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SPECIAL ISSUE – *The importance of common lands' management for sustaining ecosystem services*

POSEBNA IZDAJA – *Pomen upravljanja skupnih zemljišč za zagotavljanje ekosistemskih storitev*

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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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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.

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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.

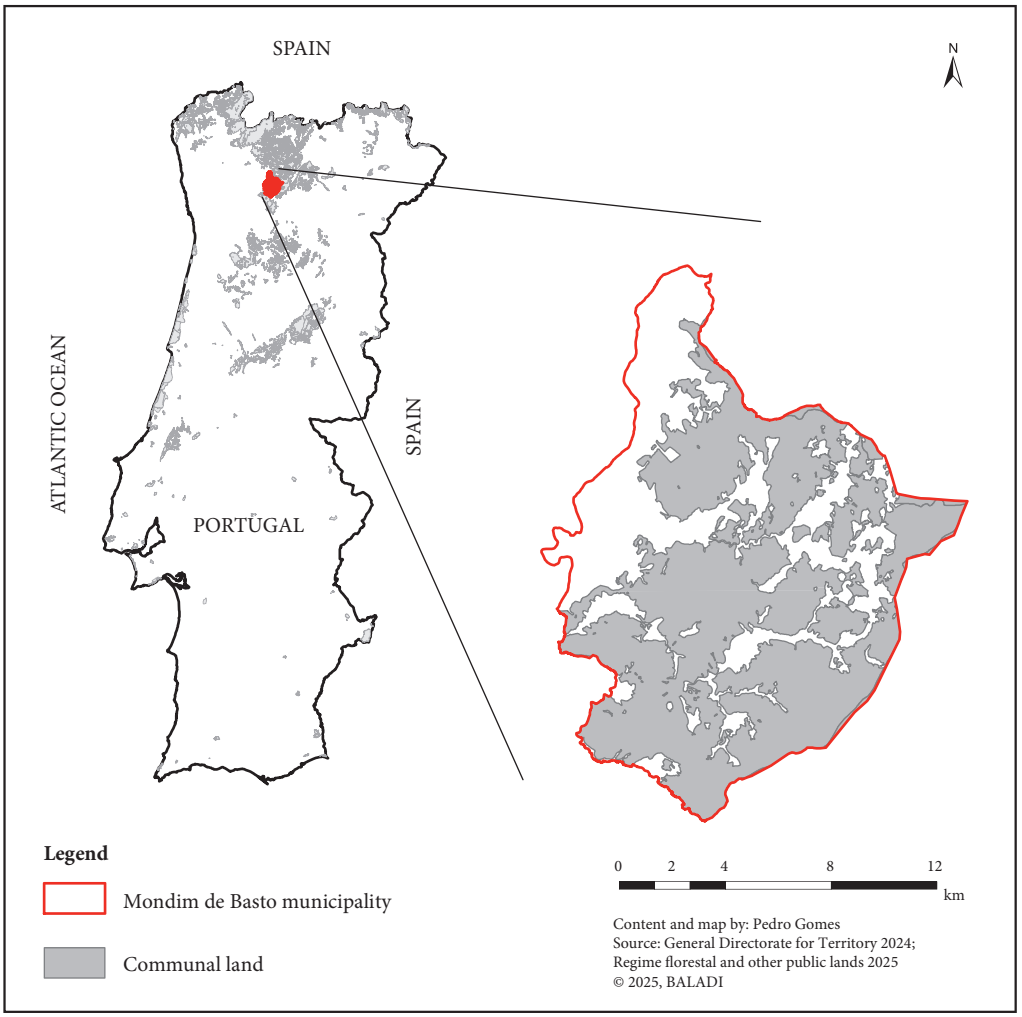

Figure 1: Map of the study area showing the location of the municipality of Mondim de Basto and the extent of communal land within its boundaries.

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.

