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ORIGINAL ARTICLE

Increased policy ambition is needed to avoid the effects of climate change and reach carbon removal targets in Portugal

Jiesper Strandsbjerg Tristan Pedersen[1,2] · Luís Filipe Dias[1] · Kasper Kok[3] · Detlef van Vuuren[2,4] · Pedro M. M. Soares[5] · Filipe Duarte Santos[1] · João C. Azevedo[6,7]

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Abstract

The Paris Agreement's goal of limiting global warming hinges on forest carbon sequestration as a key in several national strategies. However, Portugal's rising forest fire occurrences threaten its ability to meet ambitious 2030 and 2050 carbon sequestration targets. Considering fire and forest trends, this study aims to quantify whether Portugal can reach its carbon sequestration ambitions as stated in its 2030 and 2050 targets. We tested three national forest scenario extensions of the global Shared Socioeconomic Pathways (SSPs) and Shared Policy Assumptions (SPAs) based on a dynamic model, simulating forest area and carbon sequestration related to future fire risk and policies of fire management, forest management, restoration of burnt areas, and climate change adaptation. The model projects a rapidly decreasing forest area under existing Portuguese policies (PT-SSP3), a slow decline under moderate policy improvements (PT-SSP2), and an almost stable forest area under long-term sustainable policy developments (PT-SSP1). In PT-SSP3, carbon sequestration will be reduced to 60% by 2050 compared to 2015, while it declines to about 85% and 90% under PT-SSP2 and PT-SSP1, respectively. It is still plausible to reach Portugal's 2030 sequestration obligations under the EU's Paris Agreement target under all three scenarios, while the Portuguese GHG neutrality target is not reached in the presented scenarios. Our four introduced policy areas (increasing focus on fire and forest management, forest restoration, and climate change adaptation of forest stands) must be supplemented by other policy strategies, such as reforestation.

Keywords Climate change targets · Forest policy · Climate-induced fires · Carbon sequestration · National scenario extensions · RCP-SPA-SSP scenario framework

Introduction

As climate policies are implemented to anticipate climate change and reduce climate impacts, scenario-based assessments (CAT 2022; Kriegler et al. 2014; UNEP 2023) play a vital role in informing national policy designs (Moss et al. 2010; van Beek et al. 2020; Pedersen 2023). Estimates of current emission levels (Friedlingstein et al. 2023) and emission scenarios (UNEP 2023) are vital to

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✉ Jiesper Strandsbjerg Tristan Pedersen
jiespertristan@gmail.com

Luís Filipe Dias
lfdias@fc.ul.pt

1 cE3c - Centre for Ecology, Evolution and Environmental Changes & Change - Global Change and Sustainability Institute, Faculdade de Ciências da Universidade de Lisboa, Faculty of Science, University of Lisbon, Campo Grande, Building C1, Room 38, Lisbon 1749-016, Portugal

2 Geosciences, Copernicus Institute of Sustainable Development, Environmental Sciences, Utrecht University, Utrecht, Netherlands

3 Earth Systems and Global Change Group, Wageningen University, Wageningen, The Netherlands

4 PBL Netherlands Environmental Assessment Agency, Den Hague, The Netherlands

5 Faculdade de Ciências, Instituto Dom Luiz, Universidade de Lisboa, Lisbon, Portugal

6 Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

7 Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

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assessing policy progress for implementing the Paris Agreement (Schleussner and Fyson 2020). In addition, long-term scenarios are essential for evaluating the interconnection between societal drivers and emission levels (Dhakal et al. 2022) to inform strategies for mitigation and carbon removal (ESABCC 2024, 2023).

Forest policies are fundamental since almost all national mitigation strategies (CAT 2022; UNEP 2023; UNFCCC 2021) and Paris Compliant Pathways (IIASA 2022; van Vuuren et al. 2018) involve carbon dioxide (CO_2) sequestration compensating for emissions in other (hard-to-abate) sectors (APA 2019; EU 2020). Although forest sinks currently offset about 9% of total European Union (EU) CO_2 emissions, the future mitigation potential of forests is highly uncertain, considering human practices and climate change (Costa et al. 2020; Vizzarri et al. 2022). Improved fire-management strategies since the 1990s are countered by the effects of climate change, with forest fires accounting for 24% of forest damage in Europe (Schelhaas et al. 2020).

Wildfire risks are projected to increase globally (Arce 2019; Costa et al. 2020; UNEP 2022) and in Portugal (Rego et al. 2021; Vizzarri et al. 2022), jeopardizing national carbon removal targets. Due to afforestation programs, mainland Portugal's forest areas increased from 7 to 36% of total land areas between the late nineteenth century and 2020, with eucalyptus now being the dominant species (Reboredo and Pais 2014; WB 2023a). The Portuguese Forest area decreased during 1990–2010 and increased slightly between 2015 and 2020 (FAO 2020; WB 2023b), with an increasing number of burned areas where eucalyptus, maritime pine, and cork oak are the most commonly affected species (ICNF 2015). Furthermore, Portugal had the highest rate in EU-27 of annual wildfire-burned areas between 2006 and 2022 (1%/year) (EFFIS 2023). The absence of efficient forest management policies has increased the risk of forest fires (Ramos et al. 2023).

Identifying the effect of national policies on carbon sequestration is essential for informing Portuguese policy processes and is relevant to EU mitigation targets. The finite forest capacity as a carbon sink is critical to understanding the temporal values of biomass carbon (Timmons et al. 2016) and the role of national carbon sequestration in the Nationally Determined Contributions of the Paris Agreement and GHG neutrality targets.

We aim to quantify the potential future Portuguese forest area and carbon sequestration. The paper seeks to examine if Portugal can reach its 2030 EU obligation (5.8 Mt CO_2e/year) (EC 2018) and its national GHG neutrality target by 2050[1] (13 Mt CO_2e/year) (APA 2019) under various policy scenarios ranging from current national forest–related policies to a set of long-term sustainable policies. To do this, we developed three national scenario narratives (PT-SSP1, PT-SSP2, PT-SSP3) expressing short-term economic policy focus versus long-term sustainability. The narratives are based on the global scenario framework of the Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017), Shared Policy Assumptions (SPAs) (Kriegler et al. 2014), and the Representative Concentration Pathways (RCPs) (Gidden et al. 2019; van Vuuren et al. 2011). The SSP narratives (socioeconomic conditions excluding policy) and SPA policy assumptions are used as a basis to design the national scenario narratives, which include both outside conditions for climate policy (from the SSPs) and forest climate policy (from the SPAs). They are translated into four straightforward and transparent policy variables, shaping the model input (national forest policies and climate change impacts) to quantify a set of three quantitative forest scenarios expressing forest area and carbon sequestration.

Our approach allows for a customized and realistic projection of how a country's socioeconomic and environmental factors might evolve under the influence of global SSP-based trends, locally relevant climate, and other policies. The scenarios aim to facilitate strategic thinking and informed decision-making in the face of uncertainty about the future.

