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Front cover photography: Vezeira, the traditional migration of livestock, from the village of Pincães (Montalegre, Portugal) to high-altitude pastures is a community event organized to revive pastoral traditions and involve younger generations (photograph: Joana Nogueira).
Fotografija na naslovnici: Vezeira, tradicionalna selitev živine iz vasi Pincães na Portugalskem na visokogorske pašnike, ki jo izvaja lokalna skupnost, je namenjena oživitvi pašnih tradicij in vključevanju mlajših generacij (fotografija: Joana Nogueira).

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The importance of common lands' management for sustaining ecosystem services

POSEBNA IZDAJA
Pomen upravljanja skupnih zemljišč za zagotavljanje ekosistemskih storitev

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COMMON LANDS, SHARED FUTURES: THE IMPORTANCE OF ECOSYSTEM SERVICES, JUSTICE, AND SUSTAINABILITY THROUGH COMMUNITY LAND MANAGEMENT

Daniela Ribeiro, Mateja Šmid Hribar, Conor Kretsch


MATEJA ŠMID HRIBAR

The Konjščica mountain pasture and its surrounding in the heart of the Triglav National Park.

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Daniela Ribeiro[1], Mateja Šmid Hribar[1], Conor Kretsch[2]

Common lands, shared futures: The importance of ecosystem services, justice, and sustainability through community land management

ABSTRACT: This editorial article introduces the special issue »The importance of common lands' management for sustaining ecosystem services«. This special issue explores the dynamics of common lands and their role in providing ecosystem services, highlighting the interplay between local management and the environmental and social benefits they engender at both local and regional scales. It addresses an underexplored field through conceptual and empirical studies on provisioning and regulating ecosystem services of common lands. Effective management relies on the integration of local knowledge and participatory decision-making, yet faces challenges such as lack of recognition in policy, institutional silos, technical capacity and data gaps, cadastral uncertainty and conflict management.

KEYWORDS: commons, collective actions, local communities, nature's contribution to people, ecosystem services, cultural landscape

Skupna zemljišča, soustvarjena prihodnost: pomen ekosistemskih storitev, pravičnosti in trajnosti skozi upravljanje skupnih zemljišč

POVZETEK: Članek uvaja posebno izdajo »Pomen upravljanja skupnih zemljišč za zagotavljanje ekosistemskih storitev«. Ta posebna izdaja raziskuje dinamiko skupnih zemljišč in njihovo vlogo pri zagotavljanju ekosistemskih storitev, pri čemer poudarja medsebojno delovanje lokalnega upravljanja ter okoljske in socialne koristi, ki jih prinašajo na lokalni in regionalni ravni. Ukvarja se s premalo raziskanimi področji ter jih obravnava z uporabo konceptualnih in empiričnih študij o oskrbovalnih in uravnalnih ekosistemskih storitvah skupnih zemljišč. Učinkovito upravljanje temelji na integraciji lokalnega znanja in participativnem odločanju, vendar se sooča z izzivi, kot so pomanjkanje vključevanja v politiko, sektorski pristop, pomanjkanje tehničnih zmogljivosti in podatkov, nejasnost glede katastrskih podatkov in upravljanje konfliktov.

KLJUČNE BESEDE: skupna zemljišča, skupnostne prakse, lokalne skupnosti, prispevek narave ljudem, ekosistemske storitve, kulturna pokrajina

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1 Introduction: Why common lands matter for ecosystem services

The term »commons« originally referred to common lands in medieval Europe, denoting how communities collectively managed essential resources such as forests and pastures. This form of governance is based on commoners, that is on people who share and collectively manage resources (Anderies and Janssen 2013). In this Special issue, we understand commons in two ways: as shared resources (mainly common lands) and also as organisations that collectively govern such resources.

Although traditional commons still exist in some regions, such as the European Alps (Pagot et al. 2025), Portugal (Nogueira et al. 2023), Lapland (Larsson and Päiviö Sjanuja 2022), and Africa (Kaye-Zwiebel and King 2014), Asia (Shimada 2014), and Latin America (Monroy-Sais et al. 2016), numerous commons have disappeared or face pressures from economic shifts, changing social dynamics and political frameworks as well as administrative barriers (Brown 2006; Premrl et al. 2015; Šmid Hribar 2025). Although nowadays the meaning of commons has broadened (Anderies and Janssen 2013), in this special issue we focus on commons as common lands that are managed collaboratively by communities to achieve long-term sustainable management of natural resources in their local environments. By doing this, commons play a vital role in preserving biodiversity (Šmid Hribar 2025) and cultural landscapes (Šmid Hribar et al. 2023; Urbanc et al. 2025), and contribute to the provision of essential ecosystem services such as carbon sequestration (Gomes et al. 2025; Šmid Hribar et al. 2025b), groundwater provision (Bogataj and Frantar 2025), fire protection (Adagói et al. 2025), and food production (Galán et al. 2022). This community stewardship is particularly relevant in the context of current pressures on key natural resources, such as water, air, forests, and biodiversity, which are limited and prone to degradation if mismanaged. As Ostrom (1990) has shown, community-based management can yield better outcomes than individual or state-led approaches when it functions effectively.

While the Special issue »The role of traditional, transforming and new commons in landscapes« (Urbanc et al. 2023) explored various aspects of commons and their role in sustaining traditional agricultural landscapes, this special issue seeks to take a step further by presenting evidence-based research on how collectively governed and managed common lands contribute to ecosystem services. Both research fields, ecosystem services, and commons, focus on the complex interactions between humans and nature. While ecosystem services emphasise the benefits nature provides to people (Costanza et al. 1997), the research on commons explore how communities govern and manage shared resources (Rodela et al. 2019). Based on a literature review of the interaction between commons and ecosystem services, Tucker et al. (2023) emphasise that the most critical gaps in this intersection are the lack of attention to global interdependencies (e.g., international markets, climate change that influences local or regional ecosystem services and common-pool resources governance), the marginalization of equity, justice, and ethics, and the disconnection between analysis and meaningful governance action.

Ecosystem services as well as commons, offer valuable and complementary insights into human–nature interaction and address key environmental challenges to sustainability. However, empirical research on the contribution of commons to ecosystem services remains limited (Barnaud and Muradian 2024). Further research could provide valuable insights into the potential of the commons through spatial analyses and ecosystem services assessments, to integrate these perspectives into relevant nature protection policies and programs, such as the Paris Agreement, the 2030 Agenda for Sustainable Development, the Global Biodiversity Framework, and the EU Biodiversity Strategy for 2030, and inform the development of appropriate financial compensation and incentive mechanisms to encourage community engagement (Rodela et al. 2019).

Given the research gaps mentioned above, the aim of this special issue is to provide up-to-date, primarily empirical research that highlights the links between common lands governance and the provision of ecosystem services. In chapter 2 of this article, the significance of inclusive governance, the recognition of community rights, and the equitable distribution of benefits in the administration of common lands are addressed, as central to their sustainable administration and to the long-term maintenance of both ecological integrity and social equity. The text goes on to discuss how justice and equity are both challenges and necessary conditions for the conservation and enhancement of ecosystem services. The chapter 3 provides a synopsis of the contributions made to this special issue. The final chapter examines the key messages and insights pertaining to common lands and their contribution to ecosystem services, with a particular focus on the bureaucratic and institutional barriers to collective management.

2 Justice, equity, and governance in commons management

The concept of commons has played an important role in the development of science and policy on the conservation and sustainable use of natural resources, including biodiversity, linking community perspectives on issues of natural resources, livelihood security, culture and governance. The biodiversity crisis is frequently discussed as an issue of global justice, reflecting concerns about rights of access to ecosystem services. The loss and unsustainable use of biodiversity and ecosystem services is both a driver of inequality, and a symptom of it (Timmer and Juma 2005; Rees 2008; Lenzi et al. 2023). Communities facing the loss of access to essential ecosystem services resulting from ecosystem degradation (or exclusion from private lands) may become more vulnerable to poverty, food and nutrition insecurity, the impacts of natural hazards, and illness, in some cases being forced to abandon traditional livelihoods, or pushed towards unsustainable modes of resource exploitation (Millennium Ecosystem Assessment 2005). Commons can provide an important place- and community-based setting to examine these issues and explore equitable solutions. However, there are many examples of nature conservation policy or interventions driving inequalities, where the rights of land users and their access to natural resources are marginalised by strict protection regimes (Colchester 2004; Tauli-Corpuz et al. 2020). Such cases overlook the vital role which commoners (and local communities more widely) can play in conservation and sustainable use of natural resources and associated ecosystem services, as long as their autonomy, values, perspectives, and historical, cultural and ecological knowledge are respected (Iordăchescu 2022; Dawson et al. 2024).

Since the reports of the Millennium Ecosystem Assessment (2005) provided policy makers with a clear framework for understanding the links between ecosystems and human well-being, and with further exploration of the ways in which those linkages are determined by national, regional, and local perspectives, increased attention has been given to the importance of equitable and inclusive approaches to conservation that acknowledge, respect, invite and account for the voices and perspectives of diverse communities, actors and stakeholders (Sikor 2013; Tallis and Lubchenco 2014; Tauli-Corpuz et al. 2020), including commoners (Rodgers and Mackay 2017). Unfortunately, experience across continents has demonstrated that injustice can also result from the implementation of conservation policies (Bagnoli et al. 2008; Martin et al. 2013; Shoreman-Ouimet and Kopnina 2015; Pascual et al. 2021). In the same way that climate action plans aim for a »just transition« to a low carbon future, strategies for restoring biodiversity and ecosystem services must avoid creating or exacerbating inequality (Mabon et al. 2024; Brown et al. 2025). Commons provide important cases for exploring and addressing these issues and for developing ethical transformative approaches (Iordăchescu 2022).

Any form of natural resource management and governance may raise a diversity of concerns regarding equity, equality and rights. Understanding how these concerns may arise, their geographic and temporal scales, whom they may affect or be affected by, and how they may be addressed in a sustainable manner, generally requires careful consideration of a range of social, cultural, environmental, and/or economic factors. One of the key challenges inherent in the successful implementation of biodiversity and nature conservation policies is the difficulty in co-ordination across different spatial, temporal and administrative scales. In many cases, the costs of both biodiversity loss and conservation are felt most acutely and immediately at the local level, and unless localised implementation efforts can account for the diversity of perspectives held within local communities, such efforts not only risk failure, but loss of community support and social licence (Paloniemi et al. 2012; Martin et al. 2013). In this policy context, commons present a particularly important scale for local, community-led ecosystem management. Molnár et al. (2023) have noted that collaborative approaches to resource management can promote fair and effective results. However, this is not guaranteed, and the intent must be supported by a careful consideration of the diversity of perspectives, cultures and struggles within communities (Harmáčková et al. 2022; Koch et al. 2023).

In her 2009 article, Ellinor Ostrom provided a review of responses to Hardin's original theory of the tragedy of the commons, highlighting increasing evidence that the challenge of effectively and sustainably managing commons' resources may be overcome when users communicate to develop a system of governance, based on a set of rules upholding a form of collective self-interest (Ostrom 2009). However, such systems may be contested or fail if they do not account appropriately for the diversity of user experience, needs, local knowledge and world views that may guide their individual conceptions of fair use. Armitage (2008) addressed the importance of understanding the specific social and cultural contexts which shape not only individual approaches but also the readiness of existing governance systems to adapt in order to meet sustainability challenges. A review by Loos et al. (2023) further notes the importance of recognising the multiple values attributed to ecosystem services which may be held within any community, and of attempting to work towards a common approach to governance of natural resources, whilst also addressing the ways these approaches may be complicated by local political perspectives, history, or trends.

For example, Šmid Hribar et al. (2018) have highlighted the role of historic experiences (at a local or national scale), both political and cultural, in determining attitudes to common land in Slovenia (path dependency). History and collective memory have a strong influence on perceptions of value and attitudes to usage and access rights, and landscapes and associated natural resources have deep significance beyond values to lives and livelihoods. However, cultural ecosystem services – particularly the ways in which habitats, ecosystems and landscapes are key to a shared sense of place and identity with a community – are often overlooked or marginalised in land use and development planning (Tengberg et al. 2012; Eliasson et al. 2022).

Addressing these issues not only demands inclusive and equitable processes in commons governance, but recognition of the social, cultural, political and historic contexts which influence the relationships between communities, ecosystems and well-being.

3 Overview of the special issue contributions

This compendium commences with an overview of the extant academic literature, which is followed by empirical contributions on the provisioning and regulating ecosystem services of common lands.

The systematic literature review by Ng et al. (2025) in this issue traces the evolving academic discourse on common land management and ecosystem services. The analysis of 53 empirical articles emphasises the central role of management practices to the provision of ecosystem services and the growing importance of traditional and innovative collective approaches. The study proposes a conceptual framework to elucidate the manner in which management structures and ecosystem services interact to generate socio-economic benefits. It also emphasises the importance of integrated strategies for improving the resilience and sustainability of common lands. The article provides a solid conceptual foundation for the empirical contributions that follow.

The second article examines the benefits of groundwater and its recharge in common lands in Slovenia's Primorska region. Bogataj and Frantar (2025) used the mGROWA hydrological model to estimate the quantity and dynamics of groundwater recharge over a 50-year period (1972–2023), focusing on the supply side of groundwater ecosystem services. The findings show that trends in groundwater recharge on common lands are generally negative, indicating rising variability in groundwater recharge, with regional differences between the Alpine and Sub-Mediterranean areas of Primorska. Forests, representing the predominant land use and covering more than 12% of common lands, play a vital role in maintaining groundwater recharge. The study also identifies a strong spatial correlation between common lands and water-protected areas, with overlaps reaching 18% in the Alpine area and 78% in the Sub-Mediterranean area. These results highlight the functional interdependence between land management, forest cover, and groundwater systems. The authors argue that agrarian communities play a significant role in maintaining these processes as collective landholders through their stewardship of natural resources and propose benefit-sharing mechanisms that would integrate them into groundwater governance.

The potential for carbon sequestration in common lands is the focus of two studies. These studies utilise remote sensing data and net primary production (NPP) to analyse the carbon sequestration capacity of these areas. The Portuguese case study by Gomes et al. (2025) combines stakeholder perceptions with quantitative remote sensing data to bridge the gap between social and biophysical perspectives on ecosystem services provision. The study reveals that while local communities often underestimate the ecosystem services potential of communal lands, these areas nonetheless play a vital role in climate regulation. A quantitative analysis was conducted on the carbon sequestration potential of common lands in the Mondim de Basto Municipality. This analysis estimated a total carbon sequestration capacity of 92,351 tons for the year 2023. In Portugal, approximately 14% of forests are situated on communal lands, thereby designating these areas as substantial potential carbon reservoirs. The article places significant emphasis on the importance of enhancing the dissemination of information regarding ecosystem service benefits. The overarching objective of this enhancement is to foster community engagement and facilitate informed decision-making processes. The authors also emphasise that financial incentives for carbon sequestration could promote sustainable land management while generating new economic opportunities for rural populations. The article demonstrates how the integration of remote sensing with participatory approaches can facilitate the incorporation of communal lands into national climate and sustainability strategies.

Šmid Hribar et al. (2025b) assess carbon sequestration in the Triglav National Park area, which has a fairly high proportion of common lands. Although the study uses MODIS NPP data to analyse carbon sequestration capacity, the data were downscaled to a resolution of 10 m to capture fine-scale forest and agricultural land mosaics in the study area. To this end, a set of predictors that are strongly linked to vegetation productivity dynamics was employed. The assessment demonstrates that, despite the moderate overall carbon sequestration capacity of the common lands in Triglav National Park, the forests and scrublands, characterised by higher productivity, play an important role due to their spatial extent. Therefore, the findings underscore the need to assess both the capacity for carbon sequestration and the spatial extent when evaluating the contribution of land use to carbon dynamics, as high productivity alone does not necessarily result in a greater overall impact at a landscape level. Ultimately, the authors suggest that private forest owners in Slovenia, including agrarian communities, could adopt improved management practices to enhance the carbon sequestration capacity of their forests.

Although this special issue does not include any articles that address cultural ecosystem services specifically, this was not an editorial decision; rather, it reflects the articles that were submitted. This category of ecosystem services has received little attention, which highlights the need to further explore how common lands enable physical, experiential, spiritual, symbolic and other cultural interactions with the natural environment.

4 Conclusion: Key messages and emerging insights

The cases presented demonstrate that common lands function as multi-service structures, supporting the provision, regulation, and cultural ecosystem services. Forests and pastures managed collectively have a significant impact on climate regulation and groundwater recharge, while supporting local practices. Studies from Portugal and Slovenia demonstrate that even where community awareness of ecosystem services is limited, the biophysical contribution of common lands can be substantial (Gomes et al. 2025; Šmid Hribar et al. 2025b). Treating commons as multi-service assets discourages silos interventions and supports integrated landscape policy.

This evidence serves to reinforce the central proposition outlined in chapter 2. The prerequisites for achieving sustainable ecosystem services outcomes are inclusive local governance, recognition of rights, and equitable benefit-sharing. Where tenure is clearly defined and rules are negotiated collectively, common lands have been shown to provide ecosystem services. However, when rules are imposed externally without local legitimacy or community heterogeneity being taken into account, and histories are disregarded, outcomes are frequently fragile and contested (Tucker et al. 2023). The effective management of common lands, therefore, necessitates the implementation of procedurally and substantively just processes (Gomes et al. 2025).

From a methodological perspective, the articles demonstrate the advantages of combining biophysical models and Earth observation data (e.g., NPP-based carbon estimates and groundwater recharge modelling) with social research and local knowledge (e.g., qualitative studies of institutions and meanings). This integration of mixed methods improves the ability to infer the mechanisms by which governance is translated into ecosystem services. Furthermore, it unveils the trade-offs that exist across a range of ecosystem services and groups. It also highlights the need for capacity building, as communities can rarely shoulder the technical burden of monitoring alone.

Despite the existence of significant policy frameworks that refer to community stewardship, the recognition of common lands as operational governance units remains inconsistent and understudied (Gomes 2023; Gomes et al. 2025; Bogataj and Frantar 2025). This fragmentation is evident in parallel funding streams, inconsistent eligibility rules for community entities and ecosystem services assessments that privilege individual or state tenure. This has resulted in underinvestment in common lands and the failure to capitalise on cost-effective opportunities for the delivery of ecosystem services. A pragmatic approach would be to integrate commons into existing instruments by treating recognised commoners as eligible managers for ecosystem services-related programmes.

Cultural ecosystem services are often considered to be of great importance for stewardship. Nevertheless, these ecosystem services are often underrepresented in landscape management and planning (Plieninger et al. 2015), as is the case with this special issue.

The co-production of research with communities has been demonstrated to enhance the precision of research questions, augment the relevance of data, and accelerate its uptake (Barnaud et al. 2023; Barton et al. 2024). Interdisciplinary teams have the capacity to translate local practices into policy-relevant evidence without compromising the diversity of values. The objective is not to replace local knowledge with models, but rather to combine them in a format that is useful for landscape management and decision-making (Šmid Hribar et al. 2025a).

Evidence indicates the presence of recurring impediments that hinder the potential of common lands to deliver ecosystem services. These impediments can be categorised as follows: **First**, it is important to note that common lands lack a recognised form within policy and planning frameworks (Bogataj and Frantar 2025). **Second**, the domains of forestry, water, agriculture and cultural heritage are the responsibility of different agencies, each of which is focused on achieving its own distinct objectives (Gomes et al. 2025). In contrast, common lands and ecosystems function across these established administrative boundaries. **Third**, it is evident that financial schemes, including the carbon market, need a level of technical expertise that exceeds the local community's current capabilities (Gomes et al. 2025). **Fourth**, historical arrangements, cadastral gaps or unclear liability have a deterring effect on collective action (Gomes et al. 2025). **Fifth**, local communities and decision-makers are generally without recourse to data, modelling tools and training (Gomes et al. 2025; Šmid Hribar et al. 2025a).

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THE NEXUS OF COMMON LANDS AND ECOSYSTEM SERVICES: A SYSTEMATIC REVIEW AND THEMATIC INSIGHTS

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The nexus of common lands and ecosystem services: A systematic review and thematic insights

ABSTRACT: Common lands are vital for sustaining ecosystem services that support human well-being. This study systematically reviews 53 empirical articles to examine the nexus between common lands and ecosystem services. Results show that management is fundamental in determining the provision of these services. Both traditional and innovative collective approaches are essential for maintaining ecosystem services across spatial scales. These services support biodiversity conservation and generate economic opportunities. The study highlights the need for integrated strategies to enhance the resilience and sustainability of common lands.

KEYWORDS: common land management, ecosystem services, sustainable resource use, biodiversity conservation, economic opportunities

Povezavanost skupnih zemljišč in ekosistemskih storitev: sistematični pregled in tematske ugotovitve

POVZETEK: Skupna zemljišča so ključna za ohranjanje ekosistemskih storitev, ki podpirajo blaginjo ljudi. Ta študija sistematično pregleduje 53 empiričnih člankov, da bi proučila povezavo med skupnimi zemljišči in ekosistemskimi storitvami. Rezultati kažejo, da je upravljanje ključnega pomena za zagotavljanje teh storitev. Tradicionalni in inovativni kolektivni pristopi so bistveni za ohranjanje ekosistemskih storitev na različnih prostorskih ravneh. Te storitve podpirajo ohranjanje biotske raznovrstnosti in ustvarjajo gospodarske priložnosti. Študija poudarja potrebo po celostnih strategijah za povečanje odpornosti in trajnosti skupnih zemljišč.

KLJUČNE BESEDE: skupno upravljanje zemljišč, ekosistemske storitve, trajnostna raba virov, ohranjanje biotske raznovrstnosti, gospodarske priložnosti

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1 Introduction

Common lands refer to shared natural resources, such as forests, pastures, wetlands, and water bodies, collectively accessed and managed by communities rather than privately or solely state-owned (Ostrom 1992). Governance may be formalized through state recognition or rooted in local customs and institutions (Urbanc et al. 2023). These lands exist globally in diverse forms, including grazing lands, community forests, water sources, fishing grounds, functioning as critical socio-ecological systems where human and ecological processes interact.

Common lands are vital providers of ecosystem services, which the Millennium Ecosystem Assessment (MEA) (2005) categorizes into four types: provisioning (e.g., fuelwood), regulating (e.g., watershed protection), cultural (e.g., recreation), and supporting ecosystem services (e.g., nutrient cycling). These services support livelihoods, ecological resilience, and human well-being. While recognizing these four types, Rodríguez-Ortega et al. (2014) grouped them into provisioning and non-provisioning ecosystem services. Recent frameworks like the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al. 2015) and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin 2018) moves toward a three-group typology, with supporting ecosystem services now considered integral ecological processes underlying all other services rather than a separate category. Because of conceptual clarity, historical significance, and widespread application in both empirical studies and policy communication, the four-group typology of MEA (2005) remains one of the most commonly used frameworks in ecosystem service research (Costanza et al. 2017; Mengist and Soromessa 2019).

Beyond the theoretical evolution of ecosystem service classifications, numerous studies demonstrate that land management practices critically influence the quality and provision of these services. For instance, sustainable agricultural systems and community forest governance can enhance biodiversity and water regulation, whereas intensification and monoculture reduce ecological stability (Carreño-Rocabado et al. 2016; Silva et al. 2019). These insights highlight that ecosystem service outcomes are strongly shaped by governance and management approaches. This creates an important entry point for considering the role of commons and their collective management in promoting sustainable provision of ecosystem services.

Effective management strategies are necessary to maintain the integrity of common lands so that ecosystem services can be sustained. Traditionally, management has been based on collective norms and indigenous knowledge systems aimed at ecological sustainability (Kaye-Zwiebel and King 2014; Meinzen-Dick et al. 2021; Makhubele et al. 2022; Urbanc et al. 2023). Informal or customary institutions help regulate access, distribute benefits equitably, and prevent overexploitation (Ostrom 1992). The management of common lands has become increasingly complex due to external pressures such as land conversion, climate change, and resource overexploitation that in turn threaten their long-term viability (Hristov al. 2020). More recently, hybrid models have emerged, incorporating economic instruments and regulatory frameworks, to align conservation goals with development priorities (Costanza et al. 2014; De Jong et al. 2018; Rodríguez-Ortega et al. 2014).

Despite growing research, there remains a lack of comprehensive synthesis that systematically analyzes how different management approaches impact ecosystem service outcomes across local, regional, and global scales (Bennett et al. 2015). This study addresses that gap through a systematic review of empirical literature on common land management and ecosystem services. Thematic analysis is employed to synthesize key patterns across diverse cases. The study pursues three core objectives:

1) To evaluate how management practices on common lands influence ecosystem services, both positively and negatively.
2) To examine the role of traditional and innovative collective management approaches and their contributions to ecosystem service outcomes across spatial scales.
3) To explore ecosystem services as key drivers in biodiversity conservation and economic opportunities within the context of common lands.

This paper contributes to the existing body of knowledge by offering an up-to-date synthesis of empirical research on the nexus between common land management and ecosystem services. The evidence-based insights generated can inform more effective, inclusive, and adaptive management strategies for sustaining common lands under changing environmental and socio-economic conditions.

2. Methods

2.1 Systematic review approach

This study employs a systematic review methodology following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al. 2009) to ensure transparency and replicability in identifying and analyzing literature on common lands. The data collection followed a four-stage process (Table 1).

Table 1: Results of the PRISMA procedure

Stage	Result	Explanation
Identification	176	176 papers are identified by keyword string searching in Scopus
Screening	143	17 non peer-reviewed papers are excluded; 16 non research articles are excluded; 0 duplicates are excluded
Eligibility	45	98 ineligible papers and papers published before 2014 are excluded
Included	53	8 papers were manually identified using expert knowledge

The data query was performed on 15 November 2024. Scopus was selected for the identification of relevant documents. While Scopus and WoS are considered the best choices for bibliometric studies, the former was more appropriate for this study because the field of common lands involves a broad coverage of social sciences and environmental studies (Pranckutė 2021). An initial scoping searching using the term »commons« alone yielded many irrelevant results (e.g., digital, urban, or knowledge commons). Because this study focuses on land- and resource-based commons, a refined keyword string, TITLE-ABS-KEY ((»common land« OR »common resource« OR »common-pool«) AND (»ecosystem service«)), was used to identify 176 documents.

In the screening phase, only peer-reviewed journal articles were retained to maintain scientific rigor and reliability, while other publication types, such as book chapters, conference papers, and reports, were excluded. Additionally, metadata checks were performed to identify and remove duplicate records. After applying these criteria, 143 articles remained.

During eligibility, full-text reviews were conducted. Only empirical studies published from 2014 onward were included in order to focus on the most recent decade of research developments, resulting in a final selection of 45 articles. To broaden global representation and increase European perspectives, nine additional empirical studies were identified outside the database search. These studies were journal articles published in the period 2014–2024, aligning with the inclusion criteria for the data querying, but they employed alternative terminology (e.g., »transhumance,« »High Nature Value farmland,« etc.) not captured by the keyword query. Their inclusion ensures that the dataset more adequately represents global contributions to the field. Incorporating such studies aligns with best practices in systematic reviews, which recommend complementing database searches with manual methods (Booth et al. 2016). The final dataset comprises 53 studies, the list of which is provided in Table 2. Of these, 15 were conducted in Europe, followed by nine in South America, seven in Africa, six in Asia, six in North America, three in Oceania, and seven with a global scope.

2.2 Thematic analysis

This study employed thematic analysis to extract and synthesize key insights from the selected empirical literature on common lands and ecosystem services, following Braun and Clarke's (2006) inductive method. While the overarching themes, namely, collective management practices, ecosystem services, conservation and economic opportunities, were shaped by the research objectives, the specific categories and sub-categories were derived directly from the data rather than imposed a priori.

The coding process involved two iterative steps. First, open coding assigned initial codes to recurring patterns such as management approaches, ecosystem service types, and socio-economic impacts. Specifically, examples such as »rotational grazing« and »cooperative irrigation systems,« were identified as open codes under management practices, while »water purification« and »spiritual well-being« were identified as open codes under ecosystem services. Second, axial coding was applied, where related codes were grouped into broader themes aligned with the research objectives. Codes were grouped into broader themes when they demonstrated conceptual coherence, recurred across multiple studies, and directly reflected the study's objectives. This ensured that the resulting themes were both empirically grounded and analytically relevant to the research questions. The three themes presented in the Results section correspond directly to the categories generated through axial coding, ensuring consistency between the analytical process and the reported findings. These themes were aligned with the study's research objectives, which focused on common lands' contributions to ecosystem services, the effectiveness of collective management approaches, and the role of ecosystem services in biodiversity conservation and economic opportunities.

