management-nature feature network we created aims to serve as a baseline for understanding the complex social-ecological interactions, which involve values and technologies as well, which created and maintained the traditional wood-pasture

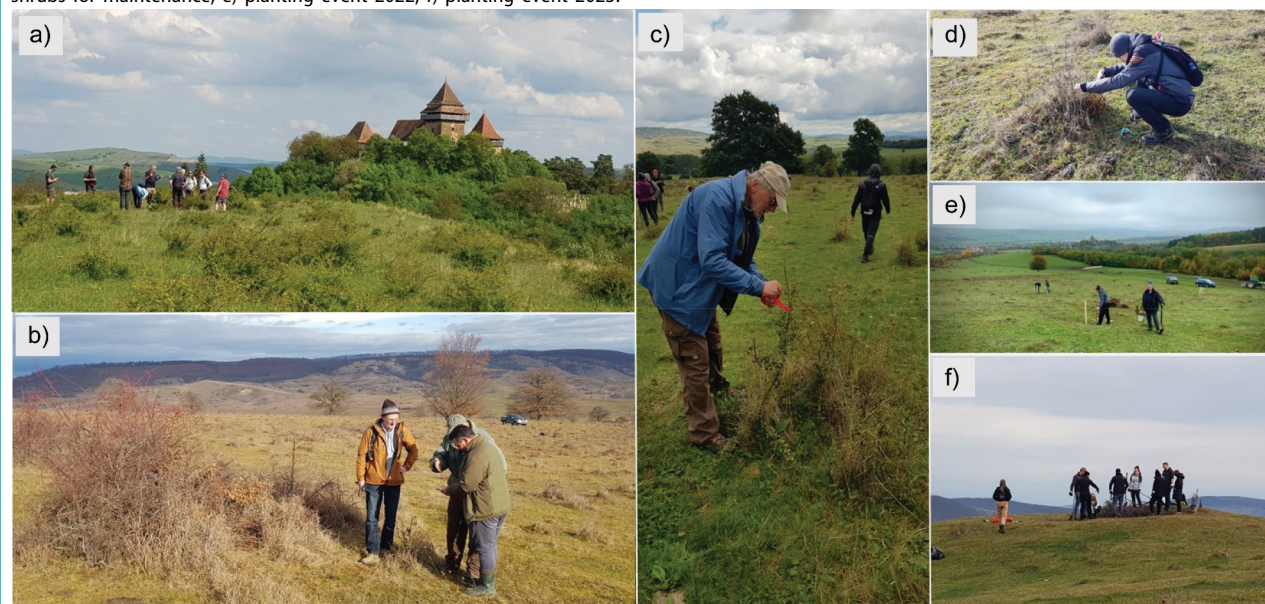
systems and partly as by-products, assured their rich NCP. We show that the traditional wood-pastures as heterogeneous and ecologically valuable systems cannot be separated from several management features, which keeps the system in open woodland state. The herder is a key steward and manager of the wood-pasture as a pastoral and ecological system. Herding is more than just a job. It is a lifestyle, and evidence towards this exist in the scientific literature (Brunson and Huntsinger 2008; Molnár et al. 2020), and our assessment of traditional herders support this statement. Several wood-pasture features, which are highly valuable from a natural perspective, including the Brown Bear, are part of the shepherd's identity. We nevertheless found very few authentic herders in the 110 wood-pastures we surveyed, suggesting that the traditional herding is disappearing even in Transylvania, a region thought to still maintain rich traditional cultural landscapes and TEK. The ancient wood-pastures of Transylvania, as well as the majority of those found in Europe, evolved as communal lands and open social-ecological systems under extensive grazing, characterized by a lack of socially or ecologically impermeable fences (Plieninger and Schaar 2008; Forejt et al. 2017). The wood-pastures of Transylvania still bear the legacy of the traditional management, although a dramatic decrease in the grazing with cattle and buffalo and an increase in intensive grazing with sheep were also documented (Hartel et al. 2013). The wood-pastures are still common feeding ground for the brown bear in Transylvania (Roellig et al. 2014), and this was the same also in historical times (Dorner 1910), suggesting that the bear presence on the wood-pastures is a biocultural legacy. The shepherds used dogs to keep the bears and wolves at a safe distance from livestock (Dorresteijn et al. 2014; Ivaşcu and Biro 2020). The establishment of electric fences in the Transylvanian wood-pastures is a recent phenomenon; during our surveys in 2010–2018 (Hartel et al. 2018) electric fences were virtually absent in the wood-pastures. During the current research, however, cca 35% of the wood-pastures had electric fences, which were used beyond the delimitation of the sheepfolds (*Unpublished data*). The social-ecological impacts of the fences were well documented in the international literature (Xu and Huntsinger 2022), and the increasing popularity of the electric fences in the ancient wood-pastures of Transylvania represents a key social-ecological sustainability challenge. Our findings indicate that natural features such as scattered trees throughout the wood-pasture, large old trees, tree regeneration across the area, the high nature value (HNV) character of the grassland, and the presence of trees regenerating under the protection of thorny shrubs in grazed pastures ('Vera trees') are critically important in maintaining the integrity of the social-ecological network. These features are closely intertwined with several management variables on one hand and NCP variables on the other. This approach entails the active preservation of management and