Methods, scenario, and model specifications

Our method followed three overall steps. First, we translated global SSPs to national PT-SSPs, consulting the scenario literature and relevant regional and national scenarios. Second, we defined policy scenarios based on a set of assumptions related to fire risks in current and expected policymaking in Portugal. Third, we built a systems dynamic model to estimate changes in forest cover and carbon sequestration from the present time to 2100 according to different levels of policy changes from current policies.

Considering that scenario development is an iterative and collaborative process, the scenarios were developed via input (interviews and meetings) from five representatives of the Portuguese Climate Ministry, four modelers at the Bank of Portugal, and two national forest experts. The stakeholder inputs aimed at facilitating strategic thinking and informed decision-making in the face of uncertainty about the future. Moreover, we consulted literature sources on, e.g., carbon density and sequestration, climate change impacts regarding parameters of survival of forests to fires, rates of depopulation, rewilding, fire-related issues, and economic policy instruments. This aimed to shape scenario assumptions and model settings, e.g., considering connections between policies, market incentives, climate impacts, forest species, and carbon densities.

[1] The Portuguese Carbon Neutrality Roadmap (Roteiro para a Neutralidade Carbónica 2050, hereafter Roteiro) (APA 2019) presents Portugal's contribution to the Paris Agreement. It is often referred to as the 2050 Carbon neutrality target, but it is in reality a GHG neutrality target, including various greenhouse gas (GHGs) emissions.

Based on the scenario narratives, we built a computational model in Stella (Structural Thinking, Experiential Learning Laboratory with Animation) (Richmond 1994) to simulate the behaviors and interactions of those critical variables over time. Stella® is a user-friendly and icon-based modeling software for complex systems (Eedara et al. 2019; Patrick Smith et al. 2005). The Stella software was chosen because of its high transparency. It is shown comprehensively in similar research projects modeling climate and impact scenarios (Costanza and Voinov 2001; Oni et al. 2012), illustrating system dynamics and comprising an appropriate modeling approach based on the PT-SSPs' complexity, requirements, and purpose. Socioeconomic variables could be further developed, including more narrative variables. However, we decided to keep the model simple and transparent. The model is a simplification of the real world. It is not a complex Integrated Assessment Model (IAM) as the global SSP models.

Scenario development

From global pathways to national SSP scenarios

The scenario framework employed in this study follows the SSP-SPA-RCP structure, integrating global narratives of socioeconomic development (SSPs), climate targets (RCPs), and policy assumptions (SPAs) to facilitate comprehensive research on climate change dynamics, mitigation, and adaptation (O'Neill et al. 2020; Riahi et al. 2017; Kriegler et al. 2014; Gidden et al. 2019). Within the SSP-SPA-RCP scenario framework, the SSPs describe narratives of socioeconomic development, e.g., future energy and land use, and how the world may evolve in the future (Riahi et al. 2017). The RCPs originally represented radiative forcing pathways, compatible with abstract emission pathways by 2100, that can be translated into temperature increases relative to 1850–1900 (van Vuuren et al. 2011). They were later implicitly included in the SSP-RCP matrix as climate targets and other plausible climate outcomes (Gidden et al. 2019). The SPAs, finally, add standardized policy assumptions to the framework (Kriegler et al. 2014). The SPAs were designed to describe mitigation and adaptation policies and the level of international cooperation to address climate change challenges (Kriegler et al. 2014; van Vuuren and Carter 2014).

The global SSPs are a set of five scenarios that describe plausible future outlooks via a range of demographic, economic, technological, social, energy, and environmental factors (O'Neill et al. 2017; Riahi et al. 2017). Of these, we chose three, SSP1 (sustainability), SSP2 (middle-of-the-road), and SSP3 (rivalry), which comprise a range from high to low population, economic, and emissions growth by 2100. These three SSPs represent a comprehensive range to guide national vulnerabilities and opportunities for mitigation and adaptation challenges (Riahi et al. 2017).

Several types of interconnectedness may exist across global and national scales. Based on Kok et al.'s (2019) operationalization of Zurek and Henrichs' (2007) conceptual approach, we aimed at making the local "consistent" with the global by adapting the global scenario narratives to the specific Portuguese national context, reflecting similar across-scale assumptions (Zurek and Henrichs 2007). We transferred the global SSPs to the national context by mapping SSP storylines and socioeconomic conditions (and SPA climate policy assumptions) to their national counterparts.[2] The PT-SSPs are not one-to-one equivalent to the global SSP narratives. For consistency, we focused on preserving the fundamental SSP characteristics at the national level, allowing for a direct comparison between international and national outcomes, e.g., focus on sustainability and high forest regulation in the PT-SSP1 and low focus on sustainability and short-term fragmented forest regulation in PT-SSP3.

While the national narratives also describe socioeconomic factors, such as economy and population, these variables are not directly included in the model. However, the model's forest policies indirectly reflect future Portuguese socioeconomic and policy conditions. Our considerations regarding regions' diversity of populations and socioeconomic characteristics in developing narratives are reflected in Dias et al. (2020). During this work, we updated estimates from the SSP database (Riahi et al. 2017) and forest scenarios (Chen et al. 2020) to reflect the most recent historical national developments (see SI Chapter 1).

The Portuguese narratives

The national and implicit SPA assumptions differ from low to high policy ambition across the three PT-SSPs. Consistent with the global SSP storylines, PT-SSP1 (long-term sustainable policies) assumes high political cooperation nationally and internationally, less intensive lifestyles, and high national policy regulation based on long-term forest policies stabilizing carbon sinks. The political focus is on conserving the current forest area. In the global SSP3 world, international cooperation is weak, and the world is deglobalizing (Fujimori et al. 2017). Similar assumptions guide the PT-SSP3 narrative. The current trend toward increasing national conservatism continues in several European countries. Such political parties affect the political agenda, which displays a low focus on ecological conservation, limited management

[2] For the SSP-SPA-RCP framework modelers normally put "outside conditions for climate policy" in the SSP and "policies" in the SPA, expressed by the RCPs. Thus, there could be an SSP2-current policy scenario (SSP2-4.5) and a SSP1-current policy scenario (SSP1-4.5), similar to assessments of the plausible effect of current NDC targets.