Each of the 53 included studies was assigned to relevant coding categories based on its core findings. The unit of analysis was the full text of each article, with coding focused on the empirical evidence presented in the Results and, where relevant, supported by insights from the Discussion and Conclusion sections. The coding scheme and results are provided in Table 2. To ensure coding consistency and minimize bias, an inter-coder reliability check was independently conducted by two researchers. Member checking was also employed to validate key interpretations with two experts in the field to reinforce the accuracy of the thematic synthesis.

3 Results of literature review

The results of literature review are described in subchapters (see 3.1, 3.2, 3.3) and presented in Table 2.

3.1 Positive and negative impacts of land management on ecosystem services (Theme 1)

Common lands offer a wide range of ecosystem services essential to both environmental integrity and human well-being (Costanza et al. 2014; Rodríguez-Ortega et al. 2014). Supporting ecosystem services sustain critical ecosystem functions such as biodiversity maintenance, nutrient cycling, and soil formation, and underpin the delivery of all other ecosystem services by maintaining ecological stability (Berman et al. 2020). Traditional community-based farmland management has been shown to support essential ecological processes like nutrient cycling and soil formation (Lomba et al. 2020). Practices such as controlled grazing and organic farming help preserve soil structure and enhance nutrient flows (Nave et al. 2019). Policy frameworks, for example the Common Agricultural Policy, have supported the integration of conservation practices with local management to improve the resilience of farmlands and grazing systems, many of which are communal farms or pastures within shared-use arrangements or managed cooperatively (Galán et al. 2022). Community forestry practices, such as protected community forests, often sustain greater species richness than unmanaged or exploited lands (Kaye-Zwiebel and King 2014), and forest conservation enhances microbial diversity, which in turn supports soil fertility and productivity (Nave et al. 2019). However, unsustainable practices within commons, such as the intensification of grazing or cultivation on shared farmlands, can disrupt ecosystem functions. For example, when common pastures are converted into intensive agricultural plots, biodiversity declines and ecological processes are disrupted (Hristov et al. 2020). Similarly, monoculture farming and excessive pesticide use on formerly diverse common lands reduce biodiversity, disrupt food chains, and impair ecosystem stability (Carreño-Rocabado et al. 2016; Silva et al. 2019).

Provisioning ecosystem services refer to the tangible resources that common lands supply resources, such as food, water, timber, and medicinal plants, that are particularly vital for rural and Indigenous communities. Traditional grazing systems illustrate how production can be balanced with ecological integrity (Nogueira et al. 2023). Agroforestry and regulated harvesting within communal or cooperative land tenure systems contribute significantly to food security and rural livelihoods (Gómez et al. 2023), and agri-environmental policy incentives often determine the viability of such practices. Watershed co-management supports water availability for both irrigation and household use (Pipan et al. 2023). Within communal grazing lands and shared agricultural landscapes, soil restoration has been shown to increase organic matter, improving crop yields and supporting carbon sequestration (González et al. 2024). Conversely, in poorly governed or open-access commons, overuse and poor management often lead to depletion of provisioning

Table 2: The coding scheme and results of 54 selected articles on common lands and ecosystem services.

Article [a]	Coding scheme [b]																								
	Theme 1 [c]								Theme 2 [d]											Theme 3 [e]					
	I				II				I					II						I		II			
	i	ii	iii	iv	i	ii	iii	iv	i	ii	iii	iv	v	i	ii	iii	iv	v	vi	i	ii	i	ii	iii	iv
1 Ban et al. (2015)		+		+								+	+			+									
2 Barton et al. (2017)	+	+													+							+			
3 Berman et al. (2020)	+		+	+			+			+							+								+
4 Beye et al. (2022)	+		+																	+					
5 Carreño-Rocabado et al. (2016)					+		+														+				
6 Cavigliasso et al. (2022)	+				+																+				
7 Chai et (2021)											+			+								+			
8 Costanza et al. (2014)	+	+	+	+										+							+				+
9 De Araujo Barbosa et al. (2016)						+	+														+			+	
10 Denham (2017)								+		+				+			+					+	+		
11 Diwediga et al. (2015)					+	+	+														+				
12 Galán et al. (2022)	+		+						+			+								+					+
13 Gómez et al. (2023)		+		+						+							+					+	+		+
14 González et al. (2024)	+		+				+														+				+
15 Guerbois et al. (2019)	+		+						+	+							+		+						
16 Gurney et al. (2021)													+			+	+						+		
17 Handberg & Angelsen (2019)														+							+	+			+
18 Hausner et al. (2014)	+	+	+	+																	+		+		+
19 Hayes & Murtinho (2018)									+					+			+				+	+			
20 Kauffman et al. (2014)			+				+														+			+	
21 Kaye-Zwiebel & King (2014)	+	+		+								+										+			
22 Makhubele et al. (2022)	+											+								+	+				
23 Måren et al. (2014)	+		+							+										+	+				
24 Meinzen-Dick et al. (2021)									+							+									
25 Mekuria et al. (2021)	+	+	+						+												+				
26 Mirza et al. (2019)							+								+				+						+
27 Nave et al. (2019)	+		+		+		+																	+	
28 Nguyen et al. (2022)								+						+		+	+					+			

29 Nkhata et al. (2017)	+		+		+		+		+							+									
30 Nkhwanana et al. (2022)					+										+			+			+				
31 Pagot & Gatto (2024)									+								+						+		+
32 Pantshwa & Buschke (2019)					+		+													+	+				
33 Plumb et al. (2018)											+			+								+			
34 Polman et al. (2016)	+		+													+	+						+		+
35 Pulhin et al. (2022)	+									+						+	+					+			
36 Ratinger et al. (2021)																+	+								+
37 Reithe et al. (2014)		+	+										+			+								+	+
38 Ricart e al. (2019)		+	+								+					+									+
39 Sattler et al. (2015)										+	+										+				+
40 Silva et al. (2019)	+		+		+		+													+	+				
41 Squires & Vestergaard (2016)													+		+										+
42 Wagner & Egerer (2022)															+			+	+						+
43 Wang & Zhang (2024)		+	+	+		+	+	+										+							
44 Wells et al. (2024)		+		+		+		+	+								+								
45 Bogataj & Krč (2023)						+		+	+											+	+			+	+
46 Hristov et al. (2020)	+	+	+							+					+				+		+				+
47 Lomba et al. (2020)	+			+	+			+				+					+			+	+				
48 Nogueira et al. (2023)		+							+	+							+								+
49 Pipan et al. (2023)			+				+			+	+					+	+				+				+
50 Renes et al. (2023)	+	+		+								+								+	+		+		
51 Rodríguez-Ortega et al. (2018)		+	+	+								+									+				+
52 Šumrada & Erjavec (2023)									+							+	+			+	+	+			
53 Tucker et al. (2023)									+	+					+	+				+	+				+
Total number	21	15	20	11	9	5	13	6	12	11	5	7	4	7	7	13	16	3	4	11	25	11	7	5	22

[a] Articles #1–44 were identified by automated keyword search, while articles #45–53 were manually selected based on expert judgment. Full citations for all articles are provided in the reference list of this paper.

[b] Coding scheme: Arabic numerals (e.g., 1, 2) indicate themes; capital Roman numerals (e.g., I, II) indicate categories; lowercase Roman numerals (e.g., i, ii) indicate sub-categories.

[c] Theme 1: Impacts of land management on ecosystem services, where Category I represents positive impacts (i: Supporting ecosystem services; ii: Provisioning ecosystem services; iii: Regulating ecosystem services; iv: Cultural ecosystem services) and Category II represents negative impacts (i: Supporting ecosystem services; ii: Provisioning ecosystem services; iii: Regulating ecosystem services; iv: Cultural ecosystem services).

[d] Theme 2: Collective management approaches, where Category I represents traditional approaches (i: Common-pool resource management; ii: Indigenous knowledge-based management; iii: Cooperative irrigation systems; iv: Traditional agroforestry and pastoral systems; v: Customary marine resource management) and Category II represents innovative approaches (i: Payments for ecosystem services (PES); ii: Ecosystem service auctions and market-based instruments; iii: Environmental cooperatives and multi-stakeholder partnerships; iv: Community-based conservation initiatives; v: Digital and data-driven management; vi: Technology-enabled adaptive management).

[e] Theme 3: Ecosystem services opportunities, where Category I represents Biodiversity conservation (i: Biodiversity refuges; ii: Ecosystem health) and Category II represents economic opportunities (i: Payments for ecosystem services (PES); ii: Ecotourism; iii: Carbon markets; iv: Sustainable resource management).

ecosystem services. Overexploitation of forest and water resources, intensive grazing, and vegetation loss have all contributed to reduced availability of plant-based resources (Diwediga et al. 2015; de Araujo Barbosa et al. 2016; Silva et al. 2019).

Regulating ecosystem services encompass ecosystem functions that help moderate environmental conditions, including carbon sequestration, water purification, and erosion control. Forest conservation plays a key role in climate change mitigation by capturing carbon (Berman et al. 2020), and wetlands filter pollutants while reducing the risk of floods (Guerbois et al. 2019). Healthy forests and wetlands buffer extreme weather events, stabilize water cycles, and minimize soil erosion (Mekuria et al. 2021). Effective common land management, such as rotational grazing, maintenance of forest cover, or restoration of traditional irrigation systems enhances environmental stability by maintaining vegetation cover, regulating water flows, and preventing soil erosion, which collectively reduce drought and flood risks (Galán et al. 2022). In contrast, repeatedly tillage in collectively managed farmlands increases greenhouse-gas emissions (Hristov et al. 2020). Land degradation increases exposure to droughts and floods, weakening ecosystem functionality and resilience (Nkhata et al. 2017).

Cultural ecosystem services refer to the non-material benefits derived from common lands, including cultural identity, spiritual well-being, and aesthetic and recreational values. Traditional land management, which occur under either communal or individual tenure arrangements, is often deeply embedded in cultural practices and can reinforce community identity and social cohesion (Kaye-Zwiebel and King 2014; Wells et al. 2024). Transhumance is one example, preserving both cultural heritage and ecological landscapes in Europe (Renes et al. 2023). However, cultural ecosystem services can be undermined by shifts in land governance and policy. For example, the marginalization of high-nature-value farming and cultural landscapes due to intensification and policy changes has eroded community traditions (Lomba et al. 2020). Policy constraints may restrict the expression of communal identity and limit cultural continuity (Nguyen et al. 2022), and ignoring Indigenous sovereignty can undermine longstanding cultural ties to land (Denham 2017).

3.2 Collective management approaches enhancing ecosystem service across spatial scales (Theme 2)

Collective management approaches, as synthesized from the reviewed studies (e.g., Meinzen-Dick et al. 2021; Gómez et al. 2023; Tucker et al. 2023), can be categorized as either traditional approaches, rooted in local customs and Indigenous knowledge systems, or innovative approaches, which incorporate new institutional designs, technological tools, or adaptive governance strategies. Regardless of form, these approaches share common features such as collective decision-making, participatory structures, and multi-stakeholder coordination. Their effectiveness varies across spatial scales, from local communities to regional or international networks, influencing ecosystem service outcomes through a variety of mechanisms.

A major strand of traditional collective management includes a range of practices that reflect deep community engagement with local ecosystems. Among the most widely documented is common-pool resource management, in which communities collectively govern access to shared forests, rangelands, or fisheries. For example, customary tenure systems in India have ensured the long-term sustainability of forest resources (Meinzen-Dick et al. 2021), while community-led conservation efforts in South Africa's Garden Route have maintained ecosystem health through cooperative governance (Guerbois et al. 2019). Forest commons governance, as seen in Slovenia, illustrates how community stewardship enhances ecological resilience (Bogataj and Krč 2023), and these systems are often influenced by national or EU-level policy frameworks. Indigenous knowledge-based practices represent another key category of collective management, as they rely on cultural rules, customary tenure, and shared norms to organize land use. In the Amazon, agroforestry systems are maintained collectively through cultural rules that promote biodiversity and ecological balance (Gómez et al. 2023). In upland Portugal, seasonal grazing and rotational systems demonstrate how traditional knowledge is embedded in community practices to support ecosystem sustainability, reinforced by agricultural policy incentives (Nogueira et al. 2023).

Another form of collective management is cooperative irrigation systems. Across Europe, cooperative networks manage water distribution for agriculture in ways that balance efficiency with local participation

(Ricart et al. 2019). In Oregon, USA, irrigation districts operate through similar principles, demonstrating the global relevance of collective water management (Plumb et al. 2018).

Traditional agroforestry and pastoral systems also contribute to sustainable land use, as access and practices are governed collectively through customary rules, rotational arrangements, and community norms that balance ecological resilience with shared livelihood benefits. Mountain grazing systems maintained under the Common Agricultural Policy illustrate how long-standing practices are adapted within policy frameworks to preserve biodiversity and resilience (Galán et al. 2022). Transhumance, a seasonal herding tradition in Europe, exemplifies a collective management approach in which communities coordinate seasonal grazing rights and herd movements, thereby maintaining habitat connectivity and cultural continuity (Renes et al. 2023).

In coastal areas, customary marine resource management illustrates the integration of local governance with ecosystem stewardship. In the Indo-Pacific, community-managed marine areas have become important for sustainable fisheries, combining cultural norms with ecological monitoring (Ban et al. 2015; Gurney et al. 2021).

Among innovative governance mechanisms are payments for ecosystem services (PES), environmental cooperatives, and market-based instruments. PES are one such mechanism, providing financial incentives for conservation. In China, PES programs have been integrated into village-level irrigation systems, blending institutional reforms with traditional collective action (Chai et al. 2021). In Vietnam, community-based PES arrangements have supported conservation goals while addressing equity concerns (Nguyen et al. 2022).

Environmental cooperatives and multi-stakeholder partnerships also exemplify innovation in governance. In Europe, environmental cooperatives have evolved from top-down interventions into collaborative networks balancing ecological and economic objectives (Ratinger et al. 2021). In marine environments, partnerships between governments and local fishing communities have enhanced the legitimacy and effectiveness of protected area management (Reithe et al. 2014).

Community-based conservation initiatives remain central to local resource management. In the Philippines, protected area co-management is supported through legal recognition of community property rights (Pulhin et al. 2022). Similar arrangements across Latin America have yielded conservation gains and empowered marginalized groups (Sattler et al. 2015; Hayes and Murtinho 2018). In Slovenia, the blending of administrative support with community norms has strengthened water commons governance (Pipan et al. 2023).

Other innovative instruments include ecosystem service auctions and market-based tools, which have been adapted to communal contexts. Studies highlight how auction systems can align with collective land tenure, influencing participation and conservation outcomes (Barton et al. 2017). Governance design remains critical for ensuring both effectiveness and equity (Squires and Vestergaard 2016).

Digital and data-driven management approaches enhance transparency and monitoring. In South Africa, community actors use Sentinel-2 satellite imagery to track ecosystem degradation and guide local interventions (Nkhwanana et al. 2022). In China's Liaohe River Delta, digital ecosystem service models inform co-management decisions across agencies and user groups (Wang and Zhang 2024).

Technology-enabled adaptive management is another frontier of collective management. In urban and rural areas, communities employ machine learning tools to assess land-use change and soil health, enabling data-driven feedback loops (Wagner and Egerer 2022). Computer models are used to simulate how policy frameworks, such as Common Agricultural Policy, affects agricultural development (Hristov et al. 2020). Broader research has emphasized the role of technological innovation in shaping environmental access and equity (Mirza et al. 2019).

Finally, cross-scale governance illustrates how collective management systems operate at multiple spatial scales, from community-level initiatives to transboundary efforts. Local projects often succeed due to participatory governance and embedded knowledge systems but face challenges such as limited funding, weak institutional support, and land-use pressures (Pagot and Gatto 2024). Improved policy coordination and data integration are also essential to advancing these innovative approaches, ensuring long-term sustainability (Nguyen et al. 2022).

At regional and international levels, common land initiatives address large-scale challenges such as watershed restoration and integrated landscape governance. These efforts frequently encounter complex institutional landscapes, overlapping jurisdictions, and diverging stakeholder interests (Pagot and Gatto 2024). Policy alignment across scales is critical for advancing effectiveness (Nguyen et al. 2022). Importantly, cross-scale linkages enhance resilience and learning. Local initiatives can benefit from technical assistance and policy alignment, while broader programs draw on local knowledge and community-based innovations (Pagot and Gatto 2024). As Tucker et al. (2023) argue, integrating commons governance across levels fosters adaptive capacity and long-term sustainability.

3.3 Ecosystem services as drivers of biodiversity conservation and economic opportunities (Theme 3)

Ecosystem services serve as critical drivers of both biodiversity conservation and local economic development on common lands. Biodiversity conservation provides the ecological foundation for economic opportunities, as species-rich commons underpin provisioning ecosystem services (e.g., grazing, non-timber products) and cultural ecosystem services (e.g., tourism). The dual role underscores the significance of commons for achieving integrated environmental and socio-economic sustainability.

Biodiversity conservation is closely linked to the ecosystem services provided by common lands (Rodríguez-Ortega et al. 2014). Forests, agroforestry systems, and rangelands managed through collective practices often serve as biodiversity refuges. For instance, traditional agroforestry systems, such as those in South Africa's Vhembe Biosphere Reserve, support diverse tree species (Makhubele et al. 2022), while community-managed Himalayan forests ensure greater species richness compared to state or privately managed forests (Måren et al. 2014). In Europe, traditional collective grazing practices prevent shrub encroachment and maintain habitats for birds and insects (Galán et al. 2022). Transhumance has also been instrumental in maintaining semi-natural high-value conservation areas and contributes to rural economies through cultural tourism (Renes et al. 2023). Managed grazing in Mediterranean landscapes promotes habitat heterogeneity (Silva et al. 2019), and wetlands and riparian commons further contribute as breeding grounds for fish, amphibians, and birds (Pantshwa and Buschke 2019).

Ecosystem health is supported by services such as soil fertility, water regulation, pollination, and carbon sequestration. In the Colombian Andes, community-managed forests enhance soil quality and microbial diversity, sustaining productive and biodiverse ecosystems (González et al. 2024). Hydrological services provided by forests and wetlands are equally important. Community land tenure in Norway has improved water retention and reduced sedimentation (Hausner et al. 2014), while conservation initiatives in Ecuador and Slovenia have improved water quality and aquatic biodiversity (Hayes and Murtinho 2018; Pipan et al. 2023).

Pollination services are essential to both biodiversity and agriculture. Enriched grasslands support greater pollinator diversity (Beye et al. 2022), and wild bee populations thrive in floral-rich common lands (Cavigliasso et al. 2022). In Slovenia, collective agri-environmental incentives have enhanced pollinator habitats in high-nature-value farmland (Šumrada and Erjavec 2023). Carbon sequestration also supports biodiversity by preserving forest, grassland, and mangrove habitats that are often managed as community or village commons. In the Dominican Republic, intact mangrove ecosystems store significant amounts of carbon and support diverse aquatic and avian species, whereas their conversion to private aquaculture ponds has led to substantial carbon emissions and habitat loss (Kauffman et al. 2014). In contrast, fire-managed savannas in Tanzania show how collective land management can sustain both biodiversity and carbon stocks (Handberg and Angelsen 2019).

Ecosystem services also provide economic opportunities. PES, already introduced in Theme 2, are also important here for linking conservation with livelihood benefits. Programs in Mexican forests have improved local incomes while preserving biodiversity (Denham 2017), and communal PES schemes in Ecuador have enhanced water quality and livelihoods in Andean regions (Hayes and Murtinho 2018). In Slovenia, agri-environmental payments linked to biodiversity support farmers managing commons (Šumrada and Erjavec 2023).

Ecotourism is another important revenue stream for communities managing common lands. In Norway, ecotourism integrated with community forest management brings financial returns and supports conservation (Hausner et al. 2014). In Mexico, cloud forest ecotourism is often organized through community-based initiatives in regions under communal tenure. It has generated jobs and fostered environmental education for the local communities (Denham 2017). In Europe, transhumance contributes to cultural tourism and supports rural economies (Renes et al. 2023). Marine commons also offer significant potential for nature-based tourism (Gurney et al. 2021).

Carbon markets monetize sequestration services through credit systems. In the Amazon, community-based carbon initiatives have improved forest conditions while generating income (de Araujo Barbosa et al. 2016). In the Dominican Republic, the conversion of formerly community-managed mangroves mangroves to private aquaculture ponds has released substantial carbon stocks. This has not only reduced competitiveness in global carbon markets but also resulted in economic and environmental losses associated with the breakdown of commons management (Kauffman et al. 2014).

Finally, sustainable resource management of commons provides long-term economic resilience. Examples include timber, non-timber forest products, and fisheries harvested under collective governance, which can balance livelihoods with ecological sustainability. In Colombia, community-based sustainable sustainable forestry has boosted both ecological and economic outcomes (González et al. 2024). In Tanzania, community-based fire management has improved biodiversity, carbon storage, and livelihoods (Handberg and Angelsen 2019). In Slovenia, forest commons support economic recovery and sustained access to natural resources following environmental disturbances (Bogataj and Krč 2023).

Taken together, these findings show that biodiversity conservation and economic opportunities on commons are often intertwined rather than separate domains. Biodiversity-supporting ecosystem services create the conditions for livelihoods, and under effective communal or collective governance, economic incentives can reinforce conservation. At the same time, pressures to generate income may lead to trade-offs that challenge ecological outcomes, highlighting the need to balance environmental and socio-economic goals.

4 Discussion

4.1 Analytical framework for common lands and ecosystem services

The thematic analysis shows that management practices, ecosystem services, and socio-economic benefits are closely interlinked. To capture these connections, an analytical framework was developed to illustrate how governance of common lands shapes ecosystem service outcomes and, in turn, broader conservation and economic benefits (Figure 1).

The framework distinguishes between two relationships. The direct relationship reflects how management structures, tenure arrangements, and day-to-day decisions affect biodiversity and livelihoods by determining

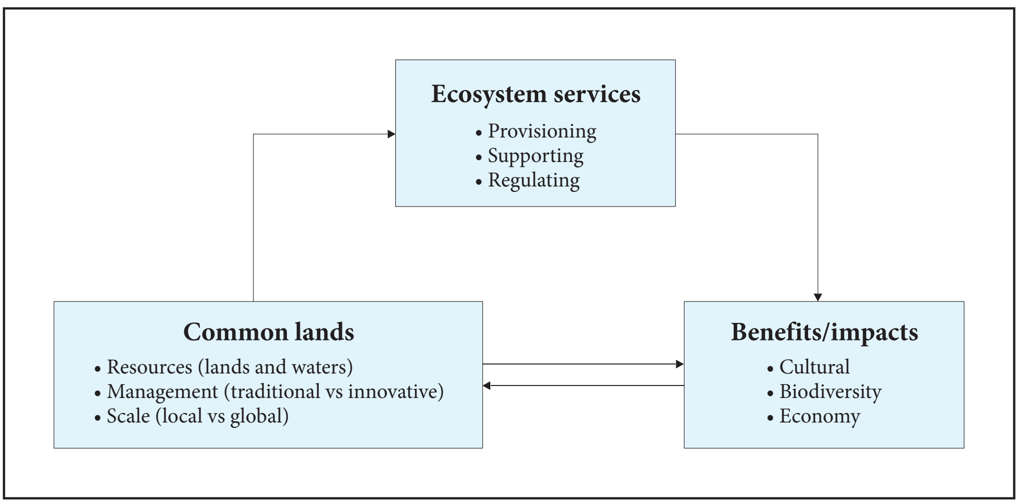

Figure 1: The analytical framework for common lands and ecosystem services.

access to and use of resources. Examples include the loss of ecological integrity through deforestation or overgrazing, and the enhancement of both biodiversity and productivity through community-based conservation when supported by strong local institutions and equitable participation (Carreño-Rocabado et al. 2016). Benefits from sustainable practices may also encourage further participation and stewardship, reinforcing positive outcomes (Urbanc et al. 2023).

The indirect relationship is understood through ecosystem services, which serve as a lens to examine how management practices connect to biodiversity and socio-economic outcomes. Ecosystem services translate governance decisions into ecological and livelihood benefits by maintaining key processes and generating both material and non-material values (Bennett et al. 2015; Berman et al. 2020). While common lands are physically shared resources, their ecological potential is largely determined by how they are governed and managed. Their sustained provision, however, relies on effective and sustainable management practices. Thus, governance and management ultimately shape whether ecosystem services can be delivered effectively, in turn influencing conservation and economic opportunities.

This dual-pathway framing highlights the novelty of the framework, since ecosystem services are recognized not only as outputs of governance but also as intermediaries that shape long-term outcomes. The framework therefore offers both a theoretical and practical tool for future research and policy, enabling comparison across cases, guiding policy design, and advancing commons scholarship by connecting ecological processes with institutional arrangements and distributive outcomes.

4.2 Theoretical and practical implications

Theoretically, this study clarifies the dynamics between common lands and ecosystem services. While ecosystem services are commonly framed as passive consequences of common lands, this study treats ecosystem services as the pathways through which governance of common lands translates into biodiversity conservation and socio-economic outcomes. Therefore, common land management should be embedded in broader socio-ecological systems influenced by markets, climate, and policy (Biggs et al. 2015).

Second, this study highlights the importance of multi-level management structures in achieving sustainable ecosystem service outcomes by sustaining multifunctional bundles, in contrast to individually or company-managed lands that often prioritize provisioning ecosystem services (Ostrom 1992; Tucker et al. 2023). Within these broader governance landscapes, polycentric management decentralizes decision-making and strengthens the governance of common lands (Meinzen-Dick et al. 2021). These dynamics are particularly relevant in contexts where both traditional management and modern interventions interact (De Jong et al. 2018). At the same time, multi-level and polycentric arrangements can present challenges. Coordination across levels may be difficult, transaction costs may increase, and overlapping or fragmented authority can weaken accountability. Power imbalances among stakeholders may also reduce inclusiveness, and resource-poor communities may face barriers to effective participation. Recognizing these potential downsides provides a more balanced understanding of polycentric governance in practice.

From a practical standpoint, the study suggests strengthening local institutions to improve conservation outcomes and equitable benefit-sharing (Meinzen-Dick et al. 2021). Tools such as PES and co-management can incentivize sustainable practices (Berman et al. 2020; Gómez et al. 2023), while cross-scale coordination can promote resilience, mitigate conflict, and align efforts across jurisdictions (Biggs et al. 2015). However, PES schemes may raise concerns. They can undermine trust (Chan et al. 2017), privilege landowners while excluding marginalized groups (Pascual et al. 2014), or conflict with cultural values and community agency (Muradian et al. 2010). PES may also favor short-term incentives over long-term stewardship (Hayes and Murtinho, 2018). Recognizing these limitations provides a more balanced perspective on the role of PES schemes in commons governance.

Second, the study underscores the need for management models that are flexible, participatory, and adaptive to changing environmental and socio-economic conditions (Tucker et al. 2023). In addition, policy interventions should be recognized as a cross-cutting factor shaping outcomes across all ecosystem services and governance levels. Effective policy alignment can reinforce traditional practices, enable innovative mechanisms such as PES, and support coordination across scales to strengthen the resilience of commons. Policymakers must ensure that management structures not only regulate access to common lands but also empower communities with the necessary tools and incentives to engage in sustainable resource management.

4.3 Limitations and recommendations for future studies

This study is limited by its reliance on keywords that explicitly link common lands with ecosystem services. While this approach was necessary to focus the dataset, it may bias the literature toward anthropocentric perspectives that frame biodiversity conservation in utilitarian terms. As a result, alternative perspectives, such as post-humanist or eco-centric approaches, or framings of economic well-being beyond land productivity, may be underrepresented. Future reviews could address this by experimenting with broader or more inclusive search strings. Second, the study relies on peer-reviewed literature, potentially excluding insights from grey literature and community-based knowledge. Future research should incorporate a broader range of sources, including policy reports and interviews. Third, language bias is another concern, as most selected articles were in English. Non-English literature is underrepresented and should be better included in future reviews. Fourth, comparability is constrained by spatial and temporal variation in management contexts. Longitudinal and cross-case studies are needed to assess the durability and scalability of different management regimes. Fifth, this study adopts the four-part typology of MEA (2005), which includes supporting ecosystem services as a distinct category. While still widely used in empirical studies, this typology differs from some recent frameworks, such as IPBES and CICES, that reclassify supporting ecosystem services as foundational ecological functions. This discrepancy may limit the comparability with some recent studies. Future reviews should consider ways to bridge these frameworks, such as mapping legacy data onto updated classifications. Finally, this study does not fully capture the influence of external drivers, such as climate change, global trade policies, or demographic shifts, which may significantly influence common land management and ecosystem service provision. Future studies should examine how such factors shape local management responses and resilience.