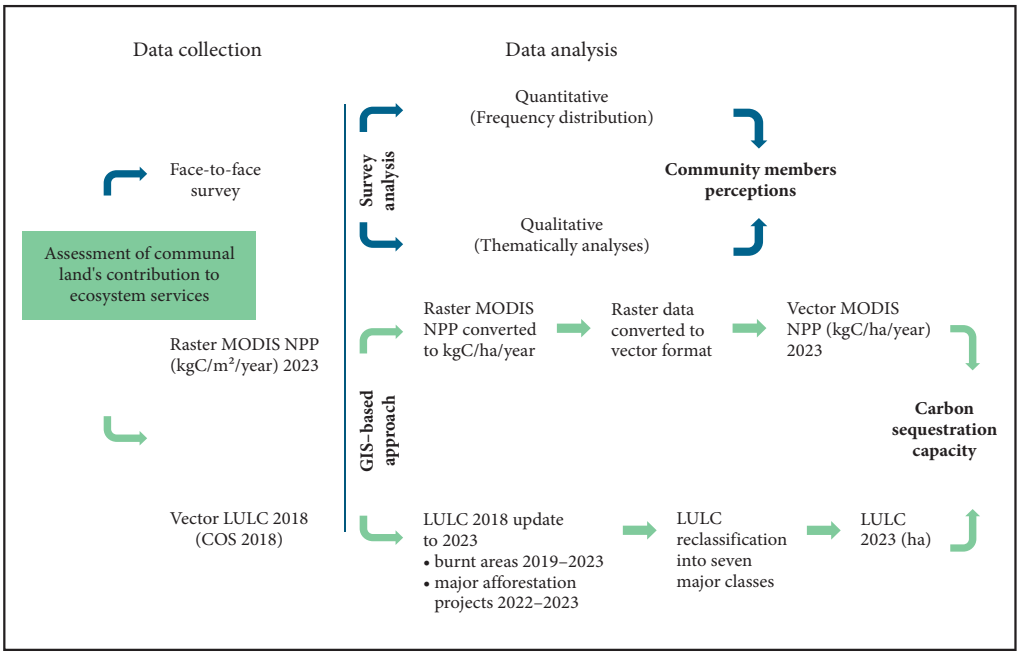

Figure 2: Methodological framework for the assessment of the contribution of Portuguese communal lands to ES.

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	
		5.2	Other broadleaved	505	5	57
		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	
		7.2	Burnt area 2020	304	3	
		7.3	Burnt area 2021	413	4	14
		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).

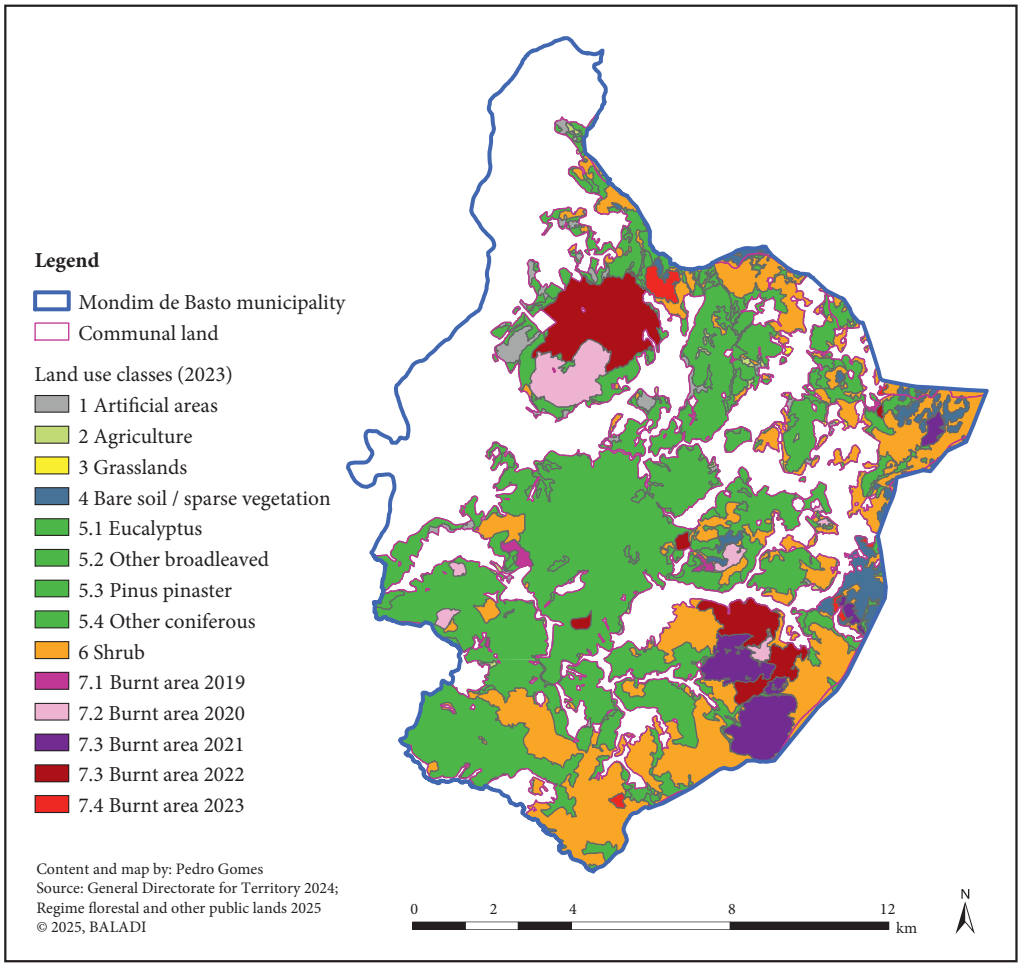

Figure 3: LULC classes on the studied communal lands in 2023.