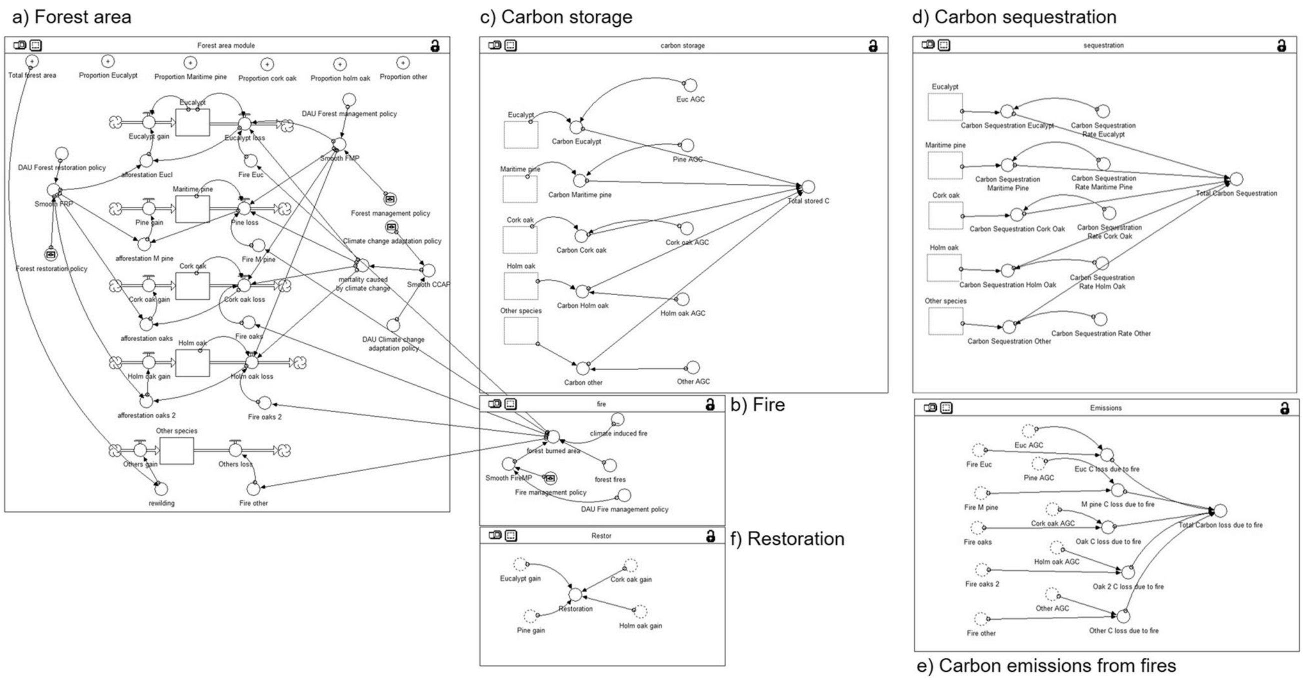

Fig. 1 A Stella system dynamic model diagram for forest area and CO_2 dynamics in 2015–2100 from a mix of four forest policies comprising five key components: (**a**) forest area, (**b**) fires, (**c**) carbon storage, (**d**) carbon sequestration, (**e**) carbon emissions from fires, and (**f**) restoration

practices, and fragmented international cooperation within the United Nations Framework Convention on Climate Change (UNFCCC). Portuguese forest, land, and fire policies develop at the same speed and ambition as in the past decade. Here, national politicians favor short-term economic interests and national security (PT-SSP3) rather than issues related to long-term environmental sustainability (PT-SSP1). PT-SSP2 represents a middle-of-the-road national scenario, including medium–high policy ambition between PT-SSP1 and PT-SSP3. Thus, PT-SSP2 is aligned with the global SSP2 narrative, and the SPA policy assumptions integrated into SSP2-4.5 (Gidden et al. 2019; Riahi et al. 2017), assuming moderate climate policy progress with several efforts to reduce greenhouse gas emissions but not as ambitious as in PT-SSP1. As in the global SSP2, PT-SSP2 assumes a slow decline in the rate of deforestation and intermediate adaptation and mitigation policy efforts.

To ensure credible cross-scenario comparisons, the global mean temperature is constant for all scenarios. It is defined by SSP2-RCP4.5, which is aligned with the current international policy pathway where current NDC targets are achieved (2.6 C) (Carvalho et al. 2020; UNEP 2023). The model does not include temperature but uses the same average increase in annual climate-induced fires for all scenarios (UNEP 2022).

National policy assumption variables

The rather complex PT-SSP narratives express essentially "long-term" (PT-SSP1) versus "short-term" (PT-SSP3) political and societal focus. These are translated into more simple policy variables that aim to inform our transparent model (Fig. 1). The numerical parameters differ between the three scenarios via four policy variables, reflecting the policies' degree of sustainability and robustness in addressing key forest challenges. The PT-SSPs have climate-induced fire risk and forest and fire policies as key input variables, analyzing how policy options may affect future forest area and emissions sequestration. Inspired by historical and current Portuguese forest policies (Dynamics-as-Usual (DAU)), we translated the global land-use and forest narratives into four Portuguese policies guiding the three PT-SSPs: fire management (P1), forest management (P2), climate change adaptation (P3), and restoration (P4).

P1 generally corresponds to the 2020–2030 National Plan for Integrated Rural Fire Management (PNSGIFR) (AGIF 2020). It is still to be completed. In 2018, the PNSGIFR replaced the previous National Defense System Against Forest Fires (Decree Law No. 124/2006 of 28 June) after the high-impact fire events in 2017. Notably, the existing PNSGIFR (and PROF, see below) were not designed to address climate change. The integrated fire management system (SGIFR) is in force until 2030, aiming to reduce burned areas and fire severity.

P2 refers to forest planning instruments inspired by the National Forest Strategy and Forest Regional Plans (PROF) (GoP 2014). PROF concerns forest and landscape change. The Regional Forest Plans that define the standards for the coming decades are very conservative and do not promote change in forest cover and management and landscape composition and configuration. For example, the revised PROF for the 2020–2040 period maintains the limits of occupation of individual forest types of the previous PROF and does not favor silvicultural models of species relative to maritime pine and eucalyptus.

P3 corresponds to adaptation policy in the forest sector, which does not yet exist. However, adaptation is becoming transversal to Portuguese society, exemplified by the Portuguese adaptation roadmap project (RNA2100) (Soares and Lima 2022). Since 2010, a National Strategy for Climate Change Adaptation has been renovated in 2015 (PdR 2015). However, its implementation has been slow and limited. According to a recent climate law, regional plans for adaptation to climate change are expected to be developed (AdR 2021). Adaptation in the forest sector is expected to result from fully implementing the newly developed Landscape Transformation Programme – LTP (Resolution of the Council of Ministers No. 49/2020) (GoP 2020).

P4 concerns forest restoration policies, which have been modest (almost absent) in Portugal and have had a limited impact. The term restoration may include a lot of different initiatives, from ecological restoration of habitats to large-scale afforestation programs. There are existing programs for emergency measures in some burned areas after fires, but these are very localized and often applied too late to have an impact (to stop degradation in these areas). Therefore, Portugal has no restoration policy, but some Common Agricultural Policy (CAP) measures dealing with afforestation and emergency measures after fire. Unlike our policy approach, Portuguese policies have not yet included significant financial instruments for forest restoration, and most areas affected by fires in 2017 have not yet been restored. Financial instruments may include financial assistance to farmers or landowners for planting new trees on burned or degraded land.

In the case of Portugal, the critical divide is introducing structural reforms into forest and fire management policy. Increasing ambition in the implementation of existing policies (P1 and P2), an existing policy "idea" (P4), plus specific adaptation measures (P3) adequate to PT-SSP1. Extending current policy ambition trends without structural changes would fit into PT-SSP2. In contrast, the policies up to 2017 are typically PT-SSP3 (including low policy with high challenges to address mitigation and adaptation. Notably, policy progress has materialized since 2017.