5 Conclusion

This study provides a systematic review on the management of common lands and their impact on ecosystem services. An analytical framework is proposed to clarify how management structures and ecosystem services interact to generate socio-ecological benefits. Common lands generate not only direct effects on biodiversity conservation and economic opportunities but also indirect effects mediated through ecosystem service. Adaptive and multi-level governance, aligning communal and collective local practices with broader policy mechanisms, contributes to sustainability. Such integration ensures that common lands remain resilient systems capable of supporting biodiversity and livelihoods in an era of environmental uncertainty.

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All intellectual content and interpretations were produced by the human authors. No AI tools were used for the conceptualization, writing, translation, summarization, analysis, or figure production of this study. Basic AI-powered software (e.g., grammar and citation checkers) was used solely for minor formatting or language refinement purposes.

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GROUNDWATER RECHARGE AS A BASIS FOR THE ASSESSMENT OF ECOSYSTEM SERVICES ON COMMON LAND: THE CASE OF THE PRIMORSKA REGION IN SLOVENIA

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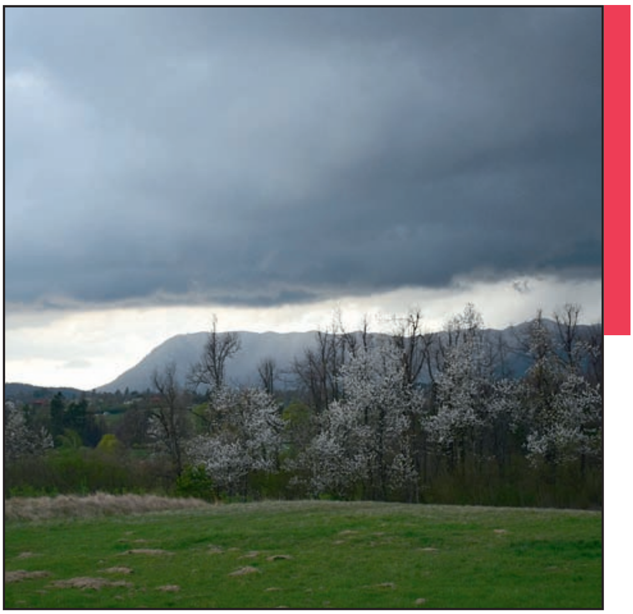

The storm brings precipitation. A view of Nanos.

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Nevenka Bogataj[1], Peter Frantar[2]

Groundwater recharge as a basis for the assessment of ecosystem services on common land: The case of the Primorska region in Slovenia

ABSTRACT: The objective of this analysis is to assess groundwater ecosystem services and collect available data, with a particular focus on the supply side of their provision in common lands. The assessment of the state and trends of its recharge is conducted using the water balance model mGROWA. The study focuses on the period from 1972 to 2023 and the Primorska region due to the availability of both, spatial and temporal data for groundwater recharge and for forests on common lands. Based on the findings, we propose to recognise and support agrarian communities as large land proprietors practising the sustainable management of natural resources, underpinned by a benefit-sharing paradigm as stakeholders in groundwater management.

KEYWORDS: common lands, ecosystem services, groundwater, hydrology, Slovenia, Primorska region, drinking water

Napajanje podzemne vode kot osnova za ugotavljanje ekosistemskih storitev na skupnih zemljiščih: primer Primorske v Sloveniji

POVZETEK: Cilj te analize je opredeliti ekosistemske storitve podzemne vode in zbrati dostopne podatke s poudarkom na njenem zagotavljanju na zemljiščih, ki jih posedujejo agrarne skupnosti. Obseg in dinamika polnjenja podzemne vode sta ocenjena z modelom mGROWA. Spričo razpoložljivosti novejših prostorskih podatkov in trendov napajanja podzemne vode ter gospodarjenja z gozdovi smo se osredotočili na Primorsko in na obdobje med letoma 1972 in 2023. Na podlagi ugotovitev predlagamo, da se agrarne skupnosti kot lastnike velikih zemljišč z delujočo lokalno tradicijo njihovega trajnostnega upravljanja, ki temelji na paradigmi deljenih skupnih virov, upošteva kot deležnike v upravljanju s podzemno vodo.

KLJUČNE BESEDE: agrarne skupnosti, ekosistemske storitve, podzemna voda, hidrologija, Slovenija, Primorska, pitna voda

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1 Introduction

Ecosystem services (ES) represent the relationship between human wellfare and ecosystems. The latest version of the internationally agreed categorization, European Union Common International Classification of Ecosystem Services (CICES), was provided by Haines-Young and Potshin (2018) who generally define ES as arising from living structures and processes, but acknowledging abiotic ecosystem outputs to stress their non-biomass base, and recognition of hydrological cycle as driven by geo-physical processes (see also MEA 2005, TEEB 2010). As we focus on groundwater as a basis for ecosystem services, we acknowledge the CICES definition, primarily classifying groundwater as a provisioning abiotic service used for drinking (4.2.2.1), non-drinking (4.2.2.2) or energy (4.2.2.3) purposes, as the regulation and maintenance of the biotic service (2.2.1.3) or the cultural biotic service (3.1.1.1) when it enables interactions with living systems (e.g., in wetlands or biodiversity). The conceptualization of groundwater ES, just recently edited by Iliopoulos and Damigos (2024), contributed to more nuanced understanding of the role groundwater plays in societies. The inherent value of these ES is inextricably linked to the quantity of groundwater, in addition to the ecological and social benefits that defy straightforward economic quantification.

Groundwater is formed by precipitation, is found beneath the land surface and is a part of the hydrological cycle, e.g., mitigating the impact of drought. As a resource it is characterised by availability which decreases with use (Ostrom 1990). Therefore, its management is challenging (Ehrman 2020). Based precisely on the case of water supply, Ostrom (1990) identified self-regulated institutions as an effective governance model. As demonstrated in the works of van Laerhoven et al. (2020) and Romanelli and Boschi (2019), numerous authors have examined and built upon Ostrom's contributions to the field and much of the international literature on collective groundwater management is based on Ostrom works, for instance local adaptations due to balancing of interests (Doneo and Conrad 2024) and local consideration of the social and cultural roles of groundwater (Smith 2002) without displacement of weaker stakeholders (e.g., farmers) where groundwater is considered a commodity. Solutions for sustainable groundwater management were sought in river basins in India and China (Shang et al. 2024; Vora 2024) and by analysing international agreements on water and other resources (Soliev and Thesfeld 2017). A shift from negotiation between conflicting actors to the identification of options for maximising co-benefits was suggested (Soliev and Thesfeld 2017) which is the way local collectives manage resources, including water. Italian constitutional law grants collective landowners rights on the basis that they have preserved natural resources despite having used them for centuries. Despite the absence of explicit mention of groundwater in this law, it can be presumed that it was meant as a natural resource.

The interdependence of groundwater with soils and surface ecosystems is a particularly sensitive issue in karst areas with water-permeable carbonate substrate. The Slovenian region of Primorska combines both, karst bedrock and climate regimes of the Alps and the Sub-Mediterranean region to which local collective resource management institutionally adapted. This typically represents small-scale benefit sharing local collectives that regularly monitor resources, and incorporate feedback into their utilisation. The fundamental reason for such an organization is the (eventual) scarcity of resources that might lead to tensions, conflicts and – in the case of water – the potential jeopardy of survival. In light of the interconnection between droughts and climate change, groundwater recharge and dynamic served as a motive for our analysis, drawing upon the reports of Vertačnik (2023) and European Mapping and Assessment of Ecosystems and their Services (European Commission … 2020).

In Slovenia, groundwater is owned by the state and according to the Act on water published in 2004 regarded a public good. The governance of water supply and water protection areas is overseen by the Water Directorate, while the management of local groundwater use falls under the responsibility of municipalities. In the Primorska region groundwater is also the subject of transboundary cooperation. Access to groundwater cannot be prevented and depends on the consent of the landowners on whose land boreholes and wells are located, and water may be abstracted for personal needs.

Primorska is an informal region in Slovenia, which includes two statistical regions, called *Goriška* and *Obalno-kraška*. The local water management culture of this region is described in the context of the Karst area (Crnko et al. 2015) exhibiting adaptations to occasional droughts by collective approach amongst its inhabitants. Furthermore, the significance of alterations in land cover has been recently documented for two main river catchments in the area, namely Rižana and Unica (Ravbar et al. 2023; Ravbar et al. 2024). There was a decline in effective precipitation of 49% in the Rižana catchment, attributable to climate change, and an increase in forest cover of 30% between 1965 and 2018 (Ravbar et al. 2023). Opposite, a 5% rise in effective precipitation has been documented for the Unica catchment, attributable to the combination of climate change and large-scale forest damage during the period 2014–2016 (Ravbar et al. 2024). These analyses do not take into account the management of land.

Groundwater on common lands has not been addressed so far, although recently Pipan et al. (2023) presented water cooperatives (Lazarević et al. 2023). They have a different conception, history, purpose and functioning of collective management than agrarian communities (AC) as long-term land owners of common lands, documented as active and effective (Bogataj and Krč 2023). However, the intermediary role of AC is unclear and marginalized and it would appear that there is a dichotomy between private ownership of the land and state ownership (and management) of groundwater. Moreover, the issue is becoming increasingly important due to the climate change (European Commission … 2020; Vertačnik 2023) and changes in land cover. The simultaneous consideration of spatial and temporal variability in groundwater may, therefore, contribute to informed and consensual decision-making by all stakeholders regarding aquifers when considering any of the groundwater ES.

1.1 The national literature review on land commons related to groundwater

The concept of common pool resources was first introduced in Slovenia by Rodela (2012) and comparatively studied by Šmid Hribar et al. (2018), who also established the first link between common lands and ES in the country (Šmid Hribar et al. 2023). Dominated by forests and pastures (Kozorog and Leban 2023; Šmid Hribar et al. 2023), common lands are managed by self-regulated local institutions officially entitled AC and defined in 2015 by Agrarian Communities Act. Decade ago, AC owned 3.7% of Slovenia's surface area (Premrl 2013), but there is an overall lack of data on this issue, with the exception of Primorska, where they own four times more, 12% (Kozorog and Leban 2023), and Triglav National Park, where according to preliminary information approximately 20% of the land is under AC ownership.

The legal protection of AC was established after the denationalisation of the land by the Act on reestablishment of agricultural communities and restitution of their property and rights (sl. *Zakon o ponovni vzpostavitvi agrarnih skupnosti ter vrnitvi njihovega premoženja in pravic*) from 1994 and the Act on agrarian communities (sl. *Zakon o agrarnih skupnostih*) from 2015, and was characterised by numerous amendments, demanding procedures and costs. Their forest management is systematically monitored and rewarded by the Slovenian Forest Service (*Zavod za gozdove Slovenije,* SFS), which is the sole state institution that regularly selects AC for models of active sustainable management. Slovenian authors have considered AC from a variety of perspectives, including legal aspects (Hafner 2011; Cerar et al. 2016), historical development (Meden 2019; Kocijančič 2022), geographical characteristics (Šmid Hribar et al. 2023) and anthropology (Hrobat Virloget 2023; Beltrametti 2024). As Bavec and Bogataj (2021) demonstrate in publication with AC self-presentations, they are particularly active in Primorska in comparison to other regions, as a high proportion of cases from there (one third) are documented.

Šmid Hribar et al. (2023) conducted a study on commons from the perspective of their ES provision, but however, the eventual groundwater-related roles of AC were not addressed by the study. It is intriguing to note that an example of efficient response to natural extremes has been documented in the context of AC, e.g., fast and focused activation (Bogataj and Krč 2023). Groundwater recharge on common lands of AC in Primorska is a subject of contemporary concern due to a number of remarkable meteorological deviations there, including a particularly hot summer in 2003, several dry springs, followed by dry summers and an increased risk of fire, as well as an extreme fire event (Sandrin 2022) and unfavourable future projections (Vertačnik 2023).

1.2 Aims and scope

The scope of the paper is to identify groundwater recharge on common lands in the Primorska region as a potential source for the provision of groundwater ES as defined by Haines-Young and Potshin in CICES (2018) by codes 4.2.2.1, 4.2.2.2 and 4.2.2.3 and listed by Iliopoulos and Damigos (2024).

The following research questions were the subject of our analysis: which ES are provided by groundwater, at least in theory? What is the amount and dynamics of groundwater recharge as a basis for groundwater ES on common lands in the Primorska region? Are there any spatial differences in groundwater ES potential between Alpine and Sub-Mediterranean common lands?

The primary objective of this study is not to categorise or score services, but rather to establish a foundation for their future evaluation by focusing on the supply side of groundwater ES and unveiling the complex interactions between groundwater dynamics, climate and collective land use and management (Ostrom 1990; Meinzen-Dick and Bruns 2024) by examining numerical data (Booth et al. 2016; Shang et al. 2024). This approach aligns with contemporary research emphasizing the use of continuous data for nuanced interpretations of spatial and temporal trends while respecting landscape heterogeneity and avoiding potential oversimplifications (Smith 2002; Vora 2024).

2 Methods

A comprehensive review of the literature on groundwater ES was conducted, with a particular emphasis on the bibliography of Slovenian karst groundwater recharge in relation to the dominant land cover and the characteristics of AC management.

Iliopoulos and Damigos (2024) provided a detailed list of groundwater ES that are useful for the purpose of our analysis:
- provisioning final ES (drinkable water, irrigation water, livestock water, water for industrial use);
- intermediate provisioning ES in case of strategic water resources, storage capacity;
- regulating intermediate services ES for water purification, seawater intrusion control, flood control, subsidence control, carbon dioxide storage, hydraulic conductivity, maintenance or microclimate mitigation;
- fundamental or supporting intermediate ES for groundwater-dependent ecosystems, water cycle support and
- cultural ES (naturalist leisure activities, aesthetic enjoyment, spiritual well-being, education and research).

Their precise and consensually built classification and categorisation frame groundwater not only as a provisioning ES, but also as a regulating and cultural ES.

The estimation of groundwater recharge was conducted utilising the water balance model mGROWA (ger. *montatliches Großräumiges Wasserhaushaltsmodell*) for the period from 1991 to 2020 (Frantar et al. 2023) and comparison was made between the Alpine and Sub-Mediterranean group of common lands. An interdisciplinary approach was adopted to establish a comparison between the geographic data of the AC lands and the results obtained from the water balance model. The Primorska region was selected for analysis due to the largest amount of common lands there, their recent mapping and forest management analysis (Kozorog and Leban 2023), and the evidence of strict local rules regarding the use of resources (Kocijančič 2022; Jurišević and Medeot 2024) which may align with eventual risk perception (Ravbar and Kovačič 2010). Contrary to the general absence of data, these data enable diverse comparisons and a step towards complex analysis of groundwater ES. A measure of forest management intensity is an average cutting over the period from 2013 to 2023 (Kozorog and Leban 2023). In the context of comparisons between common lands and other spatial features, full correspondence is defined by 100% spatial correspondence, while substantial correspondence from 50% to 99%.

2.1 Study area

Kozorog and Leban (2023) described and mapped the AC of the Primorska region according to phytogeographical characteristics as a primary factor in the formation of two distinct groups: an Alpine and a Sub-Mediterranean group of common lands. Both groups face potential drinking water scarcity, because in the Sub-Mediterranean region karst bedrock prevents surface water courses, while the steep Alpine slopes cause rapid runoff. The Alpine group of common lands is located in the area of the Julian Alps and the high Dinaric Alps, while the Sub-Mediterranean part consists of coastal Koper area, the Brkini hills and the Karst region including a few lands of the Nanos area, despite them being part of the high Dinaric range. The total grid area of all common land units is 32.708 ha.

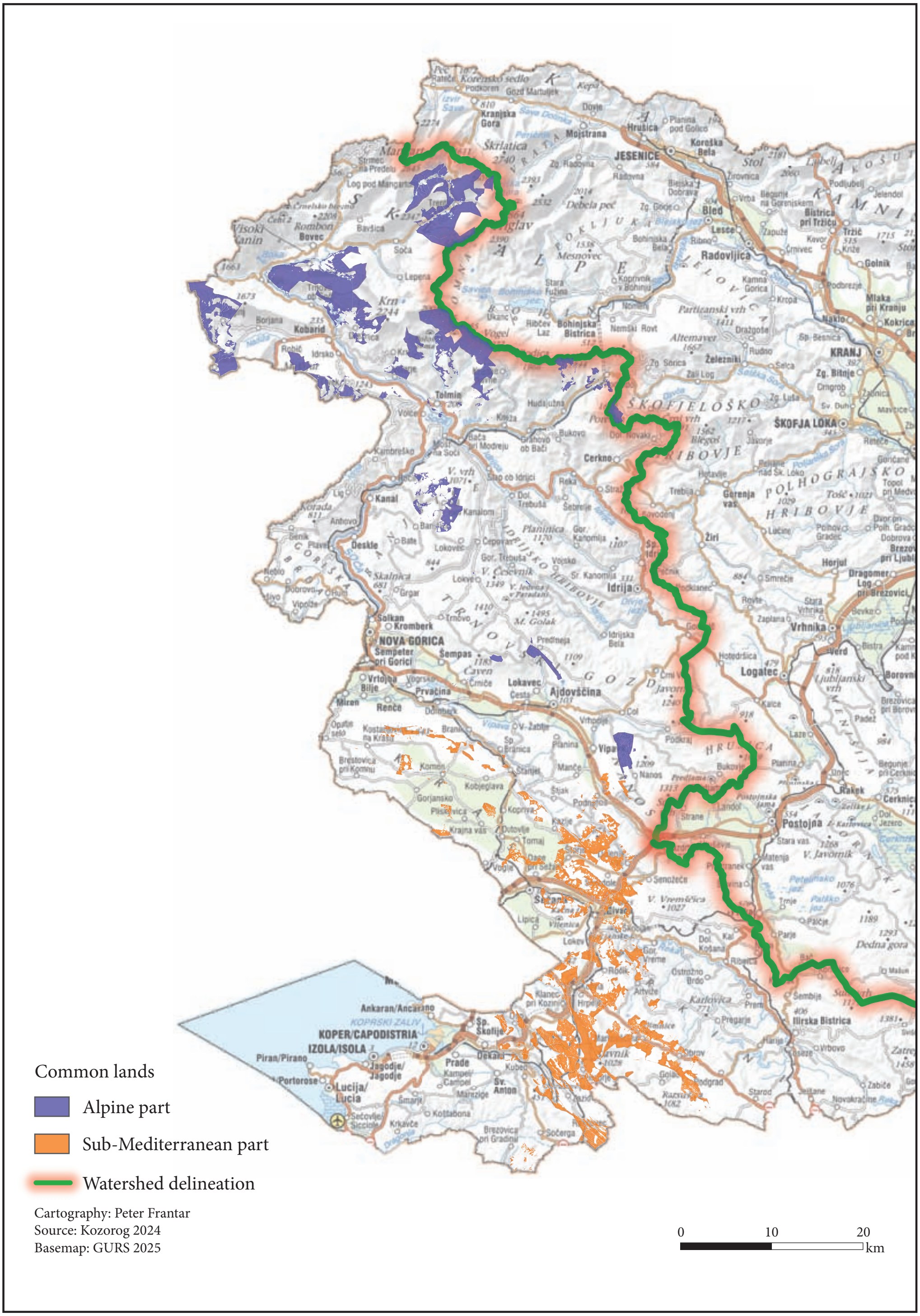


Figure 1: Common land grouped into Alpine and Sub-Mediterranean (Kozorog 2024).

2.2 Data sources

2.2.1 Agrarian Communities (AC)

An agrarian communities' layer is a polygon dataset representing lands defined and used as common lands owned by the AC. The geocoded data layer on AC was obtained from the SFS (Kozorog 2024) and analysed by Kozorog and Leban (2023) for their forest management. The layer includes merged polygons of 93 AC divided into the Alpine group in the north, and the Sub-Mediterranean group in the south.

2.2.2 The CORINE land cover layer

We used data from Coordination of Information on the Environment (CORINE). CORINE Land Cover (CLC) is general land cover layer in vector format. The coverage, definition and nomenclature of land cover classes are standardised (Bossard et al. 2000; Copernicus 2024). The mGROWA model used the CLC2006 layer to analyse the water balance across different land cover types. The main CLC categories are combined with hydro-pedological characteristics and soil water modelling. All that provides the model basis for the impact of land cover on the water balance. This also influences runoff and groundwater recharge. The model assumes constant land cover throughout the period 1991–2020, based on the CLC2006 layer.

2.2.3 Water protection zones

A water protection zone is defined as a designated area established to safeguard a water body used for or intended for public drinking water supply. There are two major water protection zone designations, namely of the state and of the municipality. Both have been joined into one layer and used as an indicator of land protection for groundwater ES. The data layer of water protection zones (version 2024) was provided by the Slovenian Water Agency.

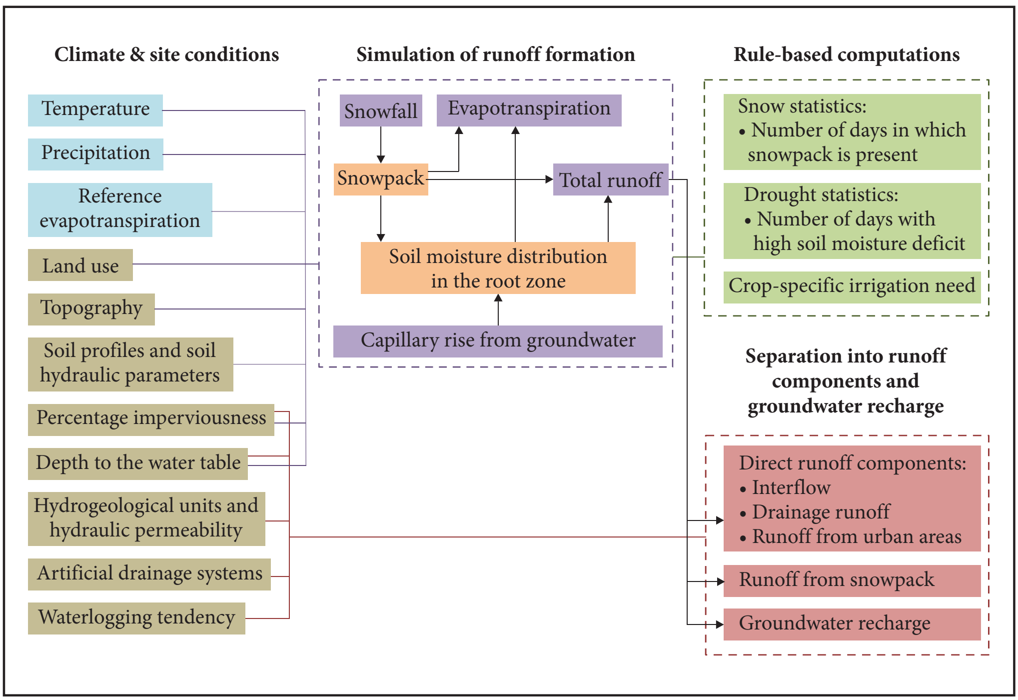


Figure 2: Model flowchart of the mGROWA water balance model.

2.2.4 The mGROWA water balance model

The mGROWA model (see Figure 2) is a deterministic raster water balance model. It is based on the German mGROWA model, which has been adapted and upgraded for Slovenia. The water balance elements in the model are calculated on the basis of static and dynamic input data and simplified hydrological processes for each 100 × 100 m model cell at a daily time step with outputs available at different time scales.

The model is based on geographical data derived from the landscape, the pedological and hydro-geological characteristics. The model analyses the water cycle in 100 m cells with the use of dynamic climate data on precipitation, potential evaporation and air temperature (Herrmann et al. 2013; Herrmann et al. 2015). The model calculates the soil-water and the snow-water separately. The output of the soil and snow modules is evaporation and total runoff. The total runoff is structured into various types of runoffs, the most significant of which is groundwater recharge. The latter can be equated to baseflow values (Frantar et al. 2023). We analysed groundwater recharge, which is calculated in the »Qrn« layer of the mGROWA model.

Groundwater recharge is approximately equivalent to the total recoverable groundwater volume. Due to the dynamics of recharge, data are aggregated on a monthly basis (Frantar et al. 2023). The mGROWA model is continuously upgraded in collaboration with the Slovenian Environment Agency (sl. *Agencija Republike Slovenije za okolje*, ARSO) and the Jülich Research Centre (ger. *Forschungszentrum Jülich*, FZJ). The groundwater recharge layers that were the subject of this analysis derived from the r158 model run at Slovenian Environment Agency in August 2024.

In the mGROWA model, baseflow is equated to groundwater recharge, which ensures flow stability during droughts and serves as a key parameter for determining ecologically acceptable flows (Herrmann et al. 2015; Frantar 2022), maintaining the natural water balance and enabling sustainable management of water resources (Herrmann et al. 2015; Andjelov et al. 2016).

2.3 The geospatial join of spatial and groundwater recharge data

The basis for groundwater data is constituted by the results of the mGROWA r158 model run – annual grids for the hydrological years from 1972 to 2023. The mGROWA grid layers were intersected with a joined raster of common lands and land cover CLC2006. This cross-section identified land use in each AC area. Based on that the »Zonal Statistics« were computed from all the groundwater recharge grids for the modelled data from year 1972 to 2023. The output was a table of recharge values for each individual AC unit that was joined with a table of area and other basic geospatial statistics.

Groundwater recharge data and basic entity parameters were merged into a new table for geostatistical analysis by a part of Primorska (the Alpine or Sub-Mediterranean group of common lands) and land cover type (CLC). The analysis considered annual values from hydrological years 1972–2023, with the 30-year period 1991–2020 as the climatological reference for climate comparisons (WMO 2017).

In addition, we linked water protection zones to the AC (intersected in GIS) to test eventual groundwater potential for ES provision.

3 Results and discussion

3.1 Groundwater as ES

Groundwater ES and evaluation of its benefits stem out of a complex mechanism of water recharge. Recent research findings on the groundwater recharge of two karst river catchments of the Primorska region have indicated that precipitation and land use changes are not the only factors influencing the availability of groundwater of ES, such as drinking water (Ravbar et al. 2023; Ravbar et al. 2024), but there are also several other factors. Forests play a pivotal role, and as such, their management is worth being analysed and, therefore, acknowledged in following sections.

3.2 The amount and dynamic of groundwater recharge on dominant land uses

According to mGROWA model both, the Alpine and Sub-Mediterranean group of common lands in Primorska are dominated by CLC Class »forests and semi-natural areas«, with the Alpine group exhibiting a forest cover of 168.5 km^2 (97%) and the Sub-Mediterranean group of common lands displaying a forest cover of 133.3 km^2 (87%). Consistently forest (CLC classes 311, 312, 313) in both groups of common lands cover almost identical share of area (67%). Forests infiltrate less water than grassland (CLC classes 231, 321) as seen in Table 2 respectively. It is evident that the Sub-Mediterranean group has significantly lower groundwater recharge than the Alpine group of common lands.

The average groundwater recharge for all land uses in the Alpine group of common lands for the 1991–2020 period is 845 mm, annually ranging from 504.7 mm in 1989 to 1,461.6 mm in 2001 (Table 1, Figure 3). As expected, the CLC class 300 (»forests and semi-natural areas«) have almost identical recharge (845 mm) as this CLC main class is dominant of this land category. On forested land, the recharge averages 779 mm, ranging from 444 mm in 1989 to 1379 mm in 2001. On grassland the recharge averages 972 mm, ranging from 548 mm in 2003 to 1686 mm in 2001.

In the Sub-Mediterranean group of common lands, the average groundwater recharge for the 1991–2020 period is 289 mm. On forested land, recharge averages 274 mm, ranging from 106 mm in 2012 to 466 mm in 2001. On grassland the recharge averages 313 mm, ranging from 126 mm in 2012 to 521 mm in 2010 (Table 2).