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.

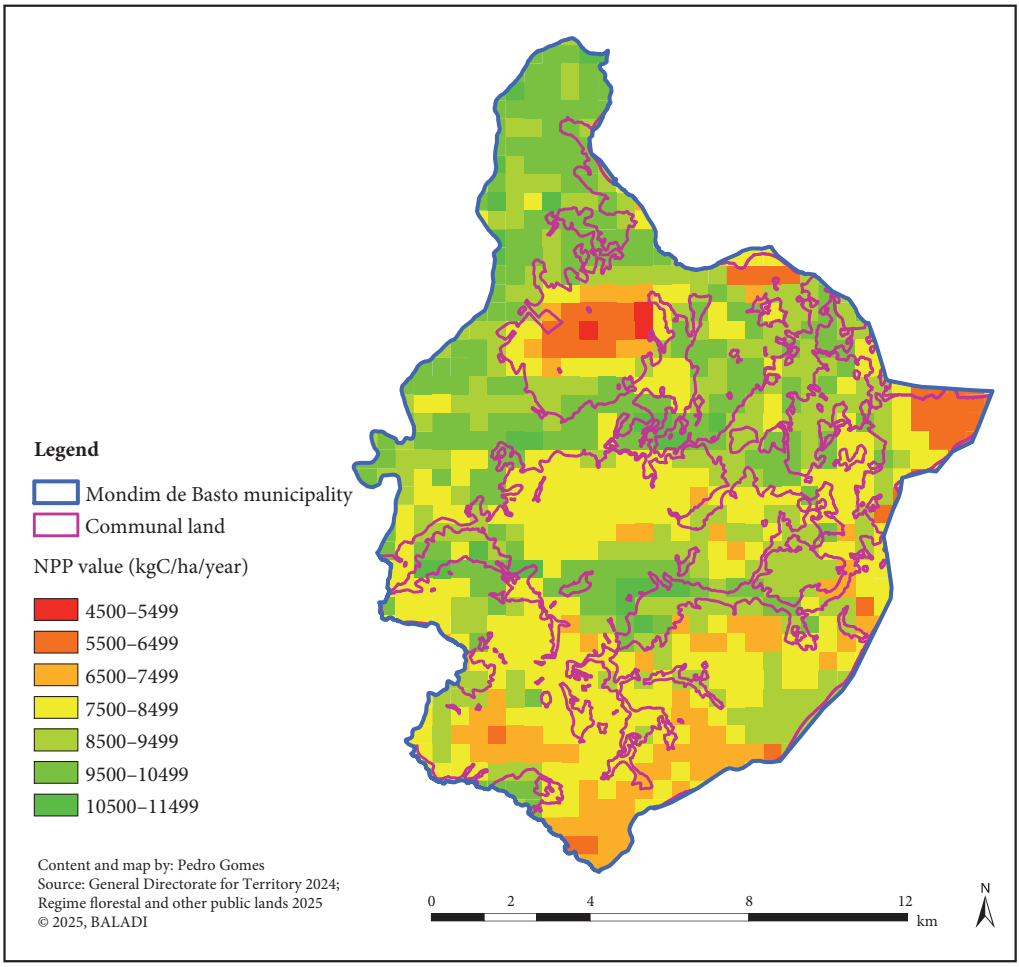

Figure 4: NPP in Mondim de Basto municipality by class (kgC/ha/year).