Box 1. The recent history of management and stewardship of an ancient wood-pasture in Sepsiszentgyörgy – Sfântu Gheorghe.

After 1945, following the nationalization, it was a quick transition from the traditional pasture management to large-scale socialist pasture management. State-owned pasture enterprises embarked on territory rearrangement without studies, erecting concrete pillars and barbed wire fences to force a new rotational grazing system. The previous communal pasture use was cancelled, the traditional extensive livestock farming (geese and pig herds) completely disappeared. After 1989, with the restoration of property rights, the local farmer community attempted to reinstate communal pasture stewardship. Hand labour, which respects nature, once again replaced large machinery, partly because the lack of opportunities to implement modern technologies. An elderly knowledgeable herder had assistants from the farmer community who re-learned the skill and knowledge of herding, sheep bathing, milking, and making milk products. All this changed again after Romania's accession to the EU, in 2007. Most farms were dissolved, and communal pasture management started to decline. Uncontrollable recreational activities are expanding, often with noise and garbage pollution. Today, there are a total of 600 sheep on approximately 200 hectares of pasture. The Farmer Association feels proud to have a knowledgeable traditional shepherd who is living on the pasture and permanently oversee the pasture's condition. While commonly present in the wood-pasture, the Brown Bear never creates economic losses, and the herder feels that the presence of the bear in the surroundings is part of the traditional shepherd's life. With the recent initiative of the wood-pasture and forest owners called 'Our Forest is Yours Too' the aim is to showcase to society the entitlement to enjoy the contributions of the wood-pasture and the surrounding forest, and the moral obligation of the owners is to make this possible. On the other hand, the society had the moral obligation to respect the nature they enjoy and the owners of these valuable ecosystems. In 2019 the protest from over 1000 local persons was able to halt the transformation of a part of the wood-pasture into a leisure park perceived to be damaging for the wood-pasture identity and biodiversity.

Box 2. Attempts to reintroduce trees in the ancient wood-pasture of Viscri.