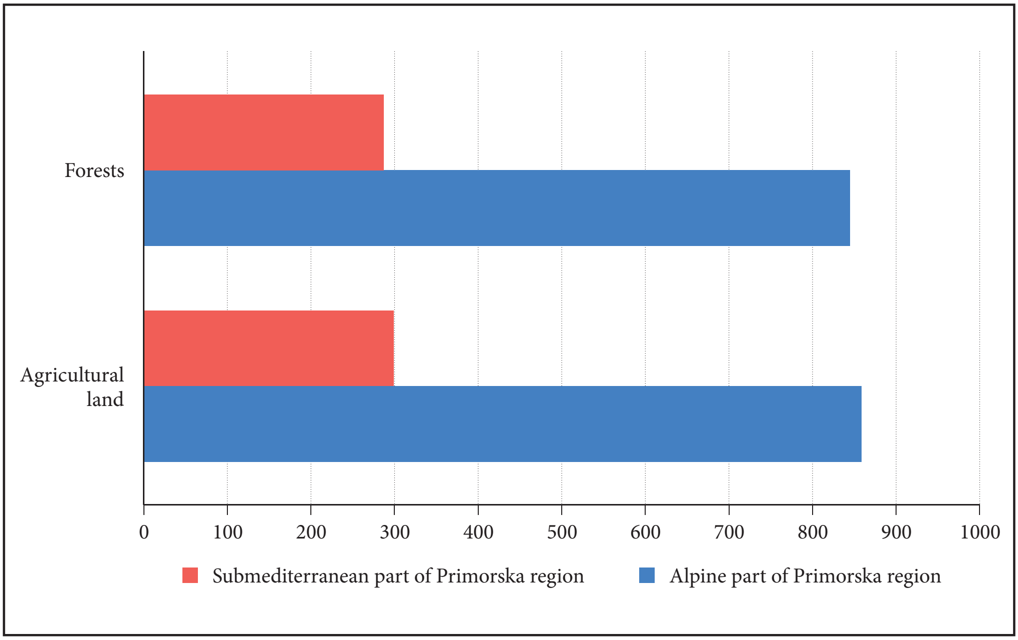


Figure 3: Average annual groundwater recharge (in mm) on dominant land uses in the Alpine and Sub-Mediterranean group of common lands.

Table 1: Annual groundwater recharge of CLC class »forest and semi natural area« for the period 1991–2020 (in mm) and indication of extreme year.

Groundwater recharge (mm) in CLC class 300 (forest and seminatural areas)	Alpine group	Sub-Mediterranean group
Average	845	287
Minimum (extreme year)	504.5 (1989)	113.2 (2012)
Maximum (extreme year)	1461.6 (2001)	483.1 (1977)

Table 2: Annual groundwater recharge of forest and grassland in the Alpine group of common lands for the period 1991–2020 (in mm).

Groundwater recharge (mm)	Forest			Grassland		
	average	min	max	average	min	max
Alpine	779	444	1379	972	548	1686
Sub-Mediterranean	274	106	466	313	126	521

These data provide evidence of a more significant impact of dry periods in the Sub-Mediterranean group of common lands, affecting vegetation, especially the dominant forest.

The amount of infiltration depends not solely on precipitation amount and distribution, but also on hydro-pedological characteristics and land cover water requirements. Forests, for instance, require greater quantities of water than meadows (Madani et al. 2018). This can be seen also from model mGROWA through land use specific evapotranspiration factors, i.e., for CLC class 321 »natural grassland« the factors in spring and summer months are from 1.00–1.06; for CLC class 312 »coniferous forest« factors are from 1.18–1.27. This indicates higher water demand of forests (Herrmann et al. 2015; Frantar 2022). Therefore, the groundwater recharge is also smaller in forest as compared to grassland. Given the same soil moisture levels, forests experience less infiltration compared to grasslands with easier percolation of water. Consequently, drought conditions may develop earlier in forests than in grasslands, leading to differences in infiltration data between these vegetation types.

Overview of relative annual variations (Figure 4) shows that the inter-annual variations can be from –60% to +70%. It also shows that after 2000 an increasing number of drier years with lower recharge is observed. The driest years for groundwater recharge were 1989, 2002, 2003, 2012 and 2022, with the largest relative negative variations in the Sub-Mediterranean group of common lands.

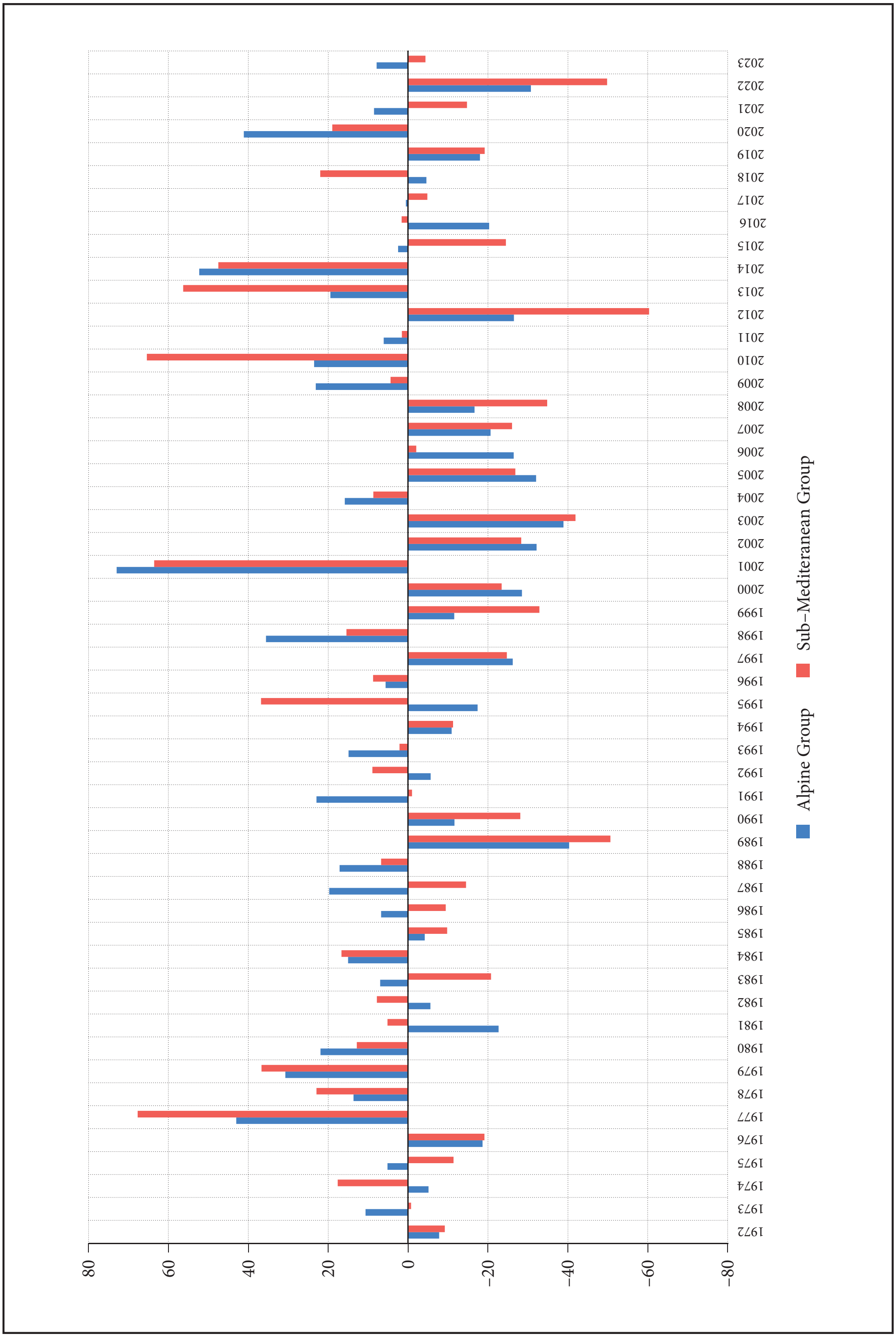
A comparison of the two subregional groups reveals greater recharge variability in the Sub-Mediterranean, with 28 of 52 years showing negative deviations and 24 positive deviations. In contrast, the Alpine group of common lands exhibits the opposite, with 25 negative and 27 positive years.

Given the lower recharge in the Sub-Mediterranean group, the management and protection of common lands are disproportionately more critical and require greater attention than in the Alpine group. The total average recharge rate in AC in the Alpine group is 4.65 m^3/s but only 1.41 m^3/s in the Sub-Mediterranean group. In the latter, annual declines of up to 50% can reduce recharge to just 700 l/s in dry years (Figure 4), with even more pronounced seasonal fluctuations. The importance of groundwater as ES is, therefore, substantially higher on the Sub-Mediterranean common lands (the lower recharge means greater sensitivity of ES to its variation) than on the Alpine common lands, exposed to eventual floods due to the increased variability in annual recharge in recent decades. In the Alpine group, there was an increase in annual recharge from 17% (1972–2000) to 24% (2001–2023), while in the Sub-Mediterranean region the absolute variation rose from 18% (1972–2000) to 27% (2001–2023). This trend reflects growing hydrological extremes, with some years experiencing greater aridity and reduced recharge that impact ES.

3.3 The correspondence between groundwater and common lands

Spatial correspondence of groundwater recharge and forest management on common lands, analysed by Kozorog and Leban (2023), inform future assessments of groundwater ES at least for Primorska where common lands cover twelve percent of land, which is predominantly forested, and exhibit lower levels of management intensity compared to other private forest properties within the same region. For instance, between the years 2013 and 2022, in the Alpine area, more than half of AC (53.8%) cut less than other private forest owners. This proportion is even higher (71.7%) in the Sub-Mediterranean region. Generally

Figure 4: Relative deviation of annual groundwater recharge from the reference period 1991–2020 in %. ➤ p. 47


Alpine Group
Sub–Mediterranean Group

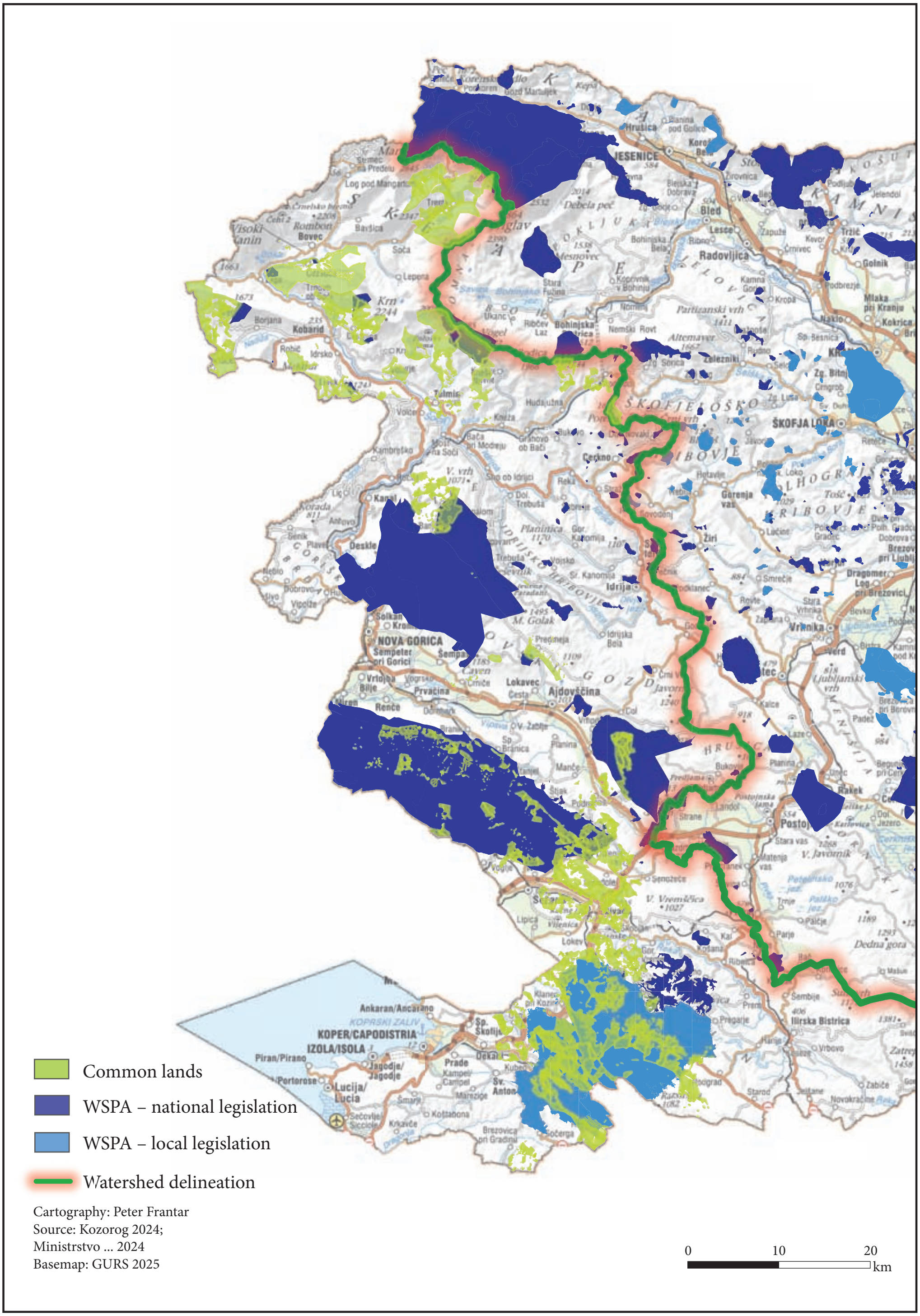


Figure 5: Water source protection areas (WSPA) in Slovenia and on common lands in Primorska.

low management intensity of forests has positive implications for quantity and quality of groundwater and ES derived from it. Furthermore, common lands, being relatively large in size, are likely to make a substantial contribution to groundwater stability when compared to fragmented individual private forest properties. Therefore, high correspondence of legally protected groundwater areas is not a surprise. In the Alpine group, 18% (2553 ha) of the common lands fall within water protection zones, whereas in the Sub-Mediterranean group, this figure reaches 78% (9749 ha in total) (Figure 5).

The Alpine group includes 35.7% of AC (namely 15 out of 42) with at least some land in a water protection zone. Among them, 5 AC have less than 5% of their area protected, while one (2.3%) is entirely within the water protection area.

In the Sub-Mediterranean group, 58% (54 AC out of 93) have land within water protection zones, with only one having less than 5% protected. Remarkably, 34 AC (36.5%) are entirely in water protection areas.

3.4 Groundwater and land management

Groundwater ES, although classified by CICES (Haines-Young and Potshin 2018) and Iliopoulos and Damigos (2024), are largely understudied. We focused on the supply side of groundwater ES as a basis for future assessments and evaluations. Despite data scarcity, we were able to identify a region that possessed numerical data on the spatial and temporal dynamics of groundwater recharge on common lands already analysed from the perspective of forest management (Kozorog and Leban 2023). Data availability and spatial correspondence of data sources are the key added values of this analysis. However, the Primorska region was selected also due to the prevalence of common lands at the national level and regular reports of the SFS on model management practices of AC in this region which corresponds with literature on the local culture of self-limiting resource use (Crnko et al. 2015) and the accent on care for water (Bogataj and Rupnik Vec 2024). CORINE data and the water balance mGROWA model provides precise numerical information and incorporates a certain degree of complexity regarding land uses.

The results indicate significant variability with regard to both geographical location and by land cover type. Natural grasslands exhibit higher infiltration rates in comparison to forested areas as found by other authors (Owour et al. 2016). An average annual groundwater recharge in Slovenia for the reference period 1991–2020 is estimated at 313 mm, while Alpine group of common land units with 845 mm is high above this average. Sub-Mediterranean group with 287 mm is slightly below this average. Deviation of annual groundwater recharge from the long-term reference period was found: an increase in the number of dry years after 2000 and more pronounced fluctuations. The 52-year record reveals substantial variability and a higher frequency of negative deviations. In the Sub-Mediterranean region at least, groundwater ES are exposed not only to eventual shortages, but also to significant risk of large-scale forest cover changes (Kozorog and Leban 2023; Ravbar et al. 2023; Ravbar et al. 2024). Moreover, in areas where forests are predominant, as is Primorska region, low management intensity reported for common land may be of critical importance for groundwater ES, irrespective of the underlying reason, such as marginal productivity on poor soils, inaccessibility of slopes, or inactive AC. Additionally, relatively large properties of common lands and their extensive use contribute to groundwater recharge comparatively more than fragmented individual properties. This suggests a significant positive potential impact on the provisioning of groundwater ecosystem services, with implications in both the short and long term. Moreover, it is important to note that local balancing of interests (Doneo and Conrad 2024) is a fundamental characteristic of AC which may be the key in provision of quantity and quality of groundwater ES (Juriševič and Medeot 2024) in the face of climate changes both regionally and beyond (Soliev and Thesfeld 2017; Bogataj and Krč 2023; Pagot et al. 2025). Finally, the SFS's recognition of AC's practice of sustainable forest management indicates important implications for groundwater ecosystem services, as evidenced by the considerable overlap between common lands and officially designated water protection zones. A full correspondence was found for 34 of the Sub-Mediterranean cases and one AC in the Alpine group of common lands. Substantial correspondence (50–99%) was noted for additional eight Sub-Mediterranean and two Alpine cases respectively. Together the substantial and full correspondence accounts for 10% of cases (14% of AC area) in the Alpine and 65% of cases (72% of AC area) in the Sub-Mediterranean group. This emphasizes the importance of land management within AC areas to protect drinking water resources and sustaining groundwater ecosystem services.

4 Conclusion

The aim of our work was not to conduct a monetary evaluation of groundwater ES, but rather to emphasise their variation and significance across different units along interdisciplinary understanding of a fragile karst socio-ecological system of Primorska, increasingly characterised with shortages of water. Rather than estimating the groundwater ES itself, our analysis provides an insight into their supply side and the complex interplay of the climate change and land-use factors (Leins et al. 2025). The mGROWA model regards both factors, consequently the present study revealed key spatial and temporal patterns for the period of five decades.

In order to quantify groundwater ES, the following should be taken into consideration: firstly, comparable circumstances to our own case should be sought; secondly, the presence of karst bedrock and land cover dynamic should be taken into account as well as the productivity of forests; and finally, management intensity and fragmentation of properties along gradual or sudden changes in land cover should be taken into account.

The common lands within the observation area largely overlap with water protection zones. Therefore, this relationship warrants further investigation to assess whether the preservation of groundwater quality is influenced by the specific land-use regulations or by adherence to conservation criteria in the management of these areas. AC manage resources (e.g., water, forest) with regard to uncertainty of their provision (Ahn et al. 2024; Rendla 2024), so a risk of losing AC, as experienced in periods of suppressive administrations is not justified. Moreover, AC should be included into the decision-making process on groundwater ES as both, theory (Ostrom 2012; Ahn et al. 2024; Meinzen-Dick and Bruns 2024) and domestic knowledge on large-scale natural disturbances, reinforce the role of local inhabitants and their organization into AC (Bogataj and Krč 2023; Ravbar et al. 2023).

It is on this basis that we argue that not only groundwater ES, but also the common lands management approach deserves recognition, protection and support, aligned with international nature conservation accents (Secretariat of the … 2011; Bassi 2022; Manzoni 2024). It is imperative to prioritise the AC land management in both, in the Alpine group with higher potential of flash floods, and in the Sub-Mediterranean group due to the expected increase of droughts (Sušnik et al. 2025) and the overlapping of 78% common lands with designated water protection zones.

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ASSESSING THE CONTRIBUTION OF COMMUNAL LANDS TO ECOSYSTEM SERVICES: A QUANTIFICATION OF CARBON SEQUESTRATION IN A CASE STUDY FROM PORTUGAL

Pedro Gomes, Daniela Ribeiro, Domingos Lopes

PEDRO GOMES

Communal land of Paradança, Ponte de Olo and Carrazedo, Municipality of Mondim de Basto.

DOI: https://doi.org/10.3986/AGS.14339
UDC: 332.24.012.34(469)
502.131.1(469)
546.26:504.5(469)

Pedro Gomes[1], Daniela Ribeiro[2], Domingos Lopes[3]

Assessing the contribution of communal lands to ecosystem services: A quantification of carbon sequestration in a case study from Portugal

ABSTRACT: The sustainable management of communal lands in Portugal faces significant challenges, due to the decline of traditional agricultural and pastoral activities, low economic returns and increasing risk of large fires. The aim of this study was to assess the perceived contribution of Portuguese communal lands to ecosystem services and investigate their potential for carbon sequestration. We selected a case study and identified the main ecosystem services provided by these areas by surveying local stakeholders. We also quantified carbon sequestration, using MODIS satellite images. We concluded that many community members do not fully recognise the contributions of communal lands in providing ecosystem services. Nevertheless, their carbon sequestration capacity in 2023 was estimated at a total of 92,351 tons.

KEYWORDS: baldio, commons, ecosystem services, carbon sequestration, forest, carbon market, satellite images

Ocena prispevka skupnih zemljišč k ekosistemskim storitvam: kvantifikacija sekvestracije ogljika na podlagi študije primera s Portugalske

POVZETEK: Pri trajnostnem upravljanju skupnih zemljišč se na Portugalskem spopadajo z velikimi izzivi zaradi upada tradicionalnih kmetijskih in pašnih dejavnosti, nizkih gospodarskih donosov in vse večje nevarnosti velikih požarov. Namen članka je bil oceniti zaznani prispevek portugalskih skupnih zemljišč k zagotavljanju ekosistemskih storitev in proučiti njihov potencial za sekvestracijo ogljika. V okviru izbrane študije primera so bile z anketiranjem lokalnih deležnikov opredeljene glavne ekosistemske storitve, ki jih ta območja zagotavljajo. Poleg tega je bila z uporabo satelitskih posnetkov MODIS kvantificirana sekvestracija ogljika. Izsledki so pokazali, da številni člani lokalne skupnosti prispevka skupnih zemljišč k zagotavljanju ekosistemskih storitev ne prepoznavajo v celoti. Kljub temu je bila njihova zmogljivost za sekvestracijo ogljika v letu 2023 ocenjena na skupno 92.351 ton.

KLJUČNE BESEDE: baldio, skupna zemljišča, ekosistemske storitve, sekvestracija ogljika, gozd, trg z ogljikom, satelitski posnetki

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1 Introduction

Baldio is the name given to Portuguese communal land property, a remnant of an ancient governance model in rural mountain regions. Today, they cover almost 550,000 ha spread over 1,100 rural communities and account for 13.8% of the country's forests (Skulska et al. 2019; Gomes 2023).

Although they have never been recognised as having great productive value, the *baldios* have always been a reservoir of countless resources that complemented the way of life of rural communities and the support of a traditional agricultural system (Baptista 2014; Lopes et al. 2015; Luz 2017; Skulska et al. 2019; Gomes 2023). These areas provided most of the water, without which agriculture would not be viable, and the necessary energy for the mills; or extensive pastures that fed hundreds of herds spread across the mountains; tons of wood or biomass to produce coal for fireplaces, wood stoves, railways, for the manufacture of tools and utensils, for construction, as fertiliser, as bedding for livestock or as food, among many others (Baptista 2014; Gomes 2023).

1.1 Challenges of managing communal land in a modern economic context and the potential of ecosystem services (ES) to promote sustainable land use

In contemporary society, communal lands are often undervalued, considered obsolete, or difficult to manage in a market economy. However, these lands hold substantial value, not only because of their cultural heritage and governance model, but also as well-preserved reservoirs of forests and natural resources that support traditional agricultural and pastoral systems and rural livelihoods (Gomes 2023).

The success or failure of communal institutions can have a significant impact on the social and economic viability of rural communities. Furthermore, it influences the capacity of mountain landscapes to provide ES to the wider society, including habitat maintenance, climate regulation and regulation of natural hazards such as wildfires (Baptista 2014; Lopes et al. 2015; Haller et al. 2021; Serra et al. 2022; Nogueira et al. 2023).

Although research on the relationship between communal land management and the provision of ES has largely been theoretical, there remain significant opportunities to integrate insights from both fields and address their respective limitations (Tucker et al. 2023).

The recent catastrophic forest fires in Portugal emphasise the importance of effective forest management, which is often hampered by the low economic returns of landowners (Couto Ferreira 2017). The sustainable management of communal land in Portugal faces significant challenges, mainly due to the decline in traditional agricultural and pastoral activities, resulting in limited economic opportunities, and the increasing risk of large fires (Skulska et al. 2019; Gomes 2023).

The benefits of sustainably managing communal land and preserving their natural ecosystems extend far beyond the rural community. The quality of water, soil, biodiversity, carbon sequestration, nature-based tourism, food, culture and traditions are just some of the many benefits to society. ES offer a fair and promising opportunity to increase the value and sustainability of communal lands and their communities through the integration of economic incentives.

1.2 Carbon sequestration as an important ES in communal lands

Although carbon sequestration is widely studied across Europe (e.g., Grimston et al. 2001; Sil et al. 2017; Cunha et al. 2021; Kilpeläinen and Peltola 2022), its importance in the context of communal lands is still under-researched.

Following the example of other countries, Portugal set up a voluntary carbon market in 2024 as established in Decree-Law 4/2024 of 5 January, which covers both greenhouse gas emission reduction projects and carbon sequestration projects developed on national territory. Several studies have highlighted the opportunities and limitations of including smallholders and community-managed lands in voluntary carbon schemes (e.g., Brown and Corbera 2003; Unruh 2008; Rennaud et al. 2013). This system offers forest producers and communal land communities the opportunity to receive financial compensation for enhancing their forests through reforestation, conservation and the adoption of sustainable practices by receiving carbon credits now or in the future (Raina et al. 2024).

Forests are one of the most important ecosystems that are not only able to remove atmospheric CO_2 but also to store it in their trunks, branches, leaves or roots over a long period of time (carbon sequestration) (Li et al. 2020; Delma et al. 2024).

Annual net primary production (NPP) represents the net amount of carbon taken up by plants each year through photosynthesis, after accounting for losses through respiration (Melillo et al. 1993; Cao and Woodward 1998), and is considered one of the most important variables for ecosystem inventory and management, as it quantifies their growth and reflects the effects of biotic and abiotic factors that may affect them (Field et al. 1995; Lopes 2005).

In order to be commercialised, carbon must be quantified and monitored. This can be done with conventional approaches based on taking direct measurements in the field and using a series of algorithms that use the dry weight of biomass to calculate the carbon present, or with more innovative models that use climatic, pedological and remote sensing data that relate the reflectance of objects to climate and earth' surface variables.

Estimates of forest carbon sequestration using traditional field inventories are possible, but they are costly and require a lot of labour (Lopes 2005). Estimating vegetation productivity using remote sensing data appears as a good alternative to measure and monitor large areas over long periods of time, and several studies have demonstrated its efficiency (e.g., Sellers et al. 1992; Goetz and Prince 1996; Lopes 2005; Zhao and Running 2010; Zhang et al. 2019).

As emphasised by Skulska et al. (2019), communal forests in Portugal have a strategic importance for multifunctional land use planning and climate policy alignment. With almost 14% of Portugal's forests in community ownership, these areas have great potential to become important carbon reservoirs in Portugal, and the carbon market can play an important role in creating the economic, social and environmental sustainability that these areas need.

Within this context, this paper aims to analyse how today's rural communities and territories navigate the challenges and opportunities of communal land management, taking Portugal as an example. An important aspect of this study is to understand their role in providing key ES. Given the increasing global focus on climate change mitigation, it is crucial to assess the extent to which these lands support carbon sequestration. Therefore, the specific objectives of this study are to: 1) Assess the perceived contribution of Portuguese communal lands to ES, and 2) Quantify carbon sequestration (CICES code 2.3.6.1; Haines-Young 2023) and analyse its relationship with land use/land cover (LULC) data.