In the PT-SSP2 and PT-SSP1 scenarios, policies are strengthened and adapted to fire and climate change impacts. Here, anticipative forest protection policies will be implemented between 2025 and 2035. These are indirectly assumed to affect population migration and the development of market-based mechanisms to incentivize landowners to adopt sustainable land-use practices and increase the carbon sequestration potential of their lands (however, not directly included in the model) for forest management (P2) and restoration (P4). The scenario policy narratives are described in Table 1 and how they are used in the model as driving variables (see The "Model description and specifications" section).

Model description and specifications

Figure 1 presents the stochastic dynamic system model to predict changes in forest area in Portugal by 2100 and associated carbon sequestration and storage potential. The Stella® software has been used to construct a variety of forest models for biomass dynamics (Timmons et al. 2016), depletion of forest stock (Jathar and Rahmani 2011), and biomass production (Ouyang et al. 2021).

The model comprises five components. In the first component (a), dedicated to forest cover, we set forest cover (in ha) of the four major tree species in continental Portugal (eucalypt, maritime pine, cork oak, and holm oak) plus the remaining species (other species) as stocks affected by restoration or rewilding (inflows) and fire and/or mortality caused by climate change related factors (outflows). Restoration is the establishment of new forest areas. It is controlled by the forest restoration policy, which defines the percentage of the areas lost in a specific year due to fire and mortality that are replanted the following year. In the case of other species, forest area growth is determined by rewilding, a rate relative to the percentage of other land uses (farmland and shrubland) that become forest due to the natural establishment of trees. Tree mortality caused by climate change is a rate representing the direct and indirect effects of climate change (droughts, pests, and disease outbreaks). It is affected by climate change adaptation policy. Forest cover is affected directly by forest management (P2) and indirectly by fire management (P1) policies. In the fire component (b), the forest burned area is the forest area lost to fires that affects all species and depends on fire management policy and climate-induced fire (the aggravation of larger fires over time).

The model also contains carbon components (c, d, e), covering storage and sequestration calculated directly based on forest area per class, assuming general constant carbon densities and rates in these pools, and emissions from forest fires alone, assuming all carbon stored in forest cover will be released to the atmosphere. Finally, restoration (e) calculates

Table 1 Policy variables, their use, and settings in the model

Policy variable	Policy description	Model use	Scenario settings
Policy 1. Fire management	P1 reflects the conditions of the new PNSGIFR in forest fires (forest burned area) and has multiple implicit dimensions of fire management, from awareness to firefighting. This variable is part of the Fire component of the Stella model	Ranges from 0 (forest burned area equal to zero) to 1 (forest burned area equal to burned area expected according to historical fire records) Example: PT-SSP1 settings express 50% of the expected burned forest area	PT-SSP1: 0.5 PT-SSP2: 0.7 PT-SSP3: 0.9
Policy 2. Forest management	P2 reflects efforts at the stand and landscape levels to reduce fire spread and severity. It reflects the survival of trees and regeneration after a fire, assuming that large intensive fires affect the proportion of the burned forest area that can regenerate after a fire (or that is lost to non-forest cover classes). This implies measures to motivate forest owners to claim and manage forest areas, reducing fire risks	Ranges from 10 to 30% of the area affected by fire yearly per species, assuming that forests affected by fire can recover between 70 and 90% of its forest cover in the following year due to the survival of trees and natural regeneration. It is based on a very conservative value range since it is a sensitive variable challenging to quantify because the factors that affect forest loss related to fire are diverse (e.g., terrain, major species, age of stands, and time between consecutive fires). Example: PT-SSP1 settings express a 10% loss of forest area due to wildfires	PT-SSP1: 0.1 PT-SSP2: 0.2 PT-SSP3: 0.3
Policy 3. Climate change adaptation	P3 represents the efforts to change the composition (species or genotype replacement) and management (stand structure, density, harvesting) of forests to cope with climate change and its expected impact on Portuguese forests. It involves mostly adaptation measures and affects the model through mortality due to climate change. The absence of adaptation measures increases tree mortality (and forest area loss). This policy considers the redistribution of forest species according to optimal climate conditions, considering climate trends (toward the Northwest)	Climate change policy is 0 when policies implement measures to assure that there is no mortality due to lack of adaptation and is 1 when mortality due to climate change is 100% since no adaptation measures have been implemented Example: PT-SSP1 expresses 0% mortality due to climate change	PT-SSP1: 0 PT-SSP2: 0.5 PT-SSP3: 1
Policy 4. Forest restoration	Policies to restore burned forest areas. P4 aims to control the restoration variables in each forest class, comprising inputs of new forest areas, including all types of national restoration actions. It is named restoration, considering the availability of degraded forest areas that require restoration and expressing the need to address forest recovery from a restoration perspective more than from the classic afforestation perspective	In the best policy scenario (PT-SSP1), the restoration area is up to two times the forest area lost in a year (for all species but eucalypt that is limited to a max of 845 kha; other species expand spontaneously and are not affected by this policy). In the worst scenario (PT-SSP3), restoration occurs in 10% of forest areas lost Examples: PT-SSP1 expresses 200% of the burned area in the previous year that was restored	PT-SSP1: 2 PT-SSP2: 1 PT-SSP3: 0.1

the overall area of forest expansion due to restoration practices (forest area component).

Quantitative model specification

The initial forest cover state variables (stocks) values were established based on the latest Forest National Inventory (ICNF 2015). Eucalypt area growth is limited to a maximum area of 845 kha, its current area, due to legal and ecological reasons. There is no limit to the expansion of maritime pine, cork oak, and holm oak. Forest area growth for all types except "other species" is defined via restoration, calculated based on forest loss and the strength of the restoration policy (P4). Expanding forest area under "Other Species" is based on a rewilding annual rate established as 0.05% of the non-forest area of mainland Portugal, assuming that abandoned land is converted to forest land at that rate.

The rate of climate-induced fires shifts gradually from 1 to 1.5 times in the 2015–2100 period according to the global UN Environmental Programme estimates (related to a 2.6 °C increase of global temperatures (UNEP 2022), equivalent to SSP2-4.5 (Gidden et al. 2019). The forest burned area was calculated based on a forest fire random variable following a log-transformed normal distribution with a mean of 4.60165 and a standard deviation of 0.42067 corresponding to the historically burned forest area statistics in Portugal (1990 to 2020). This represents the potential forest burned area in the country under the conditions observed in the last 30 years (EFFIS 2023).

For the carbon component of the model, we used central estimates of wide ranges of figures collected from available data on above- and below-ground carbon density (Cunha et al. 2021) and carbon sequestration (Pereira et al. 2009). The carbon component of the model is susceptible to carbon stocks and carbon sequestration rate estimates per forest type. The carbon stocks in the Portuguese forest calculated by the latest National Forest Inventory were compared with other estimates in the literature. The lack of soil organic carbon in the model was due to the impossibility of representing this attribute reliably due to significant variations in estimates and the ecological heterogeneity of the country. The forest fires carbon emissions component calculates emission by multiplying the forest area lost due to fires in forest types by the correspondent stored carbon amount.