The community of Viscri has a Farmer Association which manages the ancient oak wood-pasture. This Association also owns 300 cattle and has a herder employed with clear responsibilities to take care of the pasture and the herd. These responsibilities are collectively defined and also negotiated with the shepherd. The fate of the person overtaking the shepherd responsibilities is a permanent negotiation because the probability of suddenly interrupting this work due to better temporary income opportunities is high. The wood-pasture is not fenced, and the stewardship principles broadly follows the traditional Saxon principles. In 2021 the Association recognized that the pasture surfaces without scattered trees can become vulnerable in the context of climate change and they decided in 2022 to plant some scattered oaks which were fenced with metal fence. However, the attempt failed because the fences in one hand were destroyed by cattle and some were also stolen by unidentified persons. In 2022 the discussion of replanting was revived through TH, with repeated meetings with the Association which also included visits to the wood-pasture. The initial suggestions to build more stronger metal fences was not supported by the Association during the discussions, therefore and experiment was planned to create protective fences from shrubs. The use of more robust metallic structures was not recommended by the Association members because of the fear of vandalization. In the spring of 2023 a new plantation event was organized where the local community hosted and supported the accommodation of a university student team and 20 oaks were planted in 9 places, using locally cleared shrubs for fencing. After one year two of the planting sites were burned by unknown persons most likely during the night, and at the rest of the sites the trees survived although the fences required maintenance. The key challenge with this local community-wood-pasture relationship is related to the decreasing motivation of some farmers to work in the form of Association and the increasing individual pressures from more powerful persons to shift towards individual and more mechanized management. However, from the Association perspective, this would also mean that the small farmers (with 1-2 cattle) would be severely disadvantaged. Due to these diverging visions it is increasingly hard to engage the farmers along with the three main pillars of stewardship (West et al., 2018): agency, action, care. The local conflicts around the management of wood-pasture seems to erode the stewardship along all three above mentioned axes. Despite these challenges, the Association has future plans and visions and aspirations and will continue to foster inclusive and community based wood-pasture management which is increasingly opened towards the wise use of the modern technologies (e.g. shrub removing machines) while at the same time responsibility is manifested towards maintaining large old trees, dead trees, scattered and clumped scrubs, anthills in well established places. The figure shows various activities of the local communities in the wood-pasture. a) Discussions regarding the maintenance of the biocultural values and associated challenges, b) establishing shrub patches for maintenance, c-d) marking trees developed in shrubs for maintenance, e) planting event 2022, f) planting event 2023.



stewardship practices and the maintenance of a skilled herder. Sector-specific policies, which often emphasize intensified land use and productivity, can undermine traditional communal management practices by promoting strategies such as high-density livestock grazing and monoculture planting, which are incompatible with the natural features crucial to the sustainable management systems identified in our network analysis (Bobiec et al. 2019). Our findings are deeply rooted in the Romanian context (Nita et al. 2019), and regional historical and socio-cultural factors play a critical role in shaping landscape and social-ecological configurations. Thus, any attempt to generalize these results to other areas of Europe must be approached with caution, as differing socio-cultural and historical drivers may lead to divergent outcomes. Box 1 and Box 2 present two local communities' attempts to restore their wood-pastures and increase their socio-cultural values and the challenges associated with these desires.

Our findings demonstrate that the broad biophysical context within which the wood-pasture is situated translates into wood-pasture NCP *via* the biocultural features of the wood-pasture. Flat landscapes with extensive crop fields, open pastures, and a high density of built areas correlate with variables associated with vegetation erosion (due to overgrazing with sheep) and provisioning NCP (meat and milk). Conversely, variables indicating remoteness (i.e. high ruggedness) and high forest cover correlate with regulating, aesthetic, cultural, and supporting services. These results indicate that a gradual, farming management-related polarization in the NCP starts to be measurable in the wood-pastures of Transylvania. Notably, the establishment of modern farming is more likely in flat landscapes, and this makes the wood-pastures in lowland areas more susceptible to management induced homogenization and the expansion of buildings. On the contrary, rugged, inaccessible terrains are more prone to abandonment and a more extensive management is more likely in these areas (Stoate et al. 2009; Feurdean et al. 2016; Silva et al. 2020). Since the use of agrochemicals was low or virtually absent in most of the wood-pastures in the past century, the natural capital is still not eroded, and the ecological regeneration is ongoing as the wood-pastures are abandoned. Especially the wood-pastures with substantial forest in their surroundings respond fast to abandonment with increased tree and shrub establishment.