2 Methodology

2.1 Study area

This study was carried out in communal lands in the municipality of Mondim de Basto, in the northern interior of Portugal (Figure 1). This municipality covers approximately 17,209 ha and, according to the 2021 census conducted by the Statistics Portugal, had 6,410 inhabitants and a relatively low population density of 37 inhabitants per km^2. The same census data show that 79% of the population in this municipality is over 25 years old and 28% is over 65 years old. In terms of LULC, forests and natural and semi-natural environments (including open forests, shrubs and herbaceous vegetation as well as bare and sparsely vegetated areas) occupy 83% of the territory and agriculture and agroforestry 12% (REOT 2020). Another interesting fact about this municipality is that, according to the national dataset that delimits the lands under the *Regime florestal* as well as other public lands managed by the Institute for Nature Conservation and Forests (ICNF), together with the data from the Secretariat of Communal Lands of Trás-os-Montes and Alto Douro, 64% (11,131 ha) of the total territory are communal lands, spread over only fourteen communities. This clearly emphasises the importance of this type of property and was one of the main reasons for the selection of this area.

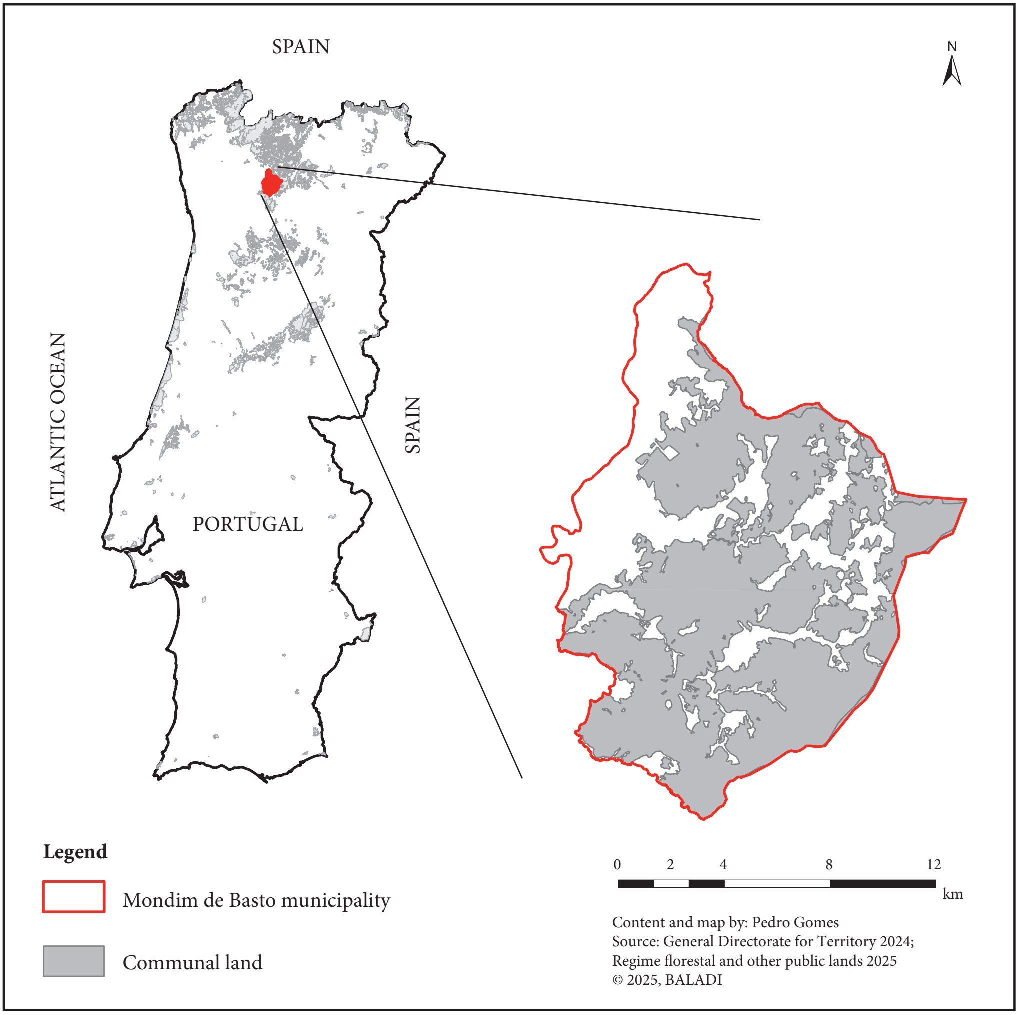

Figure 1: Map of the study area showing the location of the municipality of Mondim de Basto and the extent of communal land within its boundaries.

2.2 Data collection

2.2.1 Survey design

The data for this part of the study was collected through a questionnaire. All representatives of the 14 communal lands in the municipality were invited to take part in the study. Five of them responded and were included in the analysis. Participation was voluntary, and the final sample reflects willingness to participate rather than specific sampling criteria. A total of five people (4 men and 1 woman, with ages ranging from 38 to 74) were surveyed, each representing a communal land. The questionnaire was designed to include both multiple-choice and open-ended questions so that both quantitative and qualitative data could be collected. The questions aimed to assess respondents' perceptions of resource use, governance and challenges in managing communal lands, as well as their awareness of ES and the carbon market (Table 1). Each respondent completed the questionnaire individually and the responses were recorded and collated for later analysis.

Table 1: Questions used for the questionnaire.

Section	Question	Type of answer
1. Respondent characterisation	• Name • Age • Gender • Name of communal land • What position do you hold at communal land? • How long have you been a member of the council? • What is the approximate area of the communal land you represent?	Open-ended
2. Perception of the territory and its resources	1) Do you think that people in your community are aware of the environmental wealth and resources that the area has to offer?	Multiple choice
	2) What are the most important resources of the communal land that benefit the local community?	Open-ended
	3) Do you consider that the presence of a community area that is connected to the community is beneficial?	Multiple choice
	4) What are the main resources of the communal land that are directed outside the community (exported or used by third parties)?	Open-ended
	5) What are the main constraints on activities within the communal land?	Open-ended
	6) Do you think that these constraints have a positive or negative impact on the communal land territory?	Open-ended
	7) Do you think that these constraints have a negative impact on the profitability of the communal land or are they an economic asset?	Open-ended
	8) Who do you think are the main entities or people who influence what the community wants to do on the communal land?	Multiple choice
3. Management, benefits and challenges interritorial management	9) Do you think that the communal land or the surrounding area should be more forested or do you think the existing forest is sufficient?	Multiple choice
	10) Do you think that people who do not live in the community also benefit from the existence of the communal land and its management?	Multiple choice
	11) How has climate change already made itself felt in your area?	Open-ended
	12) In your opinion, how has the communal land been managed to mitigate the effects of climate change?	Open-ended
	13) Do you think that the communal land can help reduce the impact of climate change in the future?	Multiple choice
	14) Do you think your community should be compensated for the constraints it faces in managing its land?	Multiple choice
4. Perceptions of the carbon market involved?	15) Do you know what ecosystem services are?	Multiple choice
	16) Do you think it makes sense for the community to be compensated for providing these services?	Open-ended
	17) Are you aware of any activities or negotiations related to the carbon market or ecosystem services in which the territory is?	Multiple choice
	18) Have you ever heard of the carbon market?	Multiple choice
	19) Do you know how the carbon market can benefit the area you manage?	Multiple choice
	20) Do you think your community should participate in carbon sequestration initiatives?	Multiple choice
	21) In your opinion, is the carbon market. . .	Multiple choice

2.2.2 Remote sensing data

Moderate-resolution Imaging Spectroradiometer (MODIS) is an instrument developed by NASA for monitoring land and sea surface parameters, playing a crucial role in global change studies and the understanding of interactions between the atmosphere, oceans, land surface and biosphere. One of NASA's dedicated MODIS products is the annual net primary production dataset (MODIS NPP), which provides regular global estimates of these productivity metrics. This dataset is based on the concept of radiation use efficiency (Heinsch et al. 2003) and it is widely used for monitoring vegetation growth, forestry production, and agricultural yields, making it a valuable tool for ecological and economic decision-making.

For this study, we used MODIS NPP data (MOD17A3HGF Version 6 product) from 2023.

This dataset provides annual NPP estimates at 463 × 463 m pixel resolution (normally designated 500 m). MODIS NPP values are expressed directly in kilograms of carbon per square metre per year (kgC/m²/year) and provide a standardised measure for assessing carbon sequestration potential across different land cover types. For this study, and due to the size of the landscape, we converted the standard units to kgC/ha/year.

2.2.3 Land use/land cover data

As one of the objectives of the study was to analyse carbon sequestration at different LULCs in the study area, we used the most recent LULC data available (2018) provided by the General Directorate for Territory.

2.3 Data analysis

2.3.1 Survey data analysis

The collected survey data was analysed using a mixed methods approach. The quantitative data from the multiple-choice questions were summarised using frequency distributions to highlight important trends. Qualitative responses from open-ended questions were thematically analysed to identify recurring themes and patterns. This approach provided a comprehensive understanding of communal lands representatives' perspectives on management practices and external influences. In addition, direct extracts from respondents were included to illustrate key viewpoints and underpin thematic interpretations.

2.3.2 Quantification of carbon sequestration using remote sensing imagery

Since the objective was to estimate the carbon sequestration in 2023, it was necessary to update the LULC data from 2018 to reflect recent LULC changes. This update was conducted by cross-referencing the burnt areas from 2019 to 2023 and major afforestation projects from 2022 and 2023, where significant biomass removal had occurred. Other landscape changes, such as fuel management or small-scale tree cutting, occur but are relatively minor at the scale of the MODIS sensor. While these changes are easily visible in aerial images, they affect only small areas and were therefore not considered in this analysis. The LULC data was then reclassified into seven major classes to facilitate analysis and fourteen secondary classes (see Table 2 and Figure 3).

The MOD17A3HGF dataset was converted into vector format, enabling each pixel's NPP values to be spatially aligned with the LULC classes. A grid (463 × 463 m) was created to ensure each square corresponded precisely with a MODIS pixel. The land cover information was then cross-referenced with NPP values, allowing for a direct comparative analysis of carbon sequestration across different LULC classes. Finally, the processed data were exported to a database to establish relationships between LULC classes and carbon sequestration dynamics. As the NPP value information obtained in each pixel resulted from an area of 21.4 ha (463 × 463 m) on the site, this means that the majority of NPP values could result from areas with more than one LULC class – not pure pixels – so it was difficult to establish a direct relationship between NPP values and LULC classes. However, by crossing the two datasets, it was possible to determine average NPP values depending on the percentage of the dominant class (50%; 75%; 95%).

This approach enabled a comprehensive assessment of carbon sequestration patterns within the communal lands, considering recent LULC changes and natural disturbances.

The general methodological framework for assessing the perceived contribution of Portuguese communal lands to ES and analysing their potential for carbon sequestration is presented in Figure 2.

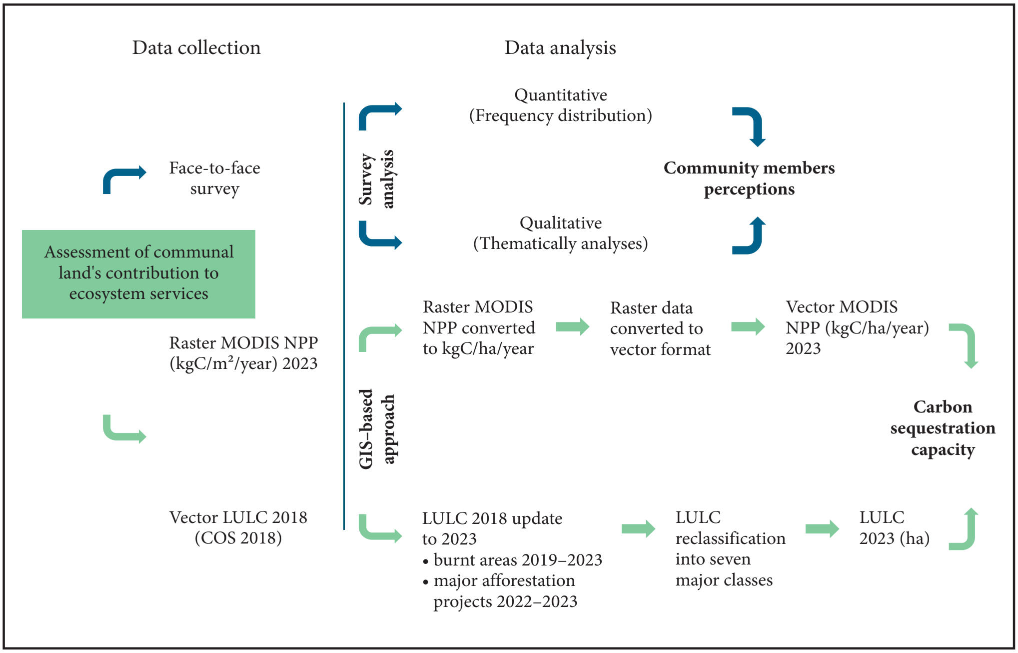

Figure 2: Methodological framework for the assessment of the contribution of Portuguese communal lands to ES.

3 Results

3.1 Questionnaires with communal land representatives: perceptions, uses and challenges of communal land management

There are conflicting views in the community about the territory and its resources. This aspect proved to be controversial among the respondents. While two of the five respondents felt that the local population is aware of the importance of community resources, three indicated a significant disconnect between the formal management of communal lands and the broader community's recognition or engagement with them. As one respondent observed »*people don't care about the communal land, they just want the president to take care of the works*« (JP 2024). This result suggests that while the use of resources is relevant, their value is not equally recognised or supported by the population.

The most important resources identified include firewood, grazing, scrubland, water and income from forest management. Firewood is the most utilised resource mentioned by all respondents. Grazing also plays an important role. Several respondents mentioned that management of the communal land facilitates access to pastures for livestock and maintains agricultural subsidies. Nature-based tourism appears as a secondary activity, mentioned by only two interviewees, with no structured impact on the local economy. In addition, income from forestry is seen as a form of financing improvements in the village and is one of the sources of income most valued by community managers.

In general, the respondents stated that the communal land is mainly used by the local community. External use was reported to limited extent, e.g., by tourists, recreational users, mushroom pickers and beekeepers. However, one respondent expressed concern about the negative impact of certain external activities, noting that »*there is no shortage of problems here with motorbikes and jeeps or people coming in groups and messing up the paths on the communal land and even on private land*« (JR 2024). Such comments indicate to emerging tensions between locals and visitors, especially when unregulated access leads to environmental damage or conflicts over land use.

Bureaucracy and unclear roles between institutions are a challenge for effective governance. The management of communal lands faces several obstacles, with the bureaucracy pose by the ICNF being the obstacle most frequently mentioned by respondents. In addition to the ICNF, respondents also mentioned other actors such as the municipal government, parish council, the state and logging companies as influential in decisions about communal lands. However, these organisations were ranked differently in importance by respondents, reflecting different perceptions of who really has influence. For example, one respondent emphasised the dominant role of the logging industry, while others highlighted the political or administrative actors.

Ecosystem services and the carbon market are poorly understood by local managers. The concept of ES is insufficiently understood by the respondents. Three of the five stated that they did not know the term and the other two had only a partial understanding.

Regarding the carbon market, all respondents said they had heard of it, but four of them said they did not understand how it worked in practice. A recurring criticism of the logic of the carbon market concerns the low value placed on old-growth forests. For example, one respondent explained that *»it makes no sense to cut down old forests to plant new ones«* (JP 2024).

The perception of climate change varies, and the link to communal land management remains vague. The respondents had different perceptions of climate change. Three of the five pointed to effects such as less precipitation, less snow and milder winters, while one respondent was sceptical and said that these fluctuations were normal. Another emphasised the increase in forest fires as the most important perceived change.

Regarding the role of communal lands in climate change mitigation, only one respondent took a structured view, suggesting that communal lands, as resource-rich areas, could provide security in times of crisis. Two others agreed that they could play an important role, but were unable to name specific measures.

Community compensation is considered necessary, but over-subsidisation can reduce commitment. Respondents agreed that the community should be compensated for the labour and costs associated with maintaining the communal land. However, one respondent warned that over-reliance on subsidies could lead to a passive attitude on the part of the population that reduces community engagement.

3.2 LULC and carbon sequestration estimation using MODIS NPP image

Updating the LULC map from 2018 (Figure 3) made it possible to determine which classes are currently most representative on the communal lands of this municipality. According to Table 2, about 57% of the

Table 2: LULC distribution on the studied communal lands.

LULC classes				Area occupied		
	Major Class		Secondary Classes	Area (ha)	Share (%)	
1	Artifical areas	1	Artificial areas	200	2	2
2	Agriculture	2	Agriculture	65	1	1
3	Grassland	3	Grassland	21	0	0
4	Bare soil/sparse vegetation	4	Bare soil/sparse vegetation	317	3	3
5	Forest	5.1	Eucalyptus	74	1	57
		5.2	Other broadleaved	505	5	
		5.3	*Pinus pinaster*	5,605	50	
		5.4	Other coniferous	117	1	
6	Shrub	6	Shrub	2,645	24	24
7	Burnt area	7.1	Burnt area 2019	43	0	14
		7.2	Burnt area 2020	304	3	
		7.3	Burnt area 2021	413	4	
		7.4	Burnt area 2022	747	7	
		7.5	Burnt area 2023	76	1	
				11,131	100	

entire communal land was forest. Of these, 50% were *Pinus pinaster* species, 5% other deciduous species and the rest eucalyptus or other coniferous species. Shrubs were also very representative with 24% of the LULC. Surprisingly, between 2019 and 2023, 14% of the communal lands burned at least once, showing very clearly the increasing risk of large fires in these ecosystems.

After processing the MODIS satellite images, it was possible to create the NPP maps, which were categorised into 7 classes for carbon sequestration to make the data easier to read (see Figure 4). The analysis of the data showed us that the minimum value of the NPP was 4,863 kgC/ha/year, which corresponds to some areas of the class »Burnt areas 2022«, and the maximum value was 11,171 kgC/ha/year, which corresponds to some areas with »*Pinus pinaster*« or »other deciduous trees«. On average, the communal lands had 8,595 kg/ha/year of carbon sequestration in 2023. Overall, the carbon sequestration capacity for communal lands in the municipality of Mondim de Basto could be estimated at a total of 92,351 tons in 2023. This corresponds comparatively to 63% of the total carbon sequestered in the municipality of Mondim de Basto in that year.

If we analyse the NPP production and focus only on communal lands, we can see that almost 40% of the area has yields between 7,500 and 8,500 kgC/ha/year. Similarly, almost 65% of the area has carbon sequestration between 7,500 and 9,500 kgC/ha/year (Figure 5).

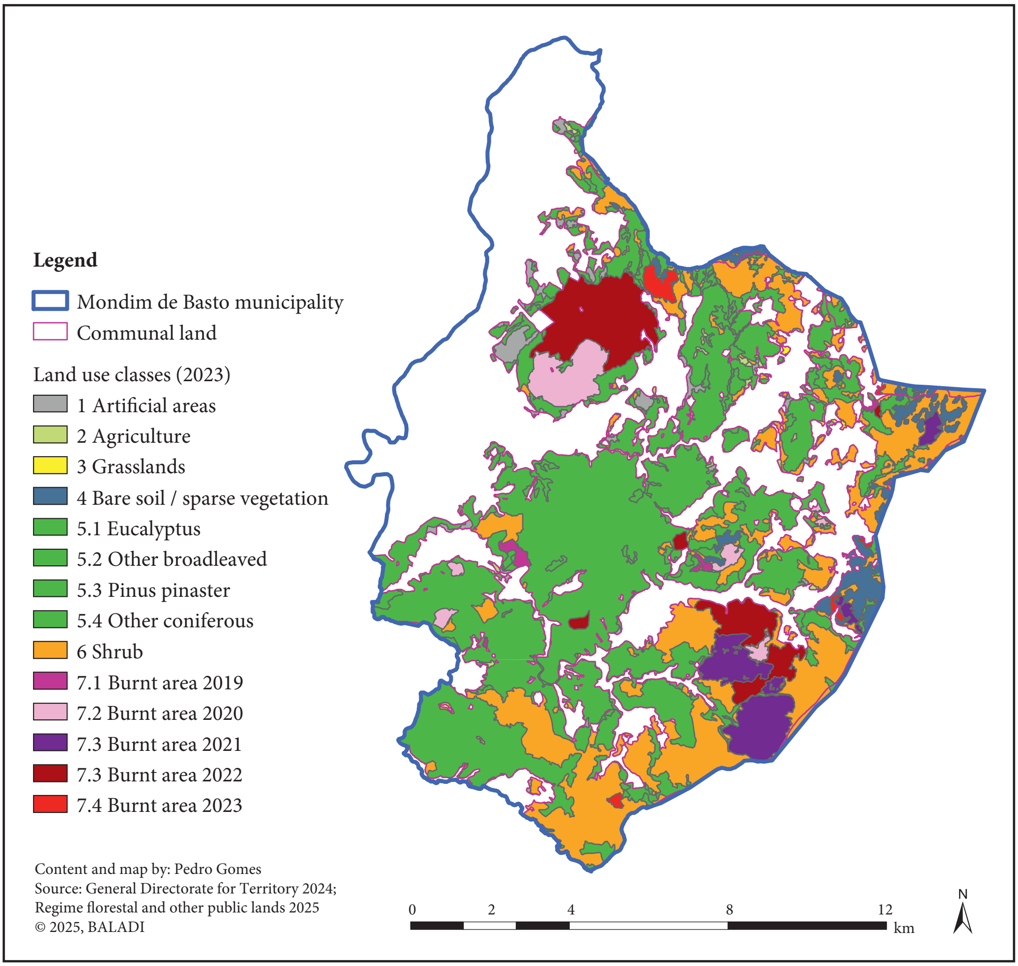

Figure 3: LULC classes on the studied communal lands in 2023.

Considering that Portugal's rural landscape is highly fragmented, both in terms of land ownership and in terms of land use, land use is rarely completely homogeneous.

To address the issue of mixed pixels, i.e., pixels containing multiple LULC classes, and to better understand the contribution of each LULC class to NPP values, the data were analysed based on whether a given LULC class occupied more than 50%, 75%, or 95% of a MODIS pixel. The results are presented in Figures 6 to 8.

As expected, the number of LULC classes decreases as we focus on purer pixels (>95%; Figure 8). Similarly, the total area associated with each NPP class also decreases. This does not imply that the calculated NPP values are incorrect but rather that, in pixels where LULC classes cover only 50% or 75% of the area, NPP or carbon sequestration values reflect contributions from multiple LULC classes rather than a single class.

Figure 6 shows that the criterion of achieving 50% pixel purity leads to the existence of 11 LULC classes, with *Pinus pinaster* and shrubland proving to be the most representative classes. The NPP values given in each class seem to correspond to the amount of vegetation present, but also to its growth in that year, with artificial areas or areas burnt in the previous year (2022) showing the lowest values. Burnt areas from 2019 show the highest NPP values, perhaps due to the maximum response recovery of vegetation after the fire in those years (3–4 years post fire). Other conifers showed an unexpectedly low NPP value.

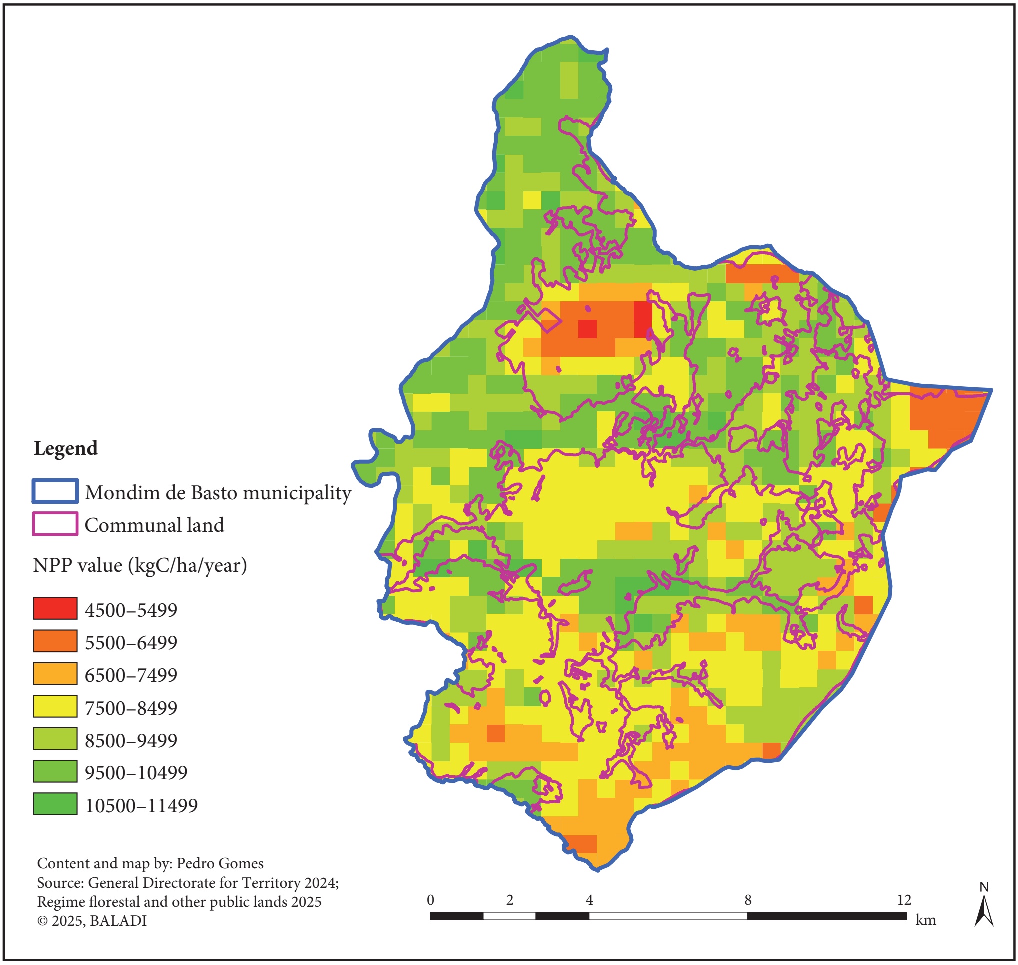

Figure 4: NPP in Mondim de Basto municipality by class (kgC/ha/year).

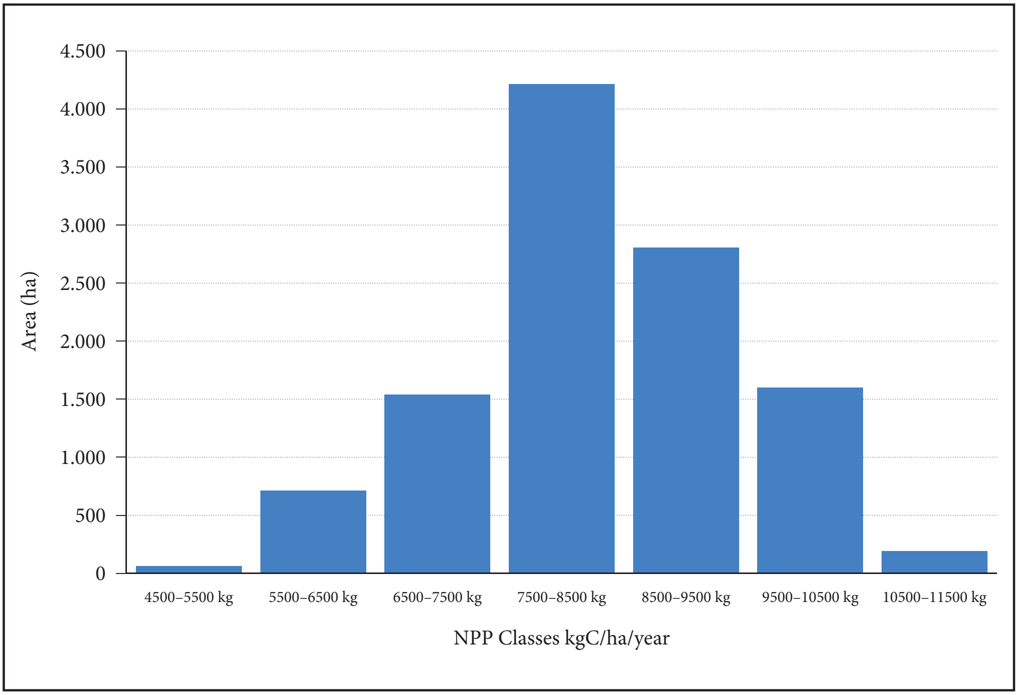

Figure 5: Distribution of the total area by NPP class in communal lands in 2023.