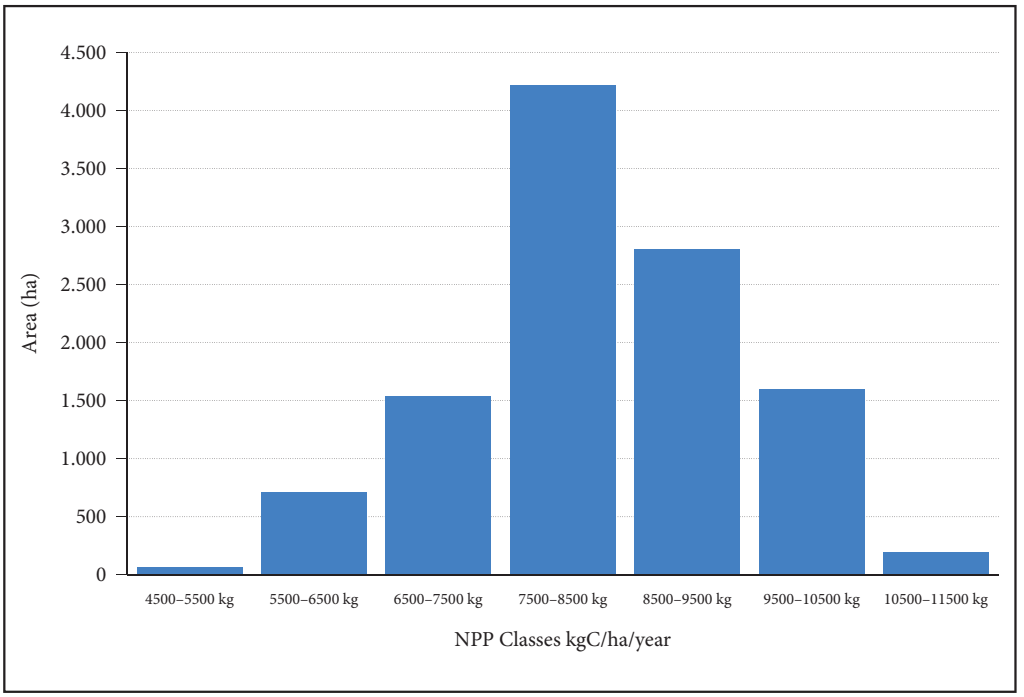

Figure 5: Distribution of the total area by NPP class in communal lands in 2023.

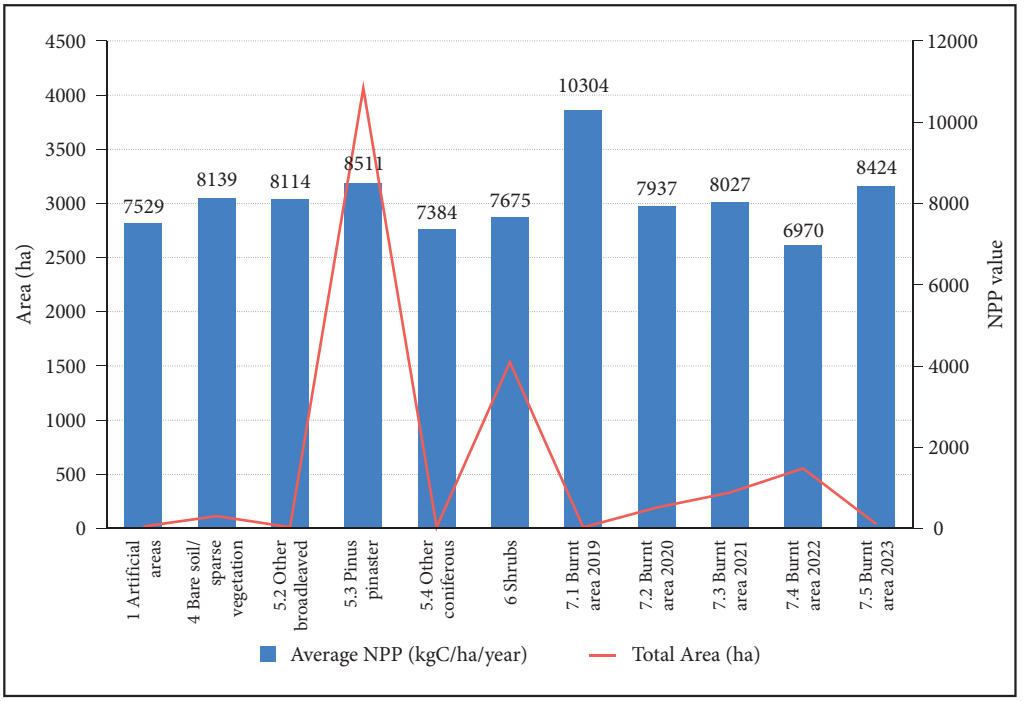

Figure 6: NPP values for LULC classes occupying more than 50% of the pixel area.