As stated earlier, the scenario narratives and policy assumptions are translated into numerical values expressing "long-term" versus "short-term" political and societal focus and the degree of sustainability and robustness of policies in addressing key forest challenges as regards climate impacts. Policies are included in the model as variables affecting processes leading to forest expansion, burned area, and mortality. They are defined as factors ranging from 0 to 1 in the case of fire management and climate change adaptation policies, 0.1 to 0.3 in the forest management policy, and 0 to 2 in the forest restoration policy (see specific scenario settings in Table 1).

When the fire management policy is equal to 1, fire management policies do not affect reducing the annual burned area. When it is equal to 0, there is absolute control of fires, meaning no burned area. In PT-SSP1, fire management policies (P1) are set at 0.5, indicating that P1 policies are strengthened to a degree that reduces the burned annual forest area to 50%. The current policies scenario (PT-SSP3) is set to value 0.9, resulting in 90% burned areas. In the worst-case scenario, PT-SSP3, we assume a small improvement compared to the last 30 years. The improvements are due to spontaneous policy responses within the fire management sector to catastrophic wildfires, as in 2017 (EFFIS 2023).

In the forest management policy (P2) case, a value of 0.1 means that 10% of burned areas in a year will be definitively lost, whereas a value of 0.3 means that 30% of the forest area affected by fire will be lost to other land use classes. A climate change adaptation policy (P3) equal to 0 implies successful implementation of adaptation measures and results in zero tree mortality due to climate change, whereas 1 indicates no adaptation policy or unsuccessful implementation. Mortality due to climate change is equal to 0.005 of the forest area per year. The mortality rate is based on the assumption that Portugal would lose all current forests due to climate change alone in 200 years (this is a moderate assumption considering current literature). A forest restoration policy (P4) equal to 0 indicates zero restoration, and equal to 2 means annual restoration equal to twice the forest area loss in the previous year. For a complete description of model specifications, see Table 1–1 to 1–6 in the Supplementary Information (SI) Chapter 4.

Model evaluation

Model evaluation was based mainly on the model structure and behavior, assessing the reasonableness of the model structure and interpretability of functional relationships within the model, and the correspondence between model behavior and expected patterns of model behavior (Grant and Swannack 2008). A sensitivity analysis was conducted on model outputs of burned area, total forest area, and carbon stock and sequestration to changes in critical parameters, one by one. The model was validated using historical observations of forest stands (2005–2020), ensuring that the results of the PT-SSP3 model settings accurately reproduced the observed forest area patterns and variability, excluding the increase in climate-induced fire effect.

The carbon component of the model is entirely dependent on carbon stocks and carbon sequestration rate estimates per forest type. Estimates of the carbon component of the model were compared with other literature sources to evaluate the model's carbon components. Our model estimates carbon stocks ranging from 71 to 67 MtC in the Dynamics-as-Usual (DAU) scenario for the initial 10 years (2015–2025), which is reasonable and acceptable for this research. Roteiro aims to reach a sequestration rate of 13 million tons ($MtCO_2e$) annually from 2030 till 2050, assuming forests sequestered 9 $MtCO_2e$/year in 2015 (APA 2019). The latest National Emissions Inventory report estimated sequestration ranging from − 10,292 to 21,454 $MtCO_2e$/year from 1990 to 2020 (APA/UNFCCC, 2022). Ameray (2018) estimated forest sequestration rates ranging from 18.9 to 20.7 $MtCO_2e$/year between 1995 and 2010, while our model's estimates for the 2015–2025 period ranged from 36 to 40 $MtCO_2e$/year, which is higher than other estimates based on other methodologies.

However, there are significant differences between what our model estimates based on the set of parameters used and the estimates available in other sources that were produced for particular conditions that our model does not address. The estimates of carbon emissions due to forest fires are within the range of values found in the literature (San-Miguel-Ayanz et al. 2022) and reports of the Copernicus Atmosphere Monitoring Service (https://t.co/B4aDuUArt2). They differ from the National Emissions Inventory

Table 2 Estimates of forest area, carbon sequestration and storage, and new forests due to restoration at selected dates from 2015 to 2100 for three PT-SSP scenarios: *PT-SSP1* long-term sustainable forest policies, *PT-SSP2* moderately increased policy ambition, *PT-SSP3* no-change in current policies. Estimates are averages of 100 model simulations

Scenario							Variation (%)	
	2015	2020	2030	2050	2080	2100	2015–2050	2015–2100
Forest area (kha)								
PT-SSP1	3224	3100	2970	3101	3309	3442	96%	107%
PT-SSP2	3224	3103	2944	2999	3087	3145	93%	98%
PT-SSP3	3224	3103	2877	2438	1802	1455	76%	45%
Restoration (kha)								
PT-SSP1	2	3	11	7	8	8	347%	386%
PT-SSP2	2	3	13	16	18	16	930%	904%
PT-SSP3	3	3	3	2	2	1	82%	24%
Carbon storage (Mt C)								
PT-SSP1	71	69	66	70	75	78	98%	110%
PT-SSP2	71	69	66	67	70	72	95%	101%
PT-SSP3	71	69	64	56	44	38	79%	53%
Carbon sequestration (Mt C/year)								
PT-SSP1	11	10	10	10	11	11	92%	102%
PT-SSP2	11	10	9	9	10	10	87%	88%
PT-SSP3	11	10	9	7	3	2	63%	15%

report (APA/UNFCCC 2022). However, these are not directly comparable since they reflect balances of emissions within the land use, land-use change, and forestry classes that are diverse. Despite its sensitivity to sequestration rates, we believe the model accurately reflects the overall trends of sequestration resulting from changes in forest cover across Portugal. Based on the results of the evaluation procedures followed, we considered the model valid for this research.

Model use

The model was established and run annually (DT = 1) for periods of 85 years, covering 2015–2100. 2015 is the reference year since the most updated forest inventory data are for that year (ICNF 2015). Policy settings are similar for all scenarios between 2015 and 2025. Hereafter, they change from current policy settings to the settings corresponding to each scenario tested. The model results are based on averages