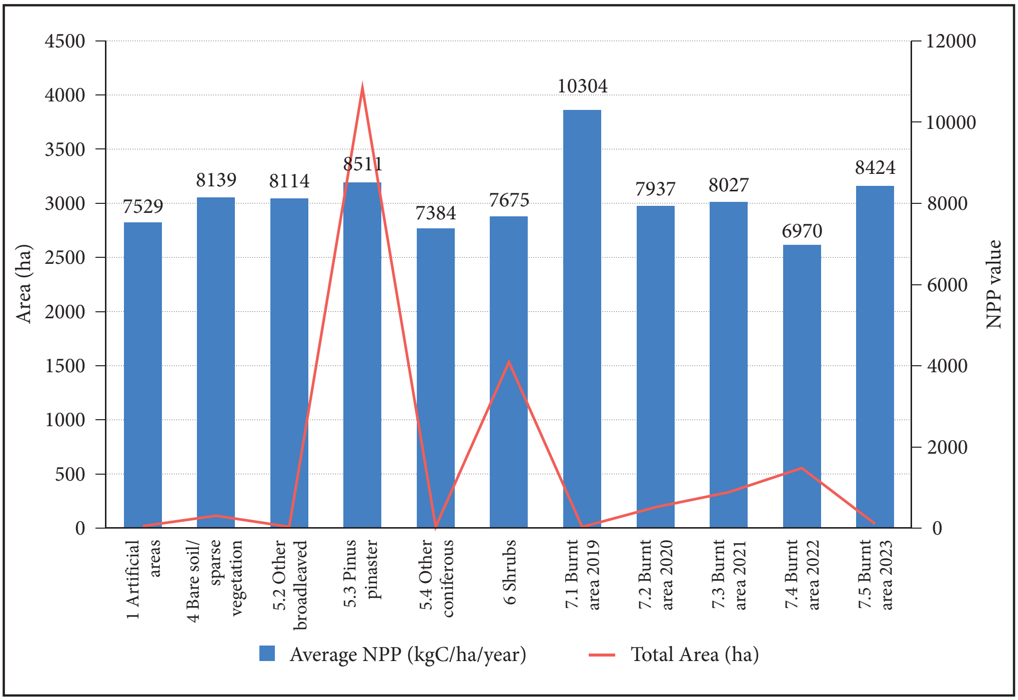

Figure 6: NPP values for LULC classes occupying more than 50% of the pixel area.

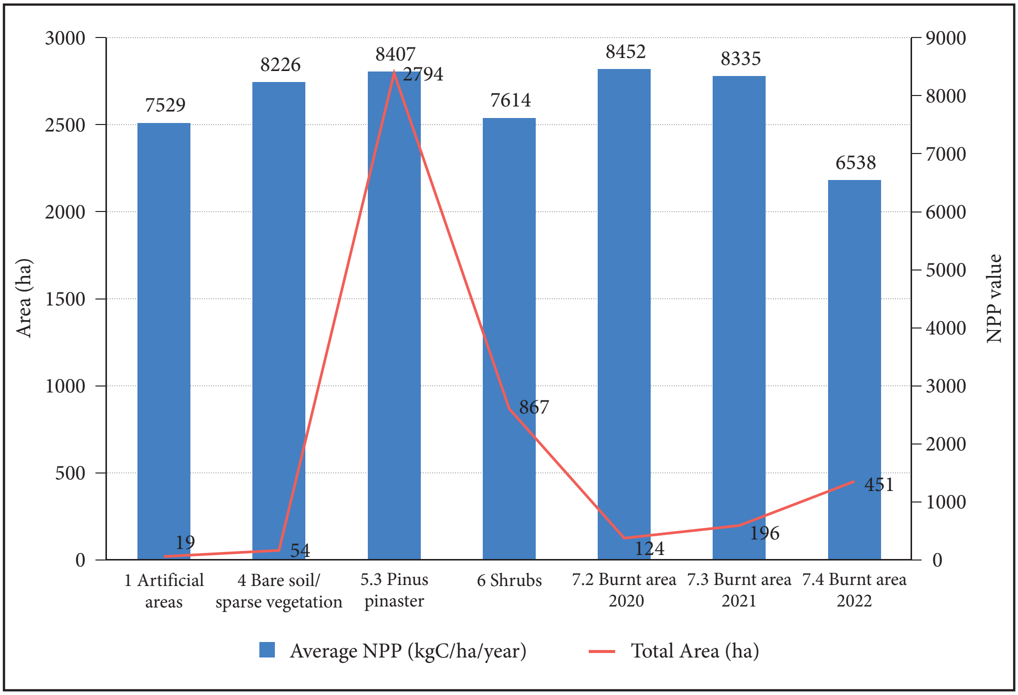

Figure 7: NPP values for LULC classes occupying more than 75% of the pixel area.

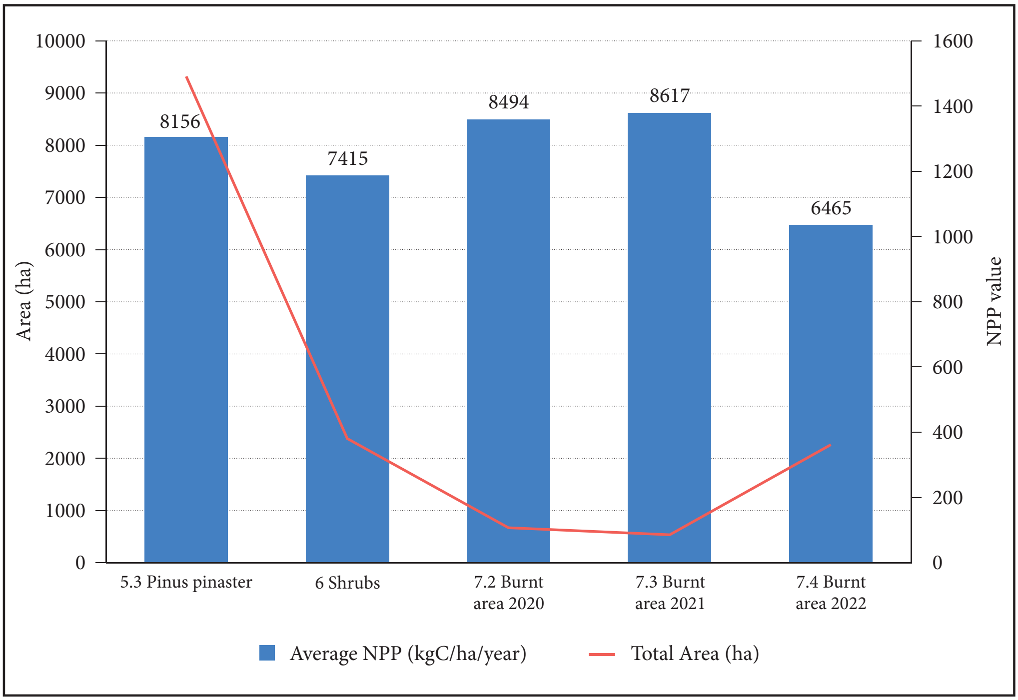

Figure 8: NPP values for LULC classes occupying more than 95% of the pixel area.

Table 3: NPP average in 2023, based on the percentage of LULC class pixels on studied communal lands. »ND« indicates absence of available data.

LULC classes – Communal Land				Area occupied (ha)	Average NPP (kgC/ha/year)		
	Major Class		Secondary Classes		>50%	>75%	>95%
1	Artifical areas	1	Artificial areas	200	7,529	7,529	ND
2	Agriculture	2	Agriculture	65	ND	ND	ND
3	Grassland	3	Grassland	21	ND	ND	ND
4	Bare soil/sparse vegetation	4	Bare soil/sparse vegetation	317	8,139	8,226	ND
5	Forest	5.1	Eucalyptus	74	ND	ND	ND
		5.2	Other broadleaved	505	8,114	ND	ND
		5.3	*Pinus pinaster*	5,605	8,511	8,407	8,156
		5.4	Other coniferous	117	7,384	ND	ND
6	Shrub	6	Shrub	2,645	7,675	7,614	7,415
7	Burnt area	7.1	Burnt area 2019	43	10,304	ND	ND
		7.2	Burnt area 2020	304	7,937	8,452	8,494
		7.3	Burnt area 2021	413	8,027	8,335	8,617
		7.4	Burnt area 2022	747	6,970	6,538	6,465
		7.5	Burnt area 2023	76	8,424	ND	ND

In Figure 7 we see that we have gone from 11 to 7 LULC classes when it is required that at least 75% of the class occupies the pixel area. This requirement further emphasises the representativeness of the *Pinus pinaster* class. It is important to note that even in artificial areas, where human interventions are more intensive and lower carbon sequestration was expected, the actual sequestration capacity is surprisingly high (7,529 kgC/ha/year). Burnt areas in 2022 show the lowest and consistent NPP value.

In Figure 8, only pure pixels were considered, i.e. situations in which the predominant LULC accounts for more than 95% area of the MODIS image pixel. The LULC classes present in the communal land area include burnt areas; shrubland areas and *Pinus pinaster* forests. The burnt areas in 2022 are the class with the lowest NPP value (6,465 kgC/ha/year), in contrast to the more dynamic classes where the vegetation grows very quickly, whether in response to the fire (burnt areas in 2020 and 2021) or even through very well adapted Pinus forest species.

The table 3 presents LULC classes in communal land, their corresponding area, and the average NPP in kgC/ha/year for different purity thresholds. Several classes have missing data (ND), indicating that no pure pixels were available at those thresholds.

Surprisingly, artificial areas show a relatively high NPP (7,529 kgC/ha/year), which is probably due to the vegetation in built-up areas. The lack of NPP data for agriculture and grassland could be due to these areas not meeting the pixel purity thresholds. Bare soil and sparse vegetation show unexpectedly high NPP values (8,139–8,226 kgC/ha/year), possibly due to mixed pixels with vegetation. Among forest types, *Pinus pinaster* stands have the highest NPP (8,511 kgC/ha/year at >50% purity), followed by other deciduous forests (8,114 kgC/ha/year at >50%) and other coniferous forests (7,384 kgC/ha/year at >50%), indicating species-specific differences in productivity. Shrublands keep NPP constant (~7,600 kgC/ha/year), with a slight decrease at higher purity levels.

Burnt areas from 2019 show the highest NPP (10,304 kgC/ha/year at >50%), while those from 2021 and 2023 also show high productivity (~8,000–8,600 kgC/ha/year), indicating post-fire recovery. In contrast, the burnt area from 2022 has the lowest NPP, possibly reflecting the early stages of regeneration.

4 Discussion

4.1 Role of communal lands in enhancing ES and rural communities

Although the role of communal lands in providing ES remains under-researched in the academic literature, a growing number of studies from different regions such as Portugal (Nogueira et al. 2023), Slovenia (Šmid Hribar et al. 2025), Ethiopia (Mekuria et al. 2013), and Guatemala (vonHedemann 2023) point to its significant ecological and social contributions.

The results of the survey with representatives of communal lands show that communal lands continue to play an important role in the life of local communities. Although they no longer carry the same weight in supporting agriculture, they are still farmed or grazed to some extent, and they still provide basic resources and generate some income for the local labour force. This study has shown that many community members do not fully recognise the contributions of communal lands or their role in providing vital ES, especially beyond the local level, as observed in the case of the Slovenian commons (Šmid Hribar et al. 2023). This limited recognition reflects a broader disconnection between the local populations and the management of communal lands.

Challenges identified include excessive bureaucracy on the part of government institutions, lack of support and difficulties in understanding new economic mechanisms such as the carbon market. To improve governance and increase community involvement, concerted efforts are needed to disseminate information, train local managers and give them more decision-making power in the use and utilisation of communal land's resources.

4.2 Carbon sequestration across different LULC classes

The capacity for carbon sequestration varies significantly across LULC classes, reflecting differences in vegetation structure, biomass accumulation, and ecological dynamics. The findings indicate that Pinus forests, shrublands, and post-fire landscapes all contribute to carbon sequestration, albeit with varying levels of efficiency and long-term retention.

Pinus forests demonstrate the highest carbon sequestration rates among the studied LULC classes, with an average NPP of 8,156 kg C ha^{-1} $year^{-1}$. These values align with estimates from previous studies (Lopes et al. 2009; Mendes 2011), which report NPP values ranging between 5,500 and 14,900 kg C ha^{-1} $year^{-1}$ for the same forest type. The long retention time of carbon in tree biomass and soils makes pine forests key carbon sinks in the landscape.

Shrublands exhibit a significant carbon sequestration capacity, averaging 7,415 kg C ha^{-1} $year^{-1}$. Shrublands provide ES beyond carbon storage, such as habitat maintenance, and regulation of natural hazards such as soil erosion, and contributes to land-use diversification (Calvo et al. 2012). However, carbon retention in shrublands tends to be shorter-term than in forested ecosystems (Kodero et al. 2024).

Burnt areas exhibit an evolving sequestration capacity, similar to shrublands, but increasing over time as vegetation regenerates. Post-fire landscapes demonstrate a progressive recovery on carbon sequestration dynamics.

Although the burnt areas are initially affected by carbon losses and lower carbon sequestration capacity, they can transform into secondary forests or shrublands that gradually regain their sequestration potential (Pausas and Keeley 2019). Long-term monitoring of these ecosystems is essential to understanding their contribution to carbon dynamics and climate change mitigation.

While carbon sequestration in agricultural and artificial landscapes is often overlooked, these areas still contribute to overall carbon cycling. Agricultural fields near villages, renaturalized quarries, and green spaces within settlements maintain photosynthetic activity, reinforcing the notion that nature is present even in human-modified environments of rural areas. Although their sequestration potential may be lower than forests or shrublands.

The findings reinforce the need for diversified land management approaches that integrate forest conservation, shrubland valorisation, post-fire recovery strategies, and sustainable agricultural practices to maximize carbon sequestration while ensuring landscape resilience and socio-economic viability.

4.3 Carbon markets and sustainable land management: A solution or a risk for communal lands?

The implementation of market mechanisms, such as carbon trading, has been promoted as a tool to mitigate greenhouse gas emissions and encourage sustainable land-use practices. However, it is essential to understand that this market should not be seen as a stand-alone solution but rather as one more instrument serving environmental management (e.g., van den Bergh et al. 2021). It must be integrated into existing planning frameworks and applied in specific situations, avoiding large-scale afforestation initiatives without a clear understanding of their ecological and social impacts.

Despite the potential of the carbon market, there are several challenges and limitations associated with its implementation. One of the main issues lies in the market's logic, which often prioritizes emission offsetting without ensuring improved forest management practices (Macintosh et al. 2024). In many regions in Portugal, there is no need for additional forest cover but rather for better management of existing forests, making them more resilient to climate change and more effective in carbon sequestration.

Furthermore, our findings highlight a critical gap in the understanding of carbon market mechanisms in local communities. Despite increasing interest and suggestions for participation, many community members lack clarity about the structure, benefits and potential risks of carbon trading. This aligns with the findings of Matekele et al. (2024), who showed that knowledge about carbon trading has a positive and significant impact on the willingness of local communities to adopt such schemes. These findings emphasise the importance of institutional support, capacity building and tailored communication strategies to ensure that emerging carbon market initiatives are both equitable and effective.

This is particularly important in the context of communal lands, which often serve as the primary setting for these initiatives. Their governance structures and land use traditions need to be taken into account when developing climate strategies and supporting policies.

Similar forms of communal land tenure exist in other southern European countries such as Spain and Italy, where they include significant forested areas and play an important role in rural livelihoods and landscape management (Bravo and De Moor 2008; Marey-Pérez et al. 2014. These areas make up a significant part of Portugal's forests and as such have considerable potential to contribute to climate change mitigation. Recognising their shared governance structures and multifunctional role can help to develop more inclusive and effective climate policies across the region.

5 Conclusion

Portuguese communal lands differ greatly in their socio-economic and biophysical characteristics, as well as in objectives and capacities of their management. Given the local focus of this mixed-methods study and the limited number of survey responses, generalisations should be made with caution.

There is still work to be done to improve community participation in communal land management. Although these areas are important resources for the local population, awareness and active participation in their management is still limited. Local people's knowledge of ES and the carbon market is generally still low. Addressing this issue is crucial to unlock the full potential of these territories and secure their long-term value. Most community members have only a superficial or no understanding of these concepts, which limits their ability to participate in initiatives that provide financial incentives for sustainable land management. Furthermore, scepticism persists, particularly in relation to the undervaluation of old forests. This reflects the widespread perception that what is needed is not more afforestation but support for better management of existing forests.

The role of communal lands in carbon sequestration is clear, as the results of this study show. As an example, we have quantified the carbon sequestration on communal lands in the municipality of Mondim de Basto, which emphasises its importance not only for local livelihoods but also for climate change mitigation. The carbon market offers both opportunities and challenges: it can provide financial resources for sustainable forest management, help restore ecological and economic functions and increase resilience to forest fires. For this potential to be realised, its mechanisms must be accessible and transparent, and integrated into existing local governance structures.

To achieve sustainable management of communal lands, several structural challenges need to be overcome. Excessive bureaucracy and limited institutional support remain important obstacles. Addressing these issues by improving information dissemination, building local capacity and empowering communities is crucial to ensure that communal lands continue to fulfil both environmental and socio-economic functions in the long term.

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THE CONTRIBUTION OF COMMON LANDS TO CARBON SEQUESTRATION: A CASE STUDY FROM TRIGLAV NATIONAL PARK IN SLOVENIA

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The Triglav National Park is dominated by forests and high mountains. In the foreground are the mountain pastures of Uskovnica, which are managed by the Agrarian Community Srednja Vas.

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The contribution of common lands to carbon sequestration: A case study from Triglav National Park in Slovenia

ABSTRACT: In this article, we explore the role of the Slovenian common lands managed by agrarian communities in providing ecosystem services. The study focuses on the Triglav National Park area with a fairly high proportion of common lands. We assessed the ecosystem service carbon sequestration, using MODIS Net Primary Production as a proxy, downscaled to a spatial resolution of 10 m. Despite the moderate overall carbon sequestration capacity of common lands, their forests and scrublands, which cover 14% of Triglav National Park and are characterised by higher productivity, play an important role due to their spatial extent. However, as Slovenia's forests have experienced a decline in carbon sequestration capacity since 2014, improved management by private owners, including agrarian communities, supported by national and EU funds, is key to strengthening this vital ecosystem service.

KEYWORDS: commons, governance, ecosystem services, carbon sequestration, forest, MODIS Net Primary Production, Slovenia

Prispevek skupnih zemljišč k zajemu in vezavi ogljika: študija iz Triglavskega narodnega parka v Sloveniji

POVZETEK: V tem članku preučujemo vlogo slovenskih skupnih zemljišč, s katerimi upravljajo agrarne skupnosti, pri zagotavljanju ekosistemskih storitev. Študija se osredotoča na območje Triglavskega narodnega parka z dokaj visokim deležem skupnih zemljišč. Ocenili smo ekosistemsko storitev zajem in vezava ogljika, pri čemer smo kot približek uporabili MODIS neto primarno produkcijo, zmanjšano na prostorsko ločljivost 10 m. Kljub zmerni skupni zmogljivosti zajema in vezave ogljika na celotnem območju skupnih zemljišč imajo njihovi gozdovi zaradi svojega velikega obsega – pokrivajo namreč 14 % Triglavskega narodnega parka – in višje neto primarne produkcije, pomembno vlogo. Vendar je zmogljivost slovenskih gozdov z vidika zajema in vezave ogljika po letu 2014 upadla, zato je za krepitev te pomembne ekosistemske storitve ključno izboljšati upravljanje zasebnih gozdov, vključno z gozdovi agrarnih skupnosti. Pri tem je nujna podpora nacionalnih in evropskih finančnih mehanizmov.

KLJUČNE BESEDE: srenja, upravljanje, ekosistemske storitve, zajem in vezava ogljika, gozd, MODIS neto primarna produkcija, Slovenija

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1 Introduction

The European Union has set ambitious climate targets, aiming to reduce greenhouse gas emissions by 55% by 2030 and to achieve climate neutrality by 2050. Among the key strategies to meet these goals is the regulation of land use, land use change, and forestry (LULUCF; Regulation EU 2023/839). The LULUCF sector is particularly relevant, as it currently functions as a net carbon sink in the EU – absorbing more carbon than it emits. This is largely due to the capacity of vegetation, particularly forests, to absorb atmospheric carbon dioxide (CO_2) through photosynthesis. Forests provide a wide range of ecosystem services (Brockerhoff et al. 2017), of which carbon storage and sequestration has received particular attention in recent years due to its crucial role in mitigating climate change (Hu et al. 2022). Proper management of land resources is therefore essential to enhance the sector's contribution to climate mitigation. According to the current EU regulation on LULUCF from 2018, Member States are required to ensure that emissions from land use and forestry are balanced by an equivalent removal of CO_2. However, under the revised LULUCF Regulation, more ambitious targets have been set to enhance net greenhouse gas removals.

A detailed account of Slovenia's greenhouse gas emissions and removals, including key trends, is provided in Slovenia's National Inventory Document 2024 (2024). The LULUCF sector acts as a significant carbon sink, accounting for 95% of the LULUCF's total net removal. According to data from the Statistical Office forests, which covered approximately 58% of Slovenia's total area in 2023 thus play a crucial role in reducing greenhouse gas emissions. However, land use changes such as deforestation and natural disturbances, notably sleet, windstorms, and droughts since 2014, have reduced this potential. Pintar et al. (2025) showed that large-scale disturbances and subsequent sanitary felling can significantly affect regulating ecosystem services in Slovenian forests. As noted in the report, net removals from the LULUCF sector declined by 35% between 1986 and 2022 mainly due to decrease in sanitary felling and mortality rates (Slovenia's National Inventory ... 2024). While Slovenian climate policy participates in the EU Emissions Trading System, the LULUCF sector is currently not included in this mechanism. Instead, the LULUCF sector is governed by separate regulations and accounting rules within the EU (Regulation (EU) 2018/841). Rather than using market mechanisms, this requires countries to ensure that removals from forests and other land categories at least offset emissions. Additionally, according to United Nations, Slovenia supports, but has not yet implemented, the mechanisms of the Paris Agreement, which enables International Carbon Markets (Article 6.2) and Non-Market Approaches (Article 6.8). Regarding LULUCF commitments, Slovenia has set two national goals: 1) for the period 2021–2025, the objective is to ensure that emissions do not exceed removals; 2) for the period 2026–2030, Slovenia aims to achieve net removals, with a minimum of 0.14 million tonnes of CO_2 equivalent by 2030 (European Commission 2025).

According to the Slovenian Forest Service, 77% of Slovenian's forests are privately owned, 20% are state-owned, and 3% are owned by municipalities (Zavod za gozdove Slovenije 2024). The Slovenian state forest company (SiDG) is the most important forest owner in Slovenia, followed by the Ljubljana Archdiocese. However, agrarian communities are also notable forest owners. As in other Alpine regions and also other European countries, these communities predominantly manage the so-called 'forest commons', i. e. common forest lands (Bogataj and Krč 2014; Gatto and Bogataj 2015; Bogataj and Krč 2023; Nogueira et al. 2023; Pagot and Gatto 2024; Pagot et al. 2025; Šmid Hribar 2025). Bogataj and Krč (2014) demonstrated that, following the sleet storm in February 2014, agrarian communities in the Postojna regional forest district of the Slovenia Forest Service organised and harvested the damaged forests more quickly than other forest owners (with the exception of large-scale private owners).

In recent years, various primarily qualitative studies have recognised significant role of common lands in providing ecosystem services (Šmid Hribar et al. 2023; Pagot et al. 2025), as well as their importance for achieving the Sustainable Development Goals (Haller et al. 2021). Yet studies that approach this topic using quantitative assessments, such as in terms of ecosystem service provision, are lacking. One of such rare studies was presented by Pagot and Gatto (2024), who found that the attitudes of community-owned forest institutions towards providing forest recreation do not differ much from those of other private forest owners. Based on landscape analysis, Šmid Hribar (2025) revealed that common lands in Triglav National Park (TNP) make a significant contribution to biodiversity and nature conservation.

Therefore, the aim of this article is to contribute to a better understanding of the role of agrarian communities in providing ecosystem services, focusing particularly on carbon sequestration in protected areas, such as the TNP. The specific objectives of the study were 1) to assess ecosystem service carbon sequestration, which is classified under the Common International Classification of Ecosystem Services (CICES v5.2; code 2.3.6.1; Haines-Young 2023) in the TNP and 2) to determine the extent to which agrarian communities contribute to this ecosystem service.

2 Materials and methods

2.1 Study area

The research was conducted in the TNP, located in the northwestern Alpine region (Figure 1). Covering approximately 84,000 hectares, around 4% of Slovenia's territory, the TNP is divided into three protection zones, each with distinct management regimes (Table 1). The predominant land cover in the park is forest, followed by high (rocky) mountain areas (Table 3). This area was chosen primarily because common lands managed by agrarian communities make relatively high proportion – up to 24% of the park's total surface (Šmid Hribar 2025).

Despite its protection, the TNP supports various land uses, including economic, recreational, and tourism activities. Managing these uses requires careful negotiation and integration of multiple, and at times conflicting, interests. This multifunctionality underscores the need to assess and manage ecosystem services and thus ensure that conservation objectives are balanced with the sustainable use of natural and cultural resources. In this area, three ecosystem services – pollination, recreation, and fodder provision were assessed (Šmid Hribar et al. 2025). The main focus of this article is to assess carbon sequestration, which is currently perceived as one of the most essential ecosystem services for mitigating anthropogenic climate change due to greenhouse gas emmisions.

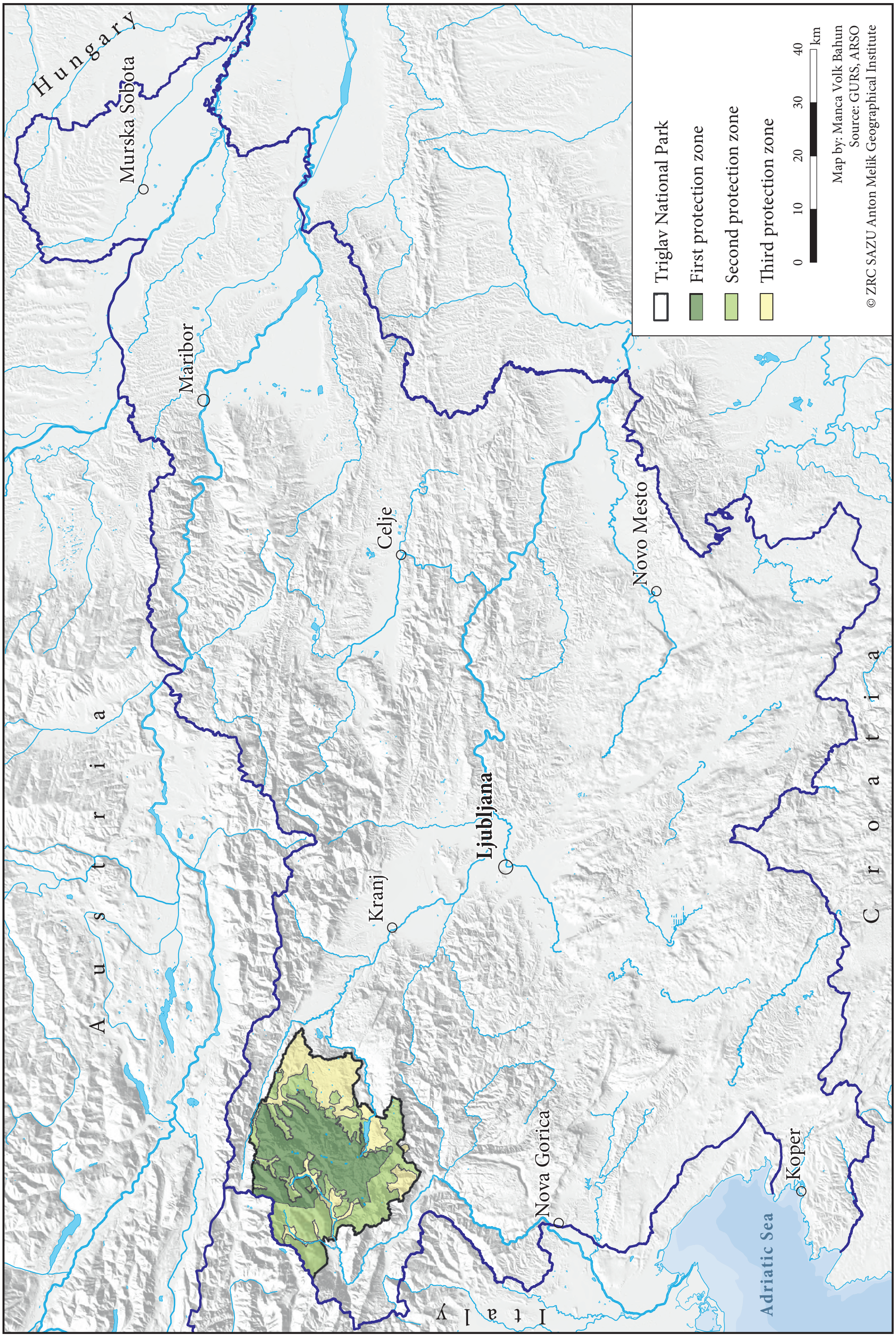
Table 1: Protection zones and their management in the TNP.