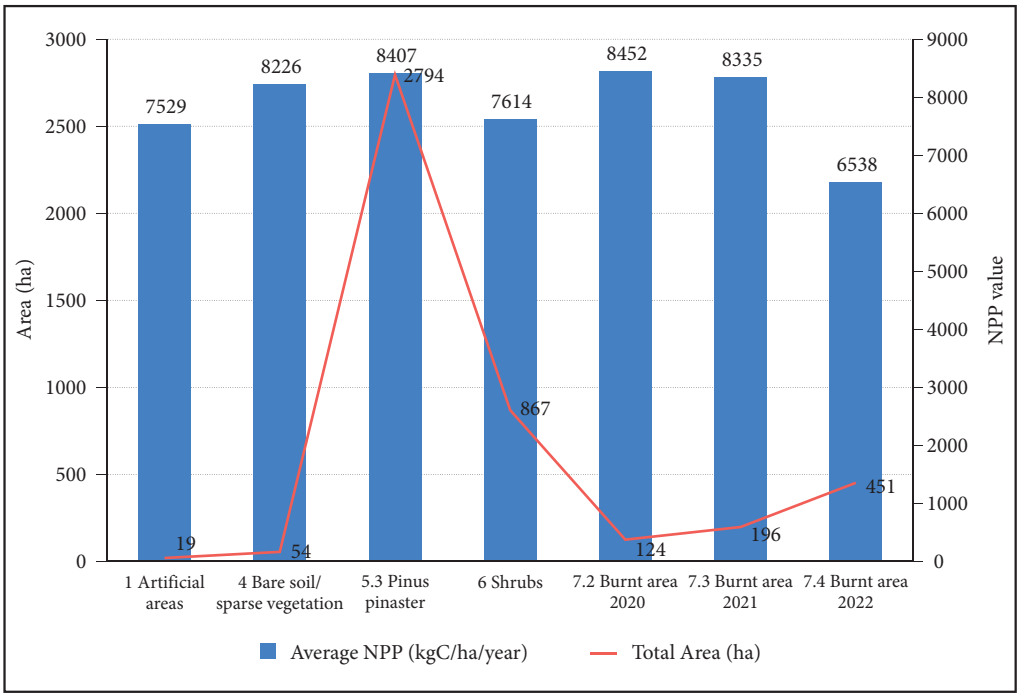

Figure 7: NPP values for LULC classes occupying more than 75% of the pixel area.

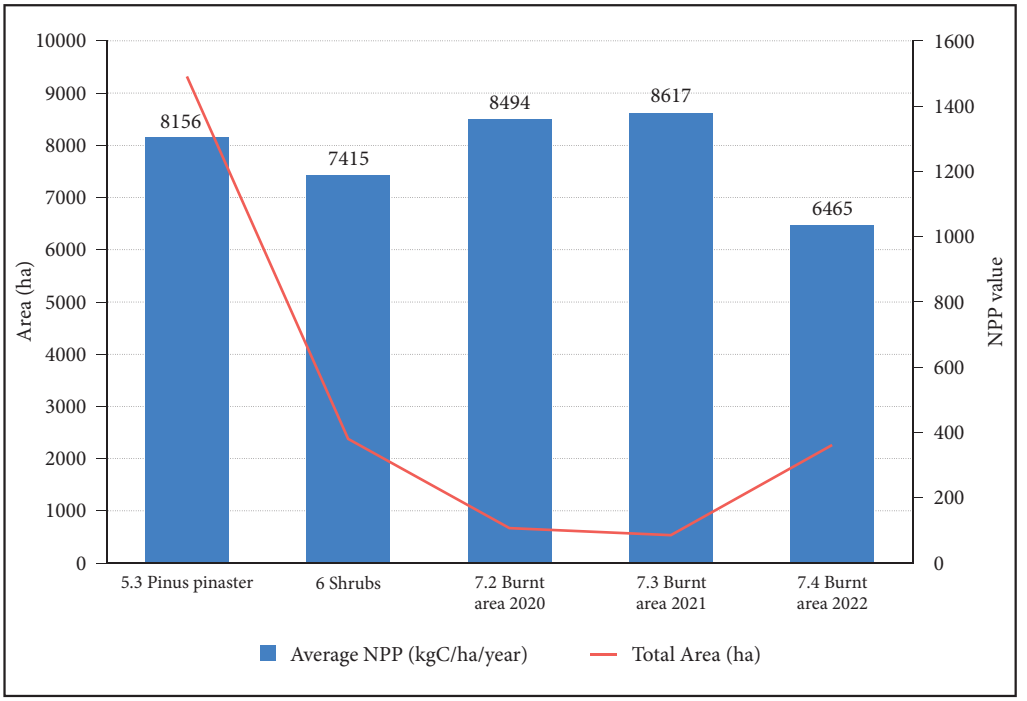

Figure 8: NPP values for LULC classes occupying more than 95% of the pixel area.

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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