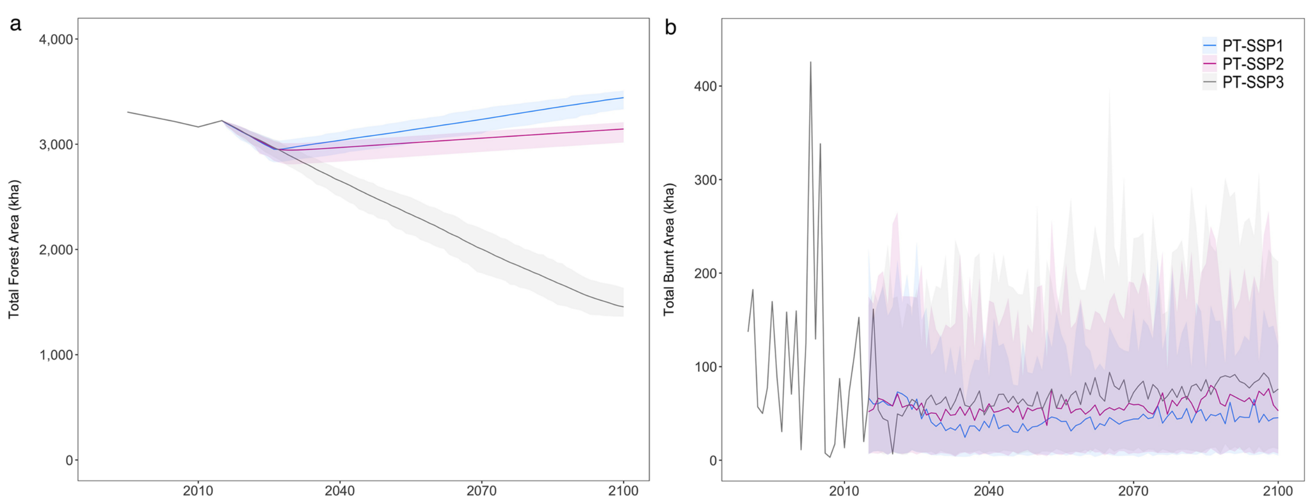

Fig. 2 Simulations of the total Portuguese forest area (**a**) and annual burned forest area in 2015–2100 (**b**) under three policy-mix combinations: long-term sustainability policy scenario (PT-SSP1, blue), moderate policy ambition (PT-SSP2, red), and no-change in current policies (PT-SSP3, gray). Estimates and uncertainty ranges are represented by averages ± 5–95% percentiles, measuring the variability in the simulation results based on 100 simulations per scenario. Graphs also include observed data before 2015 (and thus not the historical 2017 fires due to a lack of historical data post-2015)

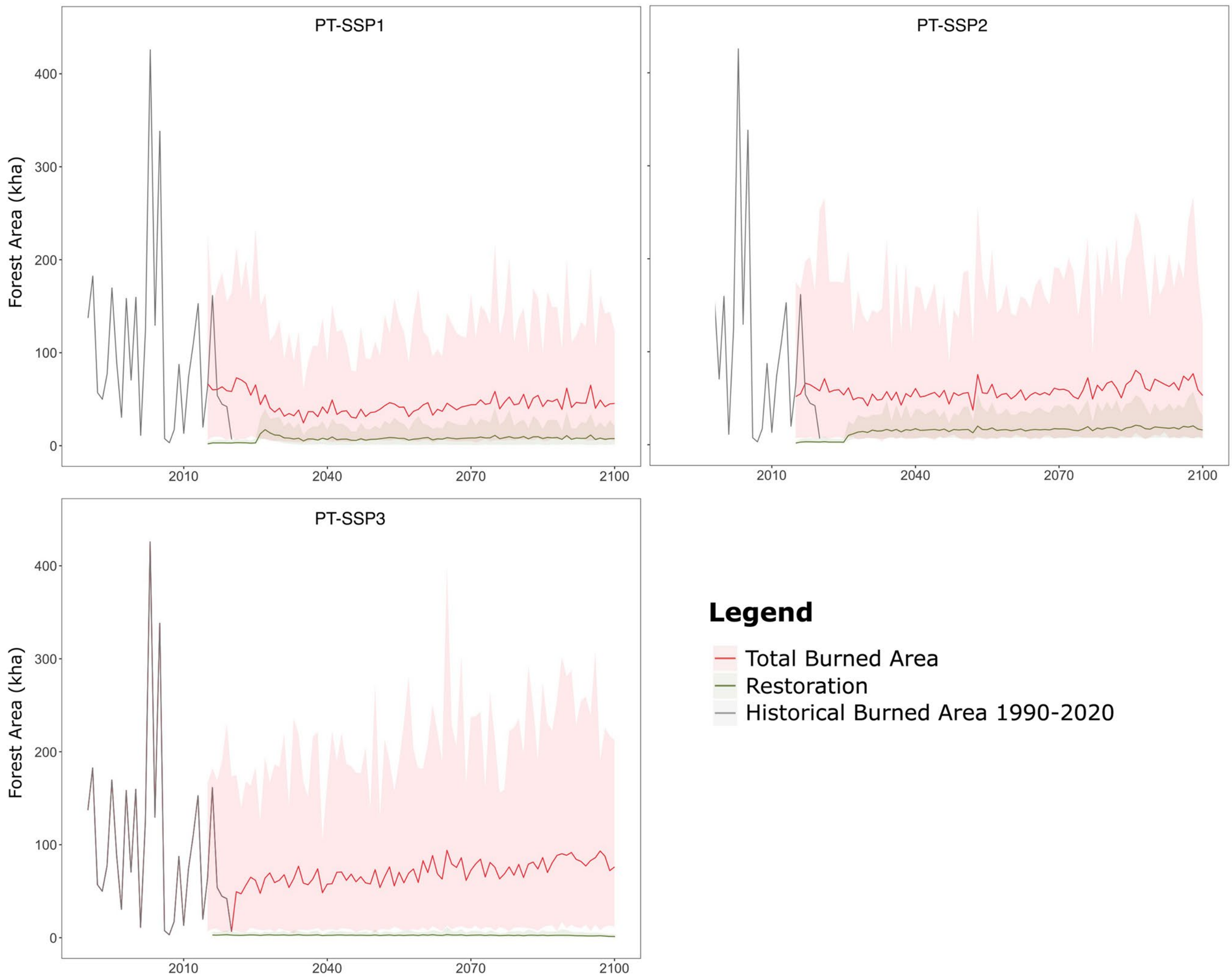

Fig. 3 Projections of burned area (red line) and area of restoration (green line) 2015–2100 under three policy-mix scenarios: a continuation of current trends (PT-SSP3), a middle-of-the-road medium policy ambition (PT-SSP2), and long-term sustainability scenario (PT-SSP1) reflecting the policy-mix implementation. The figure expresses averages ± 5–95% percentiles. Historical data source: EFFIS (2022). Notice that historical data do not include 2017 (a year of massive fires)

and a confidence interval of 5–95% percentiles based on 100 runs/simulations per scenario, under the settings considered for each PT-SSP scenario (Table 1).

Results

Forest cover

The model simulation results showed that without any policy change, in the baseline scenario (PT-SSP3), the Portuguese forest area will decrease rapidly to about 75% by 2050 compared to 2015 levels, reducing carbon sequestration to 63% of 2015 levels (Table 2). In case of strengthened policy ambition (existing fire and forest management policies and newly introduced policies adaptation and restoration policies) implemented between 2025 and 2035, the forest area may almost recover by mid-century to 96% in PT-SSP1 and 93% in PT-SSP2 (Fig. 2), with carbon sequestration levels recovering to 92% and 87% of 2015 levels, respectively (Fig. 5).