Protection zone	Management regime	Share in the TNP
First protection zone	Primarily intended for the protection and preservation of natural values, wilderness areas, species, habitats, and natural ecosystem processes without human intervention. Traditional grazing on managed mountain pastures and preservation of related cultural heritage are permitted.	37.5%
Second protection zone	It aims to preserve natural values and cultural heritage, prevent new burdens, and gradually align with the objectives of the first protection area. It also allows traditional resource use for environmentally friendly agriculture, forestry, and sustainable game and fish management.	38.6%
Third protection zone	It aims to preserve biodiversity, natural values and cultural heritage, landscape qualities, and settlements, while promoting sustainable development in line with national park objectives.	23.9%

2.2 Assessment of carbon sequestration in Triglav National Park

We assessed the carbon sequestration, which refers to the regulation of chemical composition of atmosphere and oceans, and the maintenance of continental atmospheric/oceanic circulation patterns, through the fixation and storage of carbon in plant biomass (Haines-Young 2023). Annual Net Primary Production (NPP) was used as a proxy for this service. NPP represents the net amount of carbon captured by plants through photosynthesis each year (Melillo et al. 1993; Cao and Woodward 1998), and thus expresses the carbon flux between the atmosphere and terrestrial vegetation (Goetz and Prince 1996). We acknowledge that NPP primarily captures the carbon uptake component of sequestration, and not the long-term storage in biomass and soils. It also does not explicitly consider losses of carbon due to heterotrophic respiration, decomposition or disturbances. Nevertheless, NPP provides a widely used and well-established proxy for

Figure 1: TNP, the only national park and the largest protected area in Slovenia, is located in the northwest of the country. ➤ p. 79


Triglav National Park
First protection zone
Second protection zone
Third protection zone
0 10 20 30 40 km
Map by: Manca Volk Bahun
Source: GURS, ARSO
© ZRC SAZU Anton Melik Geographical Institute
Hungary
Murska Sobota
Maribor
Celje
Novo Mesto
Ljubljana
Kranj
Nova Gorica
Koper
Austria
Italy
Croatia
Adriatic Sea

assessing ecosystems' contribution to climate regulation. We used MODIS NPP as a proxy for the carbon sequestration of each land use type, representing the ecosystem's annual contribution to global climate regulation. MODIS NPP data for the TNP were obtained through Google Earth Engine (GEE), using the MOD17A3HGF.061 product, which provides annual NPP allocated to both, above and below ground biomass at a spatial resolution of 500 m (De Leeuw et al. 2019). Annual NPP is derived from the sum of all 8-day net photosynthesis products for the year 2024 (Heinsch et al. 2003).

The coarse spatial resolution of the MODIS NPP product (500 m per pixel) limits its ability to capture the fine-scale mosaics of forest and agricultural land in the study area. To address this scale mismatch, we downscaled the MODIS NPP data to 10 m resolution, matching that of the EU Copernicus High Resolution Layers.

For the downscalling procedure, we selected a set of copredictors that are strongly linked to the vegetation productivity dynamics. To account for phenological events and dynamics, we utilized the High Resolution Vegetation Phenology and Productivity (HR-VPP) metrics provided by the Copernicus programme. The HR-VPP dataset consists of 13 raster layers at 10 m resolution, derived from Sentinel-2 image time series with a temporal resolution of five days. To produce the Plant Phenology Index (PPI) time series, the TIMESAT 4 algorithm is employed for smoothing and gap-filling (Jönsson and Eklundh 2004). Seasonal metrics are extracted by applying a sum of double logistic functions, which also delineate the phenological seasons (Jönsson et al. 2018). For a comprehensive description of the HR-VPP processing workflow, see Smets et al. (2023). From the HR-VPP collection, we selected six metrics (see Table 2 for more details), which we obtained from the WekEo data portal (https://www.wekeo.eu/).

In addition to the HR-VPP, we computed the median of three vegetation indices (Table 2) in GEE corresponding to the vegetation period June 1 – August 31, 2024, corresponding to the peak growing season. The indices were chosen for their good performance in previous studies, and their ability to distinguish relative differences in productivity, chlorophyll content, and vegetation density (Villoslada et al. 2024). The scenes used to compute the indices were obtained from the level 2A collection in GEE. We applied an atmospheric correction to obtain surface reflectance values using the Sen2Cor processor (Main-Knorn et al. 2017). We removed cloud and cloud shadow contamination by masking pixels based on cloud probability estimates from the Sentinel-2 dataset available in GEE, generated using the s2cloudless algorithm. Finally, we set the percentage of cloud cover threshold at 30%.

Once we compiled all the copredictors, we transformed the MODIS NPP scene into a vector grid, assigning each polygon the corresponding NPP value. We then calculated the median value of each copredictor within each vector cell to avoid pseudoreplication. To downscale the resolution of MODIS NPP and match

Table 2: Description of the copredictors used in this study to downscale MODIS NPP at 500 m per pixel to a spatial resolution of 10 m per pixel.

Co-predictor	Formula/Description	Reference
Season Amplitude	Corresponds to the difference between the maximum and the minimum Plant Phenology Index values reached during the growing season.	Smets et al. (2023)
Season Length	Corresponds to the number of days between the start and end of the season dates computed based on the Plant Phenology Index.	Smets et al. (2023)
Seasonal Productivity	Corresponds to the sum of daily Plant Phenology Index values during the growing season minus their base level value.	Smets et al. (2023)
Total Productivity	Corresponds to the sum of daily Plant Phenology Index values during the growing season.	Smets et al. (2023)
Maximum Season Value	The peak value reached by the Plant Phenology Index during the growing season.	Smets et al. (2023)
Start-of-Season date	Corresponds to the date when the Plant Phenology Index reaches 25% of the season amplitude during the green-up period.	Smets et al. (2023)
Normalised Difference Vegetation Index (NDVI)	(NIR – Red) / (NIR + Red)	Rouse et al. (1974)
Green Normalised Difference Vegetation Index (GNDVI)	(NIR – Green) / (NIR + Green)	Gitelson et al. (1996)
Enhanced Difference Vegetation Index (EVI2)	2.5 [(NIR – Red) / (NIR + 2.4 × Red + 1)]	Jiang et al. (2008)

it with that of the Copernicus High Resolution layers (10 m per pixel), we employed an Extreme Gradient Boost Algorithm (XGBoost). We selected the XGBoost algorithm for its effectiveness in regression tasks (Zhang et al. 2019) and its resilience to noise and class imbalance. Model development and spatial downscaling were carried out using the raster (Hijmans et al. 2015) and xgboost (Chen et al. 2019) packages in R. Hyperparameter tuning – covering learning rate, number of trees, minimum samples per leaf, maximum tree depth, number of features considered for splits, and gamma (γ) – was performed using the mlr package (Bischl et al. 2016) through 100 optimization rounds with five-fold cross-validation. To assess the importance of individual co-predictors in the XGBoost upscaling models, we used the Gain metric, which quantifies each variable's contribution to the predictive performance (Chen et al. 2019). Model training was conducted over 100 iteration rounds, using a randomly selected 20% subset of the original MODIS vector polygons to build the predictive model. This sampling strategy ensured sufficient generalization while minimizing spatial autocorrelation in the training data. All methodological steps were undertaken in R Studio 2024.09.1.

To validate the models, the XGBoost algorithm predicted a downscaled NPP map within each iteration round. Then, a different random set of MODIS NPP polygons (20% of the initial set, non-overlapping with the training set) was used to calculate the mean value of the downscaled NPP map within each MODIS polygon. In each iteration round we calculated R2, Root Mean Squared Error (RMSE), range-normalised RMSE (nRMSE), Mean Absolute Error (MAE), and bias. Finally, we calculated the mean of the validation metrics over all 100 iteration rounds. The final NPP downscaled map represents the mean of all maps produced through each model run.

Using the resulting 10 m resolution NPP data and land use data from the Ministry of Agriculture, Forestry and Food for 2024, we performed zonal statistics to calculate the average NPP for each land use type. To assess whether specific forest characteristics – such as protective forests that safeguard land from erosion, wind, flooding, and other hazards – influence carbon sequestration, we repeated the procedure using an additional dataset (Zavod za gozdove Slovenije 2024).

To facilitate the interpretation of spatial patterns, NPP values were classified using the Quantile method, which divides the dataset into intervals containing an equal number of observations. This approach ensures a uniform frequency distribution across classes, although class widths may vary depending on the underlying data distribution.

Water bodies and greenhouses were excluded from further analysis due to their marginal relevance to vegetation-based carbon dynamics and the inherent limitations of NPP models in aquatic environments.

2.3 Analysis of the role of agrarian communities in carbon sequestration in Triglav National Park

To assess the role of common lands in carbon sequestration, we analyzed mean NPP values on common land areas using Zonal Statistics in ArcGIS PRO. The shapefile of common lands in the TNP was obtained from Šmid Hribar (2025) and corrected from sliver polygons.

3 Results

3.1 Land use in Triglav National Park

The spatial analysis of land use revealed that forests dominate the TNP, covering 38,878.1 ha, which accounts for nearly half of the entire area (46.3%). They are followed by scrubland (15,908.9 ha; 18.9%), dried open areas with special vegetation (12,157.8 ha; 14.5%) and open areas with little or no vegetation (8,255.0 ha; 9.8%), mostly representing high-mountain terrain. These four land use categories together constitute 89.5% of the TNP. Among the remaining land uses, permanent grassland which include meadows and pastures (5,988.8 ha; 7.1%) stand out, as they give a significant character to the the TNP. Other land use categories are considerably smaller in extent (Table 3).

Table 3: Land uses in the TNP in 2024.

Land use	Area (ha)	Area (%)	% in protection zone 1	% in protection zone 2	% in protection zone 3
Arable land	12.51	0.0	0.0	5.0	95.0
Permanent crops on arable land	0.01	0.0	0.0	0.0	100.0
Greenhouse	0.05	0.0	0.0	0.0	100.0
Intensive orchard	1.37	0.0	0.0	5.1	94.9
Extensive orchard	50.84	0.1	0.0	1.1	98.9
Permanent grassland	5,988.84	7.1	18.8	41.7	39.6
Overgrown agricultural area	298.25	0.4	14.5	43.3	42.2
Trees and shrubs	293.23	0.3	6.1	27.8	66.1
Uncultivated agricultural land	65.83	0.1	1.6	24.2	74.1
Forest trees on agricultural land	1,004.76	1.2	41.7	44.7	13.7
Forest	38,878.10	46.3	18.5	41.7	39.8
Scrubland	15,908.88	18.9	57.7	37.2	5.0
Built-up area and related surface	479.65	0.6	2.1	14.3	83.6
Swamp	10.25	0.0	0.0	0.0	100.0
Other marshy area	0.38	0.0	0.0	100.0	0.0
Dried open area with special vegetation	12,157.83	14.5	59.6	38.4	2.0
Open area with little or no vegetation	8,255.01	9.8	75.5	24.0	0.5
Water	578.56	0.7	5.4	67.0	27.5
Total	83,984.35	100.0			

3.2. Carbon sequestration in Triglav National Park

We obtained satisfactory results from the XGBoost-based downscaling from 500 to 10 m per pixel, with an average R^2 for all modelling rounds of 0.73, and a RMSE average value of 999.1 kgC/ha/year. Table 4 provides an overview of all validation metrics.

The negative bias value (–237.5) points at an overestimation of the NPP by the downscaled models. Regarding the spatial distribution of the NPP downscaled predictions, the map (Figure 3) follows the expected distribution of NPP values, with the lowest NPP values shown in the non-vegetated rocky mountain tops (mainly presented as Open area with little or no vegetation in Table 3) and gradual increase towards the forested slopes and valleys. The largest NPP values are located in the southern limit of the park following the same trend as the original 500 m MODIS NPP product.

NPP values were classified into four categories based on quantile distribution: low (<5,820 kgC/ha/year), moderate (5,820–7,410), high (7,410–8,250), and very high (>8,250), to allow comparison of productivity across sites, and can be seen in Table 5 and Figure 3.

Table 4: Prediction accuracies for the downscaled NPP using XGBoost models. Accuracies are reported using the coefficient of determination (R^2), root mean squared error (RMSE, expressed in the same units as the modeled maps), normalized root mean squared error (% RMSE over the range of original values within the training dataset), mean absolute error (MAE), and average bias (expressed in the same units as the modeled maps).

Metrics	R2	RMSE	nRMSE	MAE	Bias
	0.73	999.1	10%	727.5	–237.5

Figure 2: Distribution of land use types in the TNP. ➤ p. 83

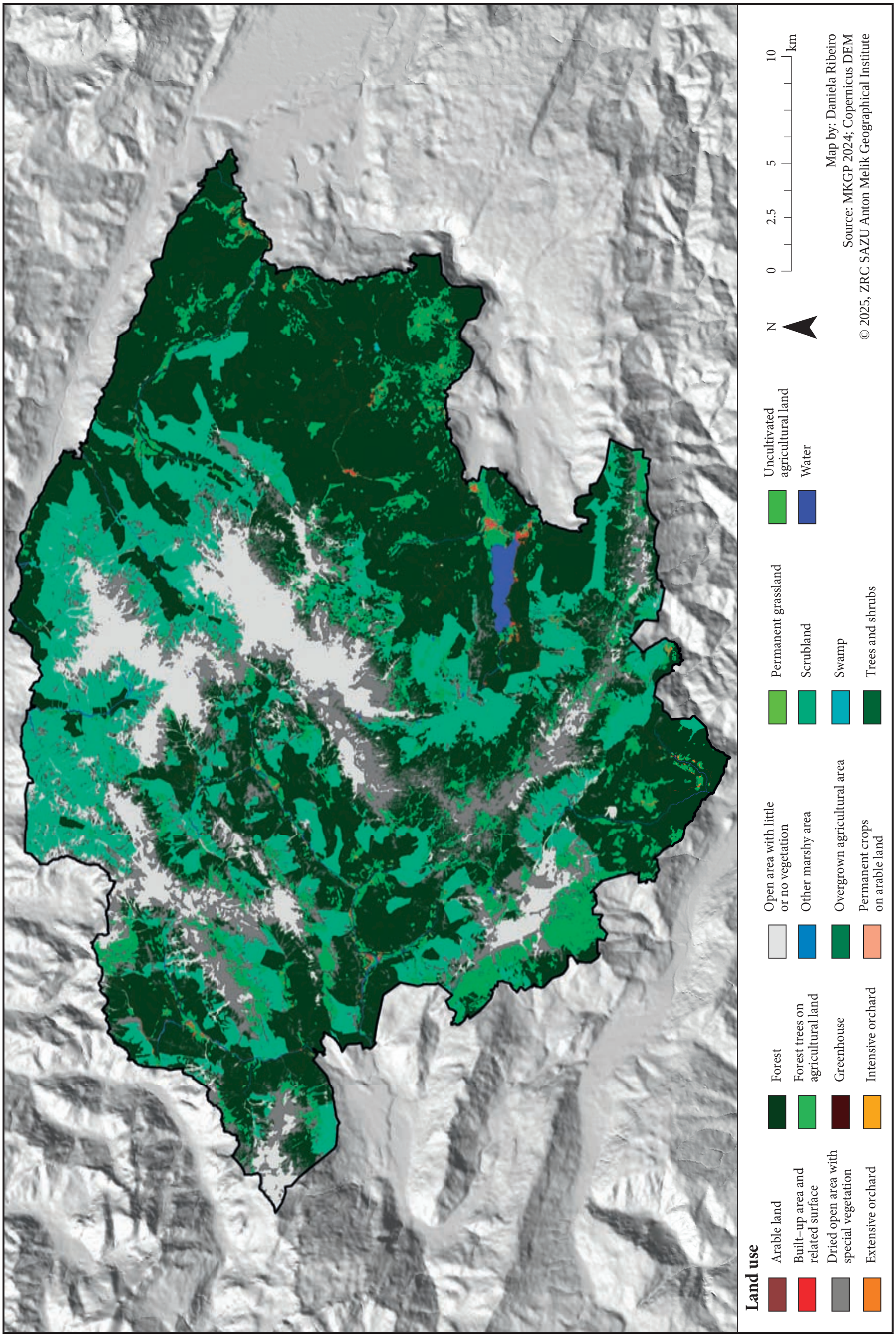

Land use
Arable land
Built-up area and related surface
Dried open area with special vegetation
Extensive orchard
Forest
Forest trees on agricultural land
Greenhouse
Intensive orchard
Open area with little or no vegetation
Other marshy area
Overgrown agricultural area
Permanent crops on arable land
Permanent grassland
Scrubland
Swamp
Trees and shrubs
Uncultivated agricultural land
Water
N
0 2.5 5 10 km
Map by: Daniela Ribeiro
Source: MKGP 2024; Copernicus DEM
© 2025, ZRC SAZU Anton Melik Geographical Institute

Table 5: Classification of mean NPP across land use types in the TNP.

Range mean NPP (kgC/ha/year)	Capacity for carbon sequestration
<5,820	Low productivity
5,820–7,410	Moderate productivity
7,410–8,250	High productivity
>8,250	Very high productivity

Table 6: Mean NPP by land use type in the TNP.

Land use type	Mean NPP (kgC/ha/year)	Capacity for carbon sequestration
Permanent crops on arable land	9,466	Very high productivity
Intensive orchard	8,193	High productivity
Extensive orchard	8,189	High productivity
Arable land	8,013	High productivity
Trees and shrubs	7,984	High productivity
Forest	7,841	High productivity
Overgrown agricultural area	7,652	High productivity
Scrubland	7,607	High productivity
Swamp	7,379	Moderate productivity
Permanent grassland	7,337	Moderate productivity
Uncultivated agricultural land	7,165	Moderate productivity
Forest trees on agricultural land	7,066	Moderate productivity
Built-up area and related surface	6,965	Moderate productivity
Other marshy area	6,673	Moderate productivity
Dried open area with special vegetation	5,398	Low productivity
Open area with little or no vegetation	3,669	Low productivity

The mean NPP – the average NPP (kgC/ha/year) for each land use type – can be seen in Table 6.

Additionally, we calculated the mean NPP for the TNP and each of its protection zones, as well as for the TNP's protective forests, to evaluate the influence of protective status on carbon sequestration capacity. In 2024, the mean NPP was 6,960 kgC/ha/year for the TNP as a whole, 6,022 kgC/ha/year for protection zone 1, 7,227 kgC/ha/year for protection zone 2, and 8,013 kgC/ha/year for protection zone 3 (Table 7). The mean NPP for protective forests was 7,571 kgC/ha/year, which is slightly lower than the mean NPP for all forested areas in the TNP (7,841 kgC/ha/year).

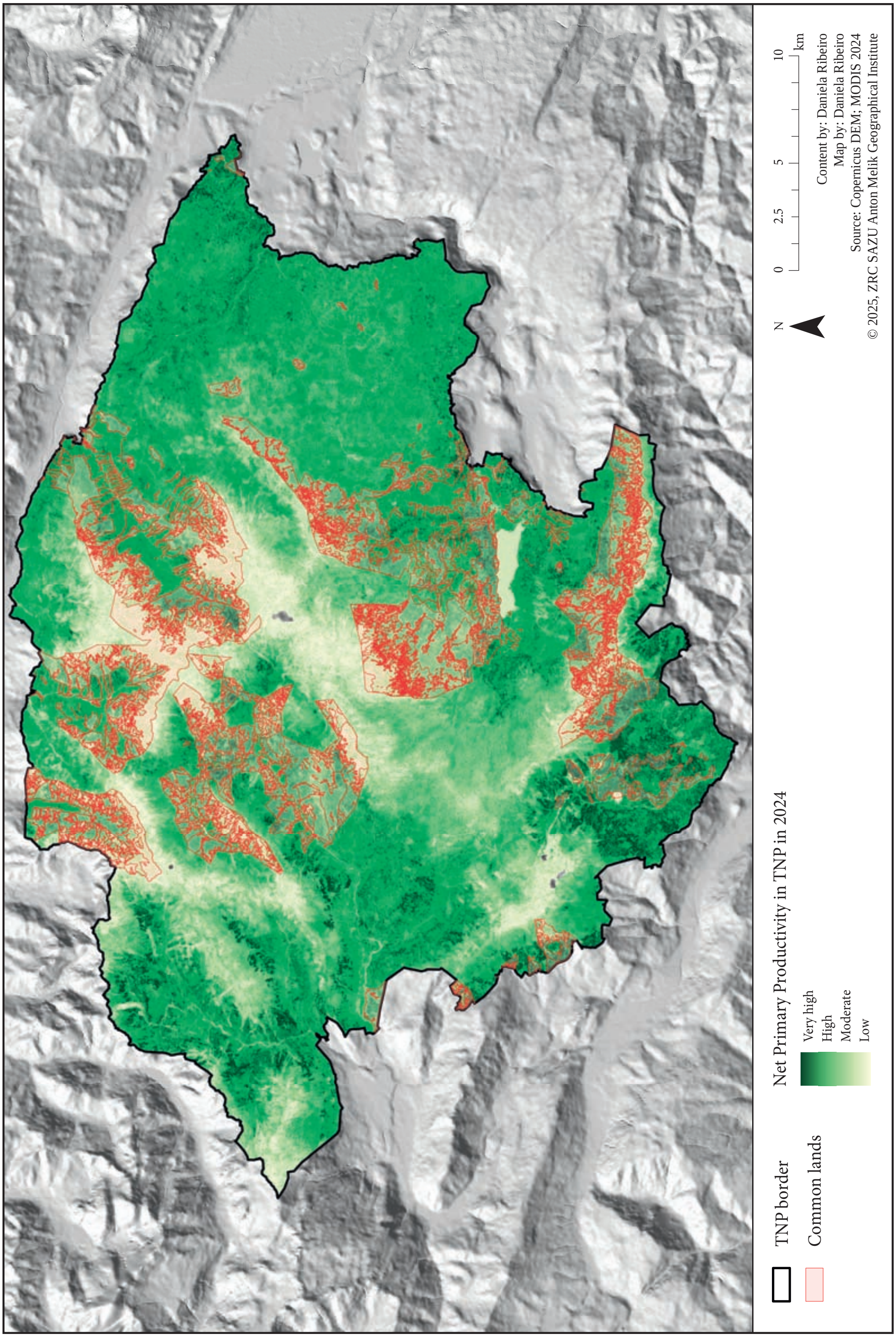
3.3 Carbon sequestration on common lands in Triglav National Park

Agrarian communities manage nearly one quarter of the TNP (19,400 ha). Forests dominate among the common land areas (31.9%), followed by high mountain areas, which include scrubland (28.7%), dried open areas with special vegetation (18.5%) and open areas with little or no vegetation (14.7%), which altogether account for 93.8% of all common land areas in the TNP. The mean NPP calculated in ArcGIS Pro for the combined area of all types of common lands in the TNP in 2024 was 6,510 kgC/ha/year, indicating a moderate capacity for carbon sequestration. However, the contribution of common lands to carbon sequestration is different in the different protection zones (Table 7).

Table 7: Contribution of common lands to carbon sequestration in the different protection zones of the TNP.

	Protection zone 1	Protection zone 2	Protection zone 3
Area of common lands (ha, %)	12,826 (66%)	5,026 (26%)	1,547 (8%)
Mean NPP in common lands (kgC/ha/year)	6,127	7,232	7,865
Mean NPP in the TNP (kgC/ha/year)	6,022	7,227	8,013

Figure 3: Distribution of NPP in the TNP. The map represents the downscaled (10 m per pixel) version of the original MODIS NPP. ➤ p. 85


Net Primary Productivity in TNP in 2024
Very high
High
Moderate
Low
TNP border
Common lands
N
0
2.5
5
10
km
Content by: Daniela Ribeiro
Map by: Daniela Ribeiro
Source: Copernicus DEM; MODIS 2024
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4 Discussion

The aim of this research was to improve understanding of the role of agrarian communities in the provision of ecosystem services through the application of quantitative and measurable methods. The study presents one of the first quantitative estimation assessments of its kind in Slovenia, and in comparable contexts elsewhere, thus contributing to the growing body of literature on common land management and the provision of ecosystem services (Pagot and Gatto 2024; Gomes et al. 2025).

4.1 Interpretation of carbon sequestration in Triglav National Park

The analysis of mean NPP across land use types and protective zones reveals differences that reflect both land management and ecological characteristics of this alpine park. Permanent crops on arable land exhibit the highest mean NPP values (9,466 kgC/ha/year), likely due to practices that enhance biomass productivity. Orchards (extensive and intensive) and arable land follow closely behind, showing that farmland contributes significantly to carbon fixation.

The observed NPP values for forested areas, including forests, and trees and shrubs in the TNP (app. 7,841–7,984 kgC/ha/year) are within the ranges reported for temperate and montane forest ecosystems in the literature. These values can vary substantially depending on species composition, elevation, stand age, and site productivity (e.g., Clark et al. 2001; Tang et al. 2010). However, this estimate represents an upper bound on potential carbon uptake in the study area. Actual net carbon sequestration in temperate forests is generally lower, according to Tölgyesi et al. (2025) between 1,240 and 2,800 kgC/ha/year. Despite covering large parts of the TNP and being inherently productive ecosystems, forests are underrepresented in MODIS-derived NPP estimates. This is likely due to a combination of fragmented polygon sizes, causing mixed-pixel effects, and terrain-related limitations (e.g., slope, shadows, and seasonal snow cover), which reduce the reliability of satellite-based productivity detection. These results highlight the importance of resolution-aware analysis and suggest that forest carbon dynamics in alpine landscapes may require higher-resolution or field-calibrated data for accurate quantification.

In particular rocky surfaces and scrublands (*Pinus mugo*) contribute the least to carbon sequestration, reflecting limited photosynthetic activity in these land cover types, which aligns with expectations. Overall, these results highlight the heterogeneity of carbon uptake across land use types in the TNP. They also underscore the role of agricultural land and forests in maintaining primary productivity, even in a mountainous protected area context. This suggests that land use mosaics, including traditionally managed agricultural systems, can complement forest ecosystems in supporting carbon sequestration goals.

Built-up areas show surprisingly high NPP, likely due to mixed-classification pixels. Although certain land use types (e.g., Permanent crops on arable land) exhibit a relatively high carbon sequestration potential per unit area, their limited spatial extent within the study area constrains their overall contribution to total carbon uptake. Conversely, more widespread land use categories (e.g., Permanent grassland), despite having lower mean NPP values, may play a more significant role in total carbon sequestration due to their broader coverage. This highlights the importance of considering both sequestration efficiency and spatial distribution when evaluating the carbon dynamics at landscape level.

In addition, the protection status impacts carbon sequestration capacity. Protection zone 1, where grazing is allowed but forest management is excluded, shows the lowest mean NPP, while protection zone 3 has the highest capacity for carbon sequestration. This difference is partly related to land use composition: as shown in Table 3, protection zone 1 is largely dominated by rocky surfaces and scrublands, whereas forest, which is the predominant land use in the TNP, is much more prevalent in protection zones 2 and 3.