Policy messages and practical implications

EU biodiversity-related policies aim to put biodiversity on the path to recovery by 2030 for the benefit of people and environment through several key intervention areas such as, a substantial extension of the existing Natura 2000 network with new strict

protection for areas of very high biodiversity and climate value, a legally binding plan for nature restoration (Pindaru et al. 2023). Several other key policies include biodiversity-friendly measures, notable for our case being the Common Agricultural Policy 2023–2027 (European Commission 2021). The wood-pastures analyzed in this paper were evaluated by Miu et al. (2020) as high-priority sites for designation as areas under strict protection in all prioritization scenarios, indicating their importance for achieving the targets assumed at EU level (Miu et al. 2020). Taking into consideration that under the Biodiversity strategy for 2030, many strictly protected areas will be non-intervention areas (European Commission, 2022), the designation of wood-pastures as non-intervention areas will contribute to maintain these social-ecological systems by forbidding management-induced homogenization and the expansion of buildings and favouring traditional management. From a practical perspective, the study highlights the importance of preserving the open nature of wood-pastures through sustainable stewardship, emphasizing the cultural significance of traditional practices like the use of woody vegetation fences, while also pointing out the emerging challenge of increasing reliance on electric fences, requiring careful consideration of their social-ecological impacts for long-term sustainability. Promoting and supporting traditional farming practices in wood-pasture management, with a focus on stabilizing, regulating, and aesthetic-cultural NCPs, could serve as a sustainable strategy. Additionally, we underline that tailored conservation and management strategies, addressing overgrazing in flat landscapes and promoting ecosystem service preservation in rugged terrains, are essential to sustain wood-pasture NCPs, emphasizing the need for context-specific approaches beyond Transylvania.

Conclusion

In conclusion, this study underscores the critical importance of understanding and preserving biocultural systems, particularly within the context of traditional farming landscapes in Europe. Through an in-depth network exploration of ancient wood-pastures in Transylvania, Romania, we have revealed the intricate interplay between human activities, natural authenticity, and ecosystem services. Our research highlights the challenges facing the sustainability of these systems, including policy fragmentation, community pressures, landscape abandonment, and cultural erosion. By framing wood-pastures as complex social-ecological biocultural systems, we have provided valuable insights into the traditional social-ecological drivers behind their maintenance and the NCP. We acknowledge the intrinsic cultural

dimension of biocultural landscapes, particularly in farming and traditional wood-pasture systems, which inherently embody cultural practices and the TEK. We highlight the need for cultural and economic initiatives to increase the attractiveness of the herder lifestyle. Our categorization into biocultural features, biophysical context, and NCP may have underrepresented this cultural complexity. This oversight highlights a potential limitation in our approach, as fully capturing the cultural dimension's depth and its implications is challenging. We suggest that future studies should aim to integrate more comprehensive cultural variables to enrich the analysis and findings.

Through innovative methodologies such as network analysis and RLQ, we have identified key variables and their centrality within the biocultural network, emphasizing the pivotal role of stewardship and natural features in sustaining wood-pasture ecosystems. Our findings show gradients between co-varying landscape characteristics, site characteristics, and NCP. We emphasize the need for community-driven approaches and long-term sustainability goals to address the challenges facing these unique landscapes. By contributing to a deeper understanding of biocultural systems, our manuscript provides valuable insights into the management and governance of traditional farming landscapes not only in Europe but also beyond. Future research should focus on understanding these drivers in different regions to better account for the variability in landscape and farming system dynamics across Europe. Also, we believe that the potential of the RLQ and fourth corner analyses for understanding NCP could be better capitalized through considering datasets reflecting the NCP supply-demand and possible mismatches and broadening the description of the biophysical context through the inclusion of socio-economic variables as well. We hope that our research will inform future conservation efforts and contribute to the preservation of biocultural diversity worldwide. To mitigate the limitation arising from the geographical specificity of this study, future research could focus on diverse wood-pasture regions, thus providing a more comprehensive understanding of the interplay between social and ecological system components and facilitating the extrapolation of insights to contexts beyond Transylvania.

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