After policy implementation, from 2025 to 2035, the forest area is projected to increase in PT-SSP1 and PT-SSP2 by 4% and 2% between 2030 and 2050, respectively. If policies continue without increased ambition (PT-SSP3), the total forest area is projected to decline by 15% during the same period (Fig. 2; Table 2).

Considering future climate change, it is unlikely to avoid a reduction of the total burnt area unless active forest and fire management policies are implemented. As illustrated in Fig. 2b, PT-SSP1 projects a decling burnt area from around 60 kha in 2015-2020 period to 34 kha/year in 2050 (-44%), while the PT-SSP3 no change continuation of current forest policies (PT-SSP3) is projected to slightly increase burnt areas to 64 kha/year in 2050 (+9%). In comparison, Roteiro's Yellow Jersey projects burnt area (not exclusively forest area) will decrease from about 150 kha/year in 2020 to 70 kha/year in 2050 (-54%) (APA 2019). In 2100, burnt areas are projected to decline from around 60 kha/year (2015-2020) to 48 kha/year (-22%) in PT-SSP1, and increase to 65 kha/year (+9%) in PT-SSP2 and 83 kha/year (+40%) in an PT-SSP3 future.

Figure 3 and Table 2 show that restoration slowly declines in PT-SSP3 after 2050, while it increases in PT-SSP2 and PT-SSP1 due to P4 restoration policies. PT-SSP2 restoration is higher than PT-SSP1 because of a higher annual burnt area in PT-SSP2.

Figure 4 shows declining projections of holm oak, cork oak, eucalyptus, and maritime pine between 0.6 and 1.5% per year until 2025 in all scenarios. Eucalyptus (−1.3%/year) and maritime pine (−1.5%/year) most rapidly, while cork (−0.6%/year) and holm oak (−0.8%/year) decline at a slower rate. This declining trend continues in PT-SSP3, while the curve changes for PT-SSP1 and PT-SSP2. This is an effect of adjusted forest policies implemented between 2025 and 2035. Forest stands start stabilizing around 2028 for PT-SSP1 and 2045 for PT-SSP2. The Other species category has a projected increase of about 0.4%/year throughout the century due to natural expansion.

In 2015, "Eucalyptus," "Cork oak," and "Maritime pine" comprised the largest shares of Portuguese forest areas. The long-term policies scenario (PT-SSP1) increased eucalyptus and maritime pine areas post-2030 due to the climate adaptation and restoration policies. In comparison, in Roteiro's Yellow Jersey scenario projections, maritime pine and eucalyptus decline while oaks and other species increase (APA 2019). In all scenarios, "Other species" are favored in the long run, becoming the dominant forest class in 2100 since rewilding was assumed to be a permanent process acting at a constant rate.

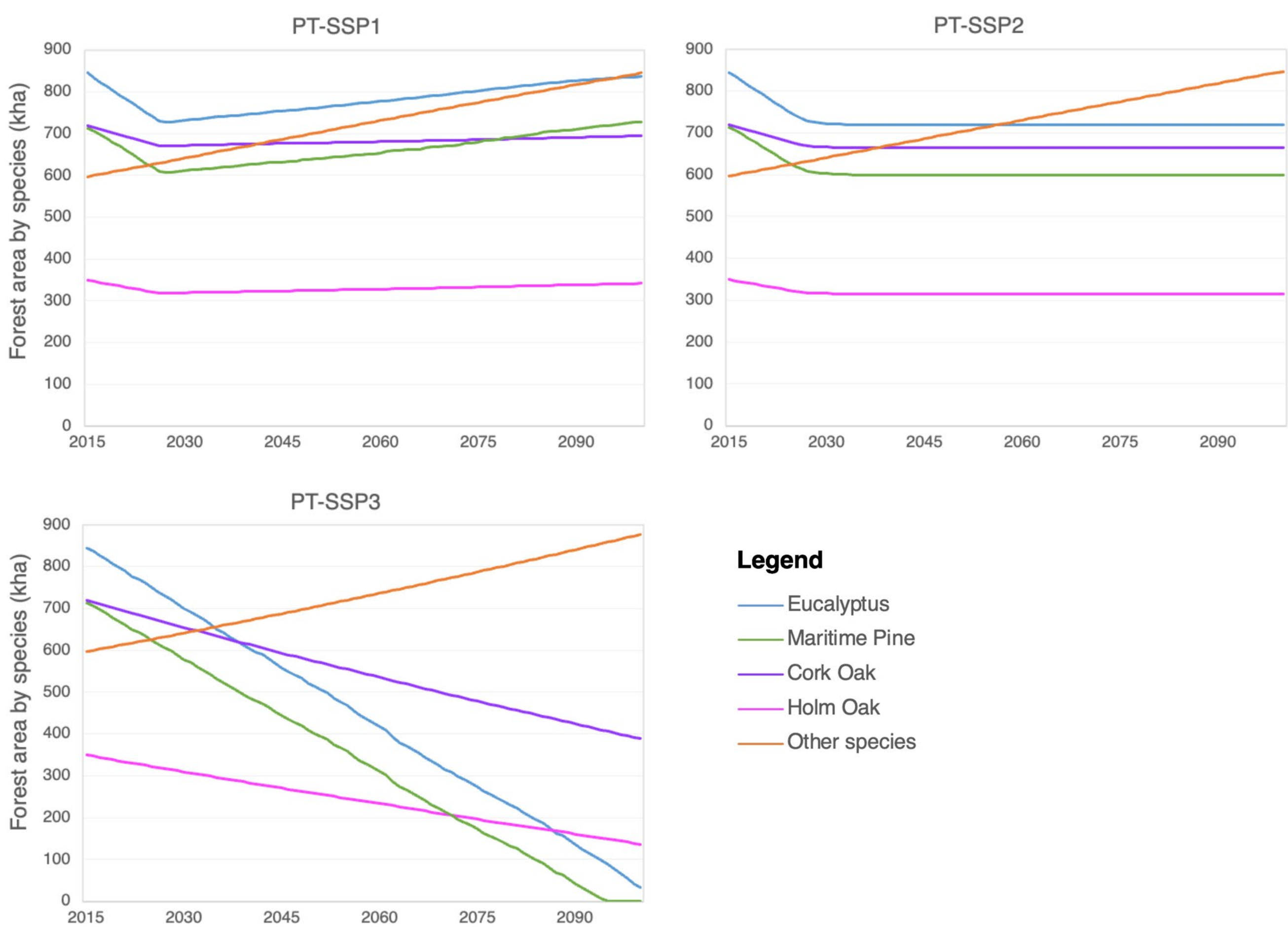

Fig. 4 Projected mainland Portugal forest area by species 2015–2100 under the three policy scenarios: a continuation of current trends (PT-SSP3), moderate policy ambition (PT-SSP2), and long-term sustainable policy scenario (PT-SSP1). The scenarios reflect implementations of the four examined forest policy-mix implementations. The figures express the averages of 100 simulations. The historical data source for 2015 is based on EFFIS (2022)

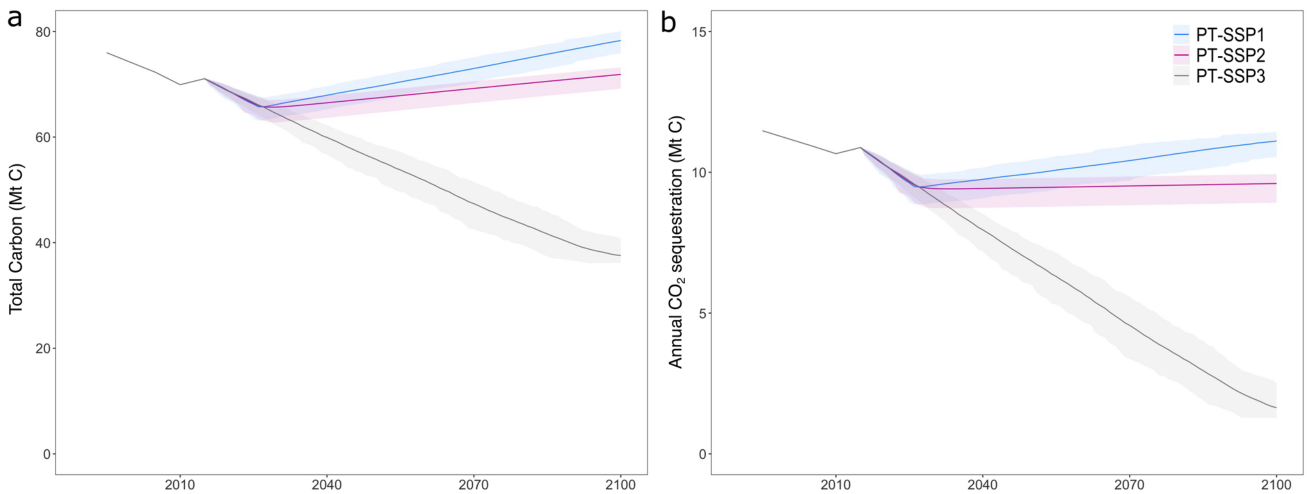

Fig. 5 Scenarios of total carbon storage (**a**) and annual carbon sequestration (**b**) 2015–2100 under three policy-mix scenarios: a continuation of current policies (PT-SSP3), medium policy ambition (PT-SSP2), and long-term sustainability scenario (PT-SSP1) reflecting implementations of the forest policy mix implementation. Estimates represented by averages ± 5–95% percentiles based on 100 simulations per scenario

In the PT-SSP1 scenario, by 2050, 90% of eucalyptus areas will persist compared to 2015 levels, while with moderate policies (PT-SSP2), 85% will remain, and without improved policies, only 60% of Portuguese eucalyptus areas will remain in 2050 (PT-SSP3). According to our model, the eucalyptus forest will almost disappear from the Portuguese mainland covering 43 kha in 2100 (6% of 2015 levels) in case no changes are made to the current policy approach (PT-SSP3). Maritime pine will practically disappear, covering only 1% of 2015 levels in 2100 (6 kha) in the PT-SSP3 scenario. Implementing adaptation policies, considering higher suitability in the north for these species, reduces the impacts of climate change, as illustrated in PT-SSP1 and PT-SSP2.

Carbon storage and sequestration

As shown in Fig. 5, our model projects a rapidly decreasing annual carbon sequestration of 1.5% per year between 2015 and 2050 under current policies (PT-SSP3). In case of strengthened policy ambition (existing and newly introduced policies) implemented starting between 2025 and 2035, carbon sequestration rates are projected to increase 0.03%/year (PT-SSP2) and 0.2%/year (PT-SSP1) between 2040 and 2050. Sequestration rates in 2050 are projected to be 63%, 87%, and 92% of 2015 levels in the PT-SSP3, PT-SSP2, and PT-SSP1 scenarios, respectively (Table 2). In 2100, carbon sequestration will have recovered to 88% of 2015 levels in PT-SSP2, while in PT-SSP1, it is projected to be similar to 2015 levels by the

Table 3 Comparing shares of forest species in 2015 and 2050 between PT-SSP1 and Roteiro's Yellow Jersey long-term sustainability scenarios (APA 2019)

	PT-SSP1					Roteiro Yellow Jersey				
	2015		2050			2015		2050		
Forest type	Area (kha)	Share (%)	Area (kha)	Share (%)	Change 2015/2050	Area (kha)	Share (%)	Area (kha)	Share (%)	Change 2015/2050
Eucalyptus	845	26%	761	25%	− 10%	850	19%	670	20%	− 21%
Maritime pine	713	22%	636	21%	− 11%	1180	27%	970	25%	− 18%
Cork oak	719	22%	678	22%	− 6%	930	21%	1060	23%	14%
Holm oak	349	11%	325	10%	− 7%	600	14%	650	14%	8%
Other species	597	19%	701	23%	17%	800	18%	950	17%	19%
Total	3224	100%	3101	100	− 3.8%	4360	100%	4170	100%	− 1.4%

Other species—PT-SSP1: other oaks, chestnut, stone pine, and other trees (this study, based on ICNF (2015)); Other species—Roteiro, Yellow Jersey: oaks, other leafy trees, stone pine, and other resinous trees (Roteito (APA 2019)) end of the century (102% of 2015 levels). In PT-SSP3, it has declined to 15% of 2015 levels, according to our projections.

The current (2015) carbon storage in living biomass is assessed at 71 MtC (Baseline). It is projected to decrease to about 56 MtC in 2050 and 38 MtC in 2100 under the no change in current policies scenario (PT-SSP3) (Fig. 5). Assuming increased policy ambition on an intermediate level (PT-SSP2), the Portuguese carbon stock will drop between 2015-3030 and then increase to about 67 MtC by 2050 and 72 MtC (by 2100, proceeding 2015 levels. Under the more ambitious policies implemented from 2025 (PT-SSP1), the forest stock is projected to reach 2015 levels around 2060 and increase to 78 MtC by 2100. Carbon sequestration follows similar patterns in the simulated period.

Discussion

We created a model to examine changes in forest area resulting from policy changes, assuming that forest area plays a significant role in carbon dynamics. Our results indicate that the current forest cover in Portugal is unlikely to be sustained under the current policy approach due to the direct and indirect effects of climate change. Portugal's relatively low EU effort-sharing obligation by 2030 is achievable despite a drop in forest area. However, it is uncertain if Portugal can reach its 2050 net-zero targets. Yet, the scenario-based results indicate that forest cover and carbon sequestration declines can be tackled extensively through appropriate policies.

Our model does not explicitly consider the mechanisms responsible for carbon emissions and sequestration in forest areas or account for variations in emission and sequestration rates based on factors such as forest age and productivity. The model also disregards age structure or forest site growth. These limitations are considered when interpreting the results. In addition, to provide a transparent model, the scenario narratives are translated into simplified or straightforward variables.

Forest cover

There are few forest cover projections for Portugal. In 2009, researchers assumed a decreasing trend of the primary forest species eucalyptus