Similarly, the mean NPP for protective forests (7,571 kgC/ha/year), which are predominant in Protective zones 1 and 2, was lower than the mean NPP for all forested areas within the TNP (7,841 kgC/ha/year). This result may reflect ecological and structural characteristics of protective forests in the TNP that play a key role in preventing natural disasters (such as erosion, landslides, etc.) as presented by Rozman and Arih (2015). These forests are often located on steep slopes, on marginal soils or at high elevations, where environmental conditions are less favourable for biomass production (Klopčič et al. 2015) but are crucial for their protective role (Rozman and Arih 2015). In addition, these forests in the TNP, especially if they are located in the first protection zone, are not managed (e.g., for timber production) and interventions may be limited to maintain stability and protective functions (Poljanec et al. 2015).

In any case, it is important to mention that sequestration is just one way in which forests contribute to mitigate climate change. Carbon sinks are even more important, so it is crucial to preserve existing forests that store carbon, even if they are older and have a lower capacity for carbon sequestration (Kilpeläinen and Peltola 2022).

4.2 The role of common lands

In addition to their significant contribution to biodiversity and nature protection presented by Šmid Hribar (2025), we anticipated that common lands in the TNP would also play a substantial role in carbon sequestration, especially considering that nearly a quarter (24.0%) of the TNP is managed by agrarian communities, and that forests and scrubland cover more than half (60.6%) of their common lands. However, this expectation was tempered by the fact that 33.2% of these common lands consist of rocky surfaces and scrublands all of which have significantly lower carbon sequestration capacity (see Table 6). In addition, two-thirds of their common lands (Table 7), are in protection zone 1, where forest management is not allowed. As a result the mean NPP of all common lands and their capacity to carbon sequestration was considerably reduced. Thus, based on our assessment, common lands in the TNP exhibit a moderate overall capacity for carbon sequestration. While this contribution is lower than initially expected, it is important to highlight that the extent of spatial distribution of communally owned forests and scrublands accounts for just over a fifth (21.5%) of all forested and scrubland areas in the park and 14.0% of the total area of the TNP, demonstrate a higher carbon sequestration capacity, despite the mean NPP across all common lands remains moderate. Taking this into account, we conclude that forest commons in the TNP still make a meaningful contribution to carbon sequestration.

On the other hand this analysis might also suggest that protective forests within common lands in Protective zone 1 in the TNP more significantly support other ecosystem services, such as erosion prevention, wind protection, nature-based recreation, etc. Therefore, further empirical research is needed to better assess the common lands contribution for broader society.

Furthermore, although our results indicate a lower mean NPP in common lands within the TNP compared to those reported for common lands in Northern Portugal (Gomes et al. 2025), this difference likely reflects contrasting ecological conditions, forest types, and climatic influences between the Alpine and Sub-Mediterranean regions as well as differences in forest management practices (as mentioned in Table 1, in the TNP protection zone 1 forest management is not allowed, while protection zones 2 and 3 allow certain practices). The Alpine landscape of the TNP is characterized by cooler temperatures, shorter growing seasons, and higher elevations, which can constrain productivity. In contrast, the sub-Mediterranean conditions in Northern Portugal, particularly in managed *Pinus pinaster* forests, may promote higher biomass production and accumulation under favorable site conditions.

4.3 Limitations

While the MODIS-derived NPP data provide valuable insights into spatial patterns of vegetation productivity, there are several limitations to using this product as a proxy for carbon sequestration. First, MODIS NPP estimates are based on light use efficiency models and a coarse spatial resolution (500 m), which means that each pixel represents the average productivity of a large area that may contain multiple land use types or vegetation structures. This coarse resolution cannot accurately capture fine-scale heterogeneity. Thus, small features such as small agricultural plots or urban structures may be underrepresented within NPP pixels, leading to generalisations that reduce spatial accuracy. Second, the MODIS NPP does not account for carbon loss due to disturbance (e.g., forest fires, erosion, etc.) or carbon stored in long-lived biomass pools such as deadwood or soil organic matter. It therefore represents short-term carbon uptake rather than long-term sequestration potential. Furthermore, the algorithm relies on vegetation indices, which can be saturated in dense tree canopies and influenced by atmospheric or topographic effects, leading to uncertainties. Therefore, while the MODIS NPP is a useful comparative tool, it should be interpreted with caution and ideally supplemented with field measurements or higher resolution data to enable robust carbon accounting.

While downscaling MODIS NPP data with Sentinel-2 vegetation indices and HR-VPP layers allows for finer spatial resolution (10 m) and a better representation of land use heterogeneity, this method also comes with limitations. First, the downscaled product is still subject to the temporal and biophysical assumptions of the original MODIS NPP data. The improved spatial detail does not reflect direct measurements of NPP at 10 m, but derived patterns based on vegetation indices and land cover features from Sentinel 2. Downscaling can also introduce spatial leakage, whereby signals from adjacent land-cover types affect the downscaled estimates, so NPP from nearby features influences a pixel's predicted value. Additionally, although XGBoost can predict beyond the range observed in training, predictive performance typically degrades when extrapolating outside the MODIS-supported NPP range. As a result, estimates are effectively constrained by the training distribution, with higher uncertainty near or beyond its bounds. Due to the aforementioned uncertainties, the downscaling process can potentially lead to an overestimation of NPP values at pixel level. Some of these limitations could be addressed using LiDAR-derived vegetation height. While this approach may improve the overall precision of estimates, it could disproportionately weight predictions towards tree-dominated areas. Moreover, the typically low temporal resolution of LiDAR products fails to capture management-driven dynamics. In summary, although downscaling improves spatial resolution and visual coherence with land use maps, it should be interpreted as a model-derived approximation of carbon sequestration.

5 Conclusions

We hypothesised that agrarian communities greatly contribute to the sustainable management of their common lands. However, the available literature lacks information on their management, which is an area for future qualitative studies (e.g., semi-structured interviews with agrarian community representatives). This study offers one of the first estimation insights into the role of agrarian communities in ecosystem service provision focusing specifically on carbon sequestration in the TNP. Our findings underscore the need to assess both, carbon sequestration potential and spatial extent when evaluating land use contributions to carbon dynamics, as high productivity alone does not necessarily translate into greater overall impact at the landscape scale.

The analysis of common lands managed by agrarian communities showed that, although their overall carbon sequestration capacity is moderate, particularly their forests and scrublands, i.e. forest commons, covering 14.0% of the TNP and demonstrating high sequestration capacity, still play a key role in supporting this essential regulating ecosystem service. However, when it comes to forests, it is important to refer back to one of the key findings from Slovenia's National Inventory Document 2024 that Slovenian forests are gradually losing their carbon sequestration capacity. Based on our analysis, this trend suggests that private forest owners in Slovenia, including agrarian communities (not only those in the TNP, where management is constrained by the protection regime), have an opportunity to adopt improved management practices that would enhance their forests' carbon sequestration. These practices include: moderate growth accumulation, reduced harvesting in protective forests, expanding managed forests without intensive interventions, preserving or increasing unmanaged forests (e.g., forest reserves, forests in the TNP), maintaining long rotation periods (especially in preserved forests), conserving forest areas in agricultural and urban landscapes, and strengthening forest resilience to climate change and its impacts (Poljanec et al. 2023). Through various national and European financial mechanisms (e.g., the Forest Fund, the Climate Change Fund, the Rural Development Programme, etc.), Slovenia already finances measures that contribute to improving the condition of forest stands, making them more resilient in the long term to climate change impacts (such as storms and droughts), and capable of ensuring effective carbon sequestration (Konjar et al. 2023). In addition, as previously mentioned, carbon storage of existing forests with their enourmous capacities to retain carbon is arguably even more important than sequestration for mitigating climate change, which makes the preservation of existing forests (and other intact ecosystems) essential (Cook-Patton et al. 2020). From this perspective, communaly managed forests play a notable role. Still, as strongly highlighted by Cook-Patton et al. (2020) and Tölgyesi et al. (2025) carbon sequestration and storage should not be seen as substitutes for reducing greenhouse gas emissions. Reducing these anthropogenic emissions remains essential.

Last but not least, future studies could benefit from incorporating data from the European Space Agency's Biomass satellite. This mission is designed to provide unprecedented insights into how much carbon is stored in the world's forests. As it is the first satellite with signal capable of penetrating forest canopies to measure woody biomass – trunks, branches and stems. Integrating such data would enhance the precision of carbon sequestration estimates, particularly in complex landscapes like alpine environments and the long-term role of communal lands in climate regulation.

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RESEARCH DATA: For information on the availability of research data related to the study, please visitthe article webpage: https://doi.org/10.3986/AGS.14491.

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Guidelines for contributing authors in Acta geographica Slovenica

EDITORIAL POLICIES

1 Focus and scope

The *Acta geographica Slovenica* journal is issued by the ZRC SAZU Anton Melik Geographical Institute, published by the ZRC SAZU Založba ZRC, and co-published by the Slovenian Academy of Sciences and Arts.

Acta geographica Slovenica publishes original research articles from all fields of geography and related disciplines and provides a forum for discussing new aspects of theory, methods, issues, and research findings, especially in Central, Eastern, and Southeastern Europe.

Articles presenting new developments and innovative methods in geography are welcome. Submissions should address current research gaps and explore state-of-the-art issues. Research based on case studies should have the added value of transnational comparison and should be integrated into established or new theoretical and conceptual frameworks.

The target readership is researchers, policymakers, students, and others who are studying or applying geography.

The journal is indexed in the following bibliographic databases: Clarivate Web of Science (SCIE – Science Citation Index Expanded; JCR – Journal Citation Report/Science Edition), Scopus, ERIH PLUS, Directory of Open Access Journals (DOAJ), GEOBASE Journals, Current Geographical Publications, EBSCOhost, Georef, FRANCIS, SJR (SCImago Journal & Country Rank), OCLC WorldCat, Google Scholar, and CrossRef.

2 Types of articles

Unsolicited or invited original research articles and review articles are accepted. Articles and materials or sections of them should not have been previously published or be under consideration for publication elsewhere. The articles should cover subjects of current interest within the journal's scope.

3 Special issues

The journal also publishes special issues (thematic supplements). Special issues usually consist of invited articles and present a special topic, with an introduction by the (guest) editors. The introduction briefly presents the topic, summarizes the articles, and provides important implications.

4 Peer-review process

All articles are examined by the editor-in-chief. This includes fact-checking the content, spelling and grammar, writing style, and figures. Articles that appear to be plagiarized, are badly or ghost-written, have been published elsewhere, are outside the scope of the journal, or are of little interest to the readers of *Acta geographica Slovenica* may be rejected. If the article exceeds the maximum length, the author(s) must shorten it before the article is reviewed. The article is then sent to responsible editors, who check the relevance, significance, originality, clarity, and quality of the article. If accepted for consideration, the articles are sent to two or more peer reviewer(s) for double-blind review. Articles are rejected or accepted based on the peer reviews and the editorial board's decision.

5 Publication frequency

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6 Open-access policy

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Digital copies of the journal are stored by the repository of ZRC SAZU and the digital department of the Slovenian national library NUK, dLib.

The journal's publication ethics and publication malpractice statement is available online, as well as information on subscriptions and prices for print copies.

AUTHOR GUIDELINES

Before submitting an article, please read the details on the journal's focus and scope, publication frequency, privacy statement, history, peer-review process, open-access policy, duties of participants, and publication ethics. See also the latest version of the author guidelines online. All the materials are available at https://ags.zrc-sazu.si.

1 Article structure

Research articles must be prepared using the journal's template (available at https://ags.zrc-sazu.si) and contain the following elements:

- **Title:** this should be clear, short, and simple.
- **Information about author(s):** submit names (without academic titles), affiliations, ORCiDs, and e-mail addresses through the online submission system (available at https://ags.zrc-sazu.si).
- **Highlights**: authors must provide 3–5 highlights in the form of bullets. This section must not exceed 400 characters, including spaces.
- **Abstract:** introduce the topic clearly so that readers can relate it to other work by presenting the background, why the topic was selected, how it was studied, and what was discovered. It should contain one or two sentences about each section (introduction, methods, results, discussion, and conclusions). The maximum length is 800 characters including spaces.
- **Keywords:** include up to seven informative keywords. Start with the research field and end with the place and country.
- **Main text:** the main text must not exceed 30,000 characters, including spaces (without the title, affiliation, abstract, keywords, highlights, reference list, and tables). Do not use footnotes or endnotes. Divide the article into sections with short, clear titles marked with numbers without final dots: **1 Section title**. Use only one level of subsections: **1.1 Subsection title**.

Research articles should have the following structure:

- **Introduction:** present the background of the research problem (trends and new perspectives), state of the art (current international discussion in the field), research gap, motivation, aim, and research questions.
- **Methods:** describe the study area, equipment, tools, models, programs, data collection, and analysis, define the variables, and justify the methods.
- **Results:** follow the research questions as presented in the introduction and briefly present the results.
- **Discussion:** interpret the results, generalize from them, and present related broader principles and relationships between the study and previous research. Critically assess the methods and their limitations, and discuss important implications of the results. Clarify unexpected results or lacking correlations.
- **Conclusion:** present the main implications of the findings, your interpretations, and unresolved questions, offering a short take-home message.

Review articles (narratives, best-practice examples, systematic approaches, etc.) should have the following structure:

- **Introduction:** include 1) the background; 2) the problem: trends, new perspectives, gaps, and conflicts; and 3) the motivation/justification.

- **Material and methods:** provide information, such as data sources (e.g., bibliographic databases), search terms and search strategies, selection criteria (inclusion/exclusion of studies), the number of studies screened and included, and the statistical methods of meta-analysis.
- **Literature review:** use subheadings to indicate the content of the various subsections. Possible structure: methodological approaches, models or theories, the extent of support for a given thesis, studies that agree with one another versus studies that disagree, chronological order, and geographical location.
- **Conclusions:** provide the implications of the findings and your interpretations (separate from facts), identify unresolved questions, summarize, and draw conclusions.

– **Acknowledgments:** use when relevant. In this section, authors can specify the contribution of each author.
– **Reference list:** see the guidelines below.

The journal also features in-depth articles known as ***Geoscapes***. These are a specialized type of research contribution that explore selected topics in greater detail. *Geoscapes* articles are published by invitation only and must be pre-approved by the editorial board.

2 Article submission

2.1 Open journal system

Author(s) must submit their contributions through the *Acta geographica Slovenica* Open Journal System (OJS; available at https://ags.zrc.sazu.si) using the Word document template (available at https://ags.zrc.sazu.si).

Enter all necessary information into the OJS. Any later addition, deletion, or rearrangement of names and affiliations of the author(s) in the authorship list should be made and confirmed by all co-authors before the manuscript has been accepted, and is only possible if approved by the journal editor.

To make anonymous peer review possible, the article text and figures should not include names of the author(s).

Do not use contractions or excessive abbreviations. Use plain text, with sparing use of **bold** and *italics* (e.g., for non-English words). Do not use auto-formatting, such as section or list numbering and bullets.

If a text is unsatisfactory, the editorial board may return it to the author(s) for proofreading or reject the article. See the section on the peer-review process (available at https//ags.zrc-sazu.si) for details. Author(s) may suggest reviewers when submitting an article.

2.2 Language

Articles are published in English. All articles have English and Slovenian abstracts.

Articles can be submitted in English or Slovenian.

Authors must take care to produce a high-quality English text. In the case of poor language, the article must be proofread/translated. In such a case, the translation or copyediting costs are borne by the author(s) and must be paid before layout editing. If authors are not Slovene native speakers, Slovenian abstracts are prepared by the editorial board.

2.3 Graphic file submission

Graphic files (figures) need to be submitted to the OJS packed in a single zip file not exceeding 50 MB. Multiple zip files can be uploaded if needed. See chapter 6 for details on how to prepare figures.

3 In-text citation

In-text citations should include the last name of the author(s) or the name of the publisher and the year of publication. Arrange citations by year of publication; for example: (Melik 1955; Melik et al. 1963; Gams 1982a; Gams 1982b; United Nations 1987; Royal Australian … 1988; Ford and Williams 2007). For references with more than two authors, cite only the first, followed by et al.: (Melik et al. 1956). Give page numbers only for direct quotations, for example: Perko (2016, p. 25) states: »Hotspots are …« For indirect citations, use this format: (Gunn 2002, cited in Matei et al. 2014).

When presenting publicly archived data, such as statistical and spatial data, describe the name of the dataset, the time frame, and the data provider in the main text, for example: »The 2000–2020 population data used in the analysis were provided by Eurostat« If the statistical data were published as a report, cite the document, for example: (European Commission … 2023).

When citing legal sources such as legislative acts, white papers, etc., provide the short formal title and the year, for example: »The European Commission's White paper on transport published in 2011 sets out ten strategic goals for a competitive and resource-efficient transport system.«

4 References

All references in the reference list must be cited in the text. Arrange references alphabetically and then chronologically if necessary. Identify more than one reference by the same author(s) in the same year with the letters a, b, c, etc., added to the year of publication: (1999a, 1999b). In case there are more than seven authors, list the first seven followed by et al.

Examples of references are given below. The use of »gray literature« is strongly discouraged.

Authors can use the Zotero and Endnote AGS Style templates, which are available in the Article submission section on the https://ags.zrc-sazu.si.

4.1 Articles

Last Name1, A. B., Last Name2, C. D. Year: Title. *Journal Name* Volume-Issue. https://doi.org/…

- Breg Valjavec, M., Janža, M., Smrekar, A. 2018: Environmental risk resulting from historical land degradation in alluvial plains considered for dam planning. *Land Degradation & Development* 29-11. https://doi.org/10.1002/ldr.3168
- Kladnik, D., Kruse, A., Komac, B. 2017a: Terraced landscapes: An increasingly prominent cultural landscape type. *Acta geographica Slovenica* 57-2. https://doi.org/10.3986/AGS.4770
- Kladnik, D., Šmid Hribar, M., Geršič, M. 2017b: Terraced landscapes as protected cultural heritage sites. *Acta geographica Slovenica* 57-2. https://doi.org/10.3986/AGS.4628
- Ni, J., Jin, J., Wang, Y., Li, B., Wu, Q., Chen, Y., Du, S. et al. 2024: Surface ozone in global cities: A synthesis of basic features, exposure risk, and leading meteorological driving factors. *Geography and Sustainability* 5-1. https://doi.org/10.1016/j.geosus.2023.09.008
- Unangst, M. 2023: (De)Colonial historical geography and historical GIS. *Journal of Historical Geography* 79. https://doi.org/10.1016/j.jhg.2022.12.003
- Van de Kerk, G., Manuel, A. R. 2008: A comprehensive index for a sustainable society: The SSI – The Sustainable Society Index. *Ecological Economics* 66-2,3. https://doi.org/10.1016/j.ecolecon.2008.01.029
- Yang, D.-H., Goerge, R., Mullner, R. 2006: Comparing GIS-based methods of measuring spatial accessibility to health services. *Journal of Medical Systems* 30-1. https://doi.org/10.1007/s10916-006-7400-5

4.2 Books

Last Name1, A. B., Last Name2, C. D. Year: Book title. *Book Series Title* with Number. Publisher. https://doi.org/…

If the book is edited by editors, add '(eds.)' before the year of publication.

- Achino, K. F., Velušček, A. 2022: The lake-dwelling phenomenon. *E-Monographiae Instituti Archaeologici Sloveniae* 13. Založba ZRC. https://doi.org/10.3986/9789610506560
- Gams, I. 2004: Kras v Sloveniji v prostoru in času. Založba ZRC.
- Hall, T., Barrett, H. 2018: Urban geography. Routledge. https://doi.org/10.4324/9781315652597
- Knox, P., Marston, S. 2015: Human geography: Places and regions in global context. Pearson.
- Luc, M., Somorowska, U., Szmańda, J. B. (eds.) 2015: Landscape analysis and planning. *Springer Geography*. Springer. https://doi.org/10.1007/978-3-319-13527-4
- Marshall, T. 2016: Prisoners of geography: Ten maps that explain everything about the World. *Politics of Place*. Scribner.
- Mihelič Pulsipher, L., Pulsipher, A., Johansson, O. 2019: World regional geography: Global patterns, local lives. W. H. Freeman.

4.3 Chapters of books or proceedings

Last Name1, A. B., Last Name2, C. D. Year: Chapter title. In: Book Title. *Book Series Title* with Number. Publisher. https://doi.org/…

- Griffin, A. L. 2018: Cartography, visual perception and cognitive psychology. In: The Routledge Handbook of Mapping and Cartography. Routledge. https://doi.org/10.4324/9781315736822
- Solem, M., Boehm, R. 2015: A research coordination network for geography education. In: EUGEO Budapest 2015: Congress Programme and Abstracts. Hungarian Geographical Society.
- Stethem, C. 2013: Avalanches. In: Encyclopedia of Natural Hazards. Springer. https://doi.org/10.1007/978-1-4020-4399-4_7
- Zorn, M., Ferk, M., Lipar, M., Komac, B., Tičar, J., Hrvatin, M. 2020: Landforms of Slovenia. In: The Geography of Slovenia: Small But Diverse. *World Regional Geography Book Series*. Springer. https://doi.org/10.1007/978-3-030-14066-3_3

4.4 Reports, theses, dissertations, and other materials with authors

Last Name1, A. B., Last Name2, C. D. Year: Title. *Type of document*. Publisher. https://doi.org/…

- Davies, G. 2017: The place of data papers: Producing data for geography and the geography of data production. *Blog post*. Geo: Geography and Environment.
- Easterbrook, D. J. 1976: Geologic map of western Whatcom County, Washington (1-854-B). *1:62,500 map*. United States Geological Survey.
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- Hrvatin, M. 2016: Morfometrične značilnosti površja na različnih kamninah v Sloveniji. *Ph.D. thesis*. Univerza na Primorskem.
- Šifrer, M. 1997: Površje v Sloveniji. *Technical report*. Geografski inštitut Antona Melika ZRC SAZU.

4.5 Sources without authors

Use in-text citations (see Chapter 3). If sources need to be listed in the references use the following style: Publisher/Institution Year: Title. *Type of document*. https://doi.org/…

- Geodetska uprava Republike Slovenije 1998: Državna topografska karta Republike Slovenije 1 : 25.000 (Brežice). *1:25,000 map*.
- Royal Australian Survey Corps 1988: Australia 1:50 000 topographic survey (Tamborine, Queensland). *1:50,000 map*.
- United Nations 1987: Report of the World Commission on Environment and Development: Our common future. *Report*.
- European Space Agency 2022: Copernicus Sentinel-2 MSI Level-1C TOA Reflectance. *Dataset*. https://doi.org/10.5270/S2_-742ikth

5 Tables

Number all tables in the article uniformly and provide their own titles. The number and the title text are separated by a colon, and the title ends with a period. A table title is located above the corresponding table. Examples:

- Table 1: Number of inhabitants of Ljubljana.
- Table 2: Changes in average air temperature in Ljubljana (Velkavrh 2009).

Tables must be indicated in the main text in parentheses, for example: (Table 1), or as a part of the sentence, for example »… as can be seen in Table 1.« Tables should contain no formatting and must be inserted in the article file.

6 Figures

Figures encompass different graphic presentations used in the article: photography, graphs, illustrations, maps, etc.

Number all figures in the article uniformly and provide their own titles. The number and the title text are separated by a colon, and the title ends with a period. A figure title is located below the corresponding figure. Example:

- Figure 1: Location of measurement points along the glacier.

Figures must be indicated in the main text in parentheses, for example: (Figure 1), or as a part of the sentence, for example »… as can be seen in Figure 1.«

Figures should be exactly 134 mm wide (one page) or 64 mm wide (half page, one column), and up to 200 mm high.

Titles should appear in a caption only. Save colors in CMYK. Use Times New Roman font with a minimum size of 6.

Figures must be submitted as separate files. Multiple graphic files should be uploaded in one zip file. Figures should also be inserted in the main text file in order to ease the review process.

Regardless of the graphic/cartographic software used, save or export figures to the following formats:

- jpg or tiff file for regular photos (use a minimum of 300 dpi),
- xlsx file for graphs made with MS Office Excel,
- pdf or similar common files for maps and illustrations with vector drawings and/or text (embed the font if possible). See chapter 6.3 for details.

If the graphic files cannot be uploaded according to the guidelines, consult the editorial board (ags@zrc-sazu.si) in advance.

To make anonymous peer review possible, the authorship of figures can be added by authors at a later (copyediting) stage, after the review has been completed.

6.1 Photos

Photos must be in raster format with a resolution of at least 300 dpi, preferably in jpg or tiff format.

Figures containing a screenshot should be prepared at the highest possible screen resolution. A figure can be made using Print Screen, and the captured screen is pasted to the selected graphic program (e.g., Paint) and saved as a tiff or jpg file. The size of the image or its resolution must not be changed.

6.2 Graphs

Graphs should be made using MS Excel on separate sheets and accompanied by data.

6.3 Maps and illustrations

Maps should be informative and prepared according to the journal size limitations (see general guidelines defined in chapter 6). Use Times New Roman for the legend (size 8) and colophon (size 6). List scale, source, and copyright in the colophon. List the authors of the content and authors of the maps if needed. Write the colophon in English. Use a graphic scale if possible.

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- if using QGIS, ESRI ArcGIS Pro or similar, maps should be exported as a pdf file,
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Illustrations should be prepared according to the journal size limitations (see general guidelines defined in chapter 8). Use Times New Roman font size 8. **The preferred submission file is pdf**. As an exception, illustrations can be produced in digital raster form with at least 300 dpi resolution, preferably in jpg or tiff format.

7 Research data

Authors have to make the research data used in the article published in *Acta geographica Slovenica* publicly available in a recognized online repository and provide the editorial board with a link.

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As part of the submission process, authors are required to check off their submission's compliance with all of the following items, and submissions may be returned to authors who do not adhere to these guidelines.

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- Authors confirm that they are the authors of the submitting article, which is under consideration to be published (print and online) in the journal *Acta geographica Slovenica* by Založba ZRC, ZRC SAZU.
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- The article has been checked for spelling and grammar.
- Figures are provided as separate graphic files: editable vector format (e.g., cdr, ai, pdf) for maps and illustrations; jpg or tiff for photographs; xlsx for graphs.
- Tables are placed in the Word file with text in the appropriate place.
- The reference list was prepared following the guidelines.
- All references in the reference list are cited in the text.
- Where available, URLs and DOI numbers for references are provided.
- Graphic files are in one zip file.
- Authors agree that any costs of English proofreading are borne by the author(s). No additional costs are associated with the submission.
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- If the article is accepted, the authors will provide unique information (e.g., a DOI) about the online repository where the research data underlying the article is located. This information must be provided before the article is published. Metadata of the data in the repository must indicate that the data are part of the published article in the journal Acta geographica Slovenica. The article must be properly cited when using the data.

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This is the review form for editorial review (version 15) of an article submitted to the AGS journal.

This is an original scientific article.
(The article is original and the first presentation of research results with the focus on methods, theoretical aspects or a case study.)

- Yes
- No

The article follows the standard IMRAD/ILRAD scheme.

- Yes
- No

The article's content is suitable for reviewing in the AGS journal.
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Editorial notes regarding the article's content.

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Notes to the editor-in-chief regarding previously published scientific work.

Is the language of the article appropriate and understandable?

RECOMMENDATION OF THE EDITOR

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- Reconsider after a major revision (see notes).
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- no

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- partly

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If necessary, add comments and recommendations to improve the clarity of the title, abstract, keywords, introduction, methods or conclusion:

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Is the article technically sound? (If not, the author should discuss with the Editorial Board [ags@zrc-sazu.si] for assistance.)

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JOURNAL HISTORY

Acta geographica Slovenica (print version: ISSN: 1581-6613, digital version: ISSN: 1581-8314) was founded in 1952. It was originally named *Geografski zbornik / Acta geographica* (print ISSN 0373-4498, digital ISSN: 1408-8711). Altogether, 42 volumes were published. In 2002 *Geographica Slovenica* (ISSN 0351-1731, founded in 1971, 35 volumes) was merged with the journal.

Since 2003 (from Volume 43 onward), the name of the joint journal has been *Acta geographica Slovenica*. The journal continues the numbering system of the journal *Geografski zbornik / Acta geographica*.

Until 1976, the journal was published periodically, then once a year, twice a year from 2003, and three times a year since 2019.

The online version of the journal has been available since 1995. In 2013, all volumes of the magazine were digitized from the beginning of its publication to including 1994.

All articles of the journal are available free of charge in digital form on the journal website http://ags.zrc-sazu.si.

Those interested in the history of the journal are invited to read the article »The History of *Acta geographica Slovenica*« in volume 50-1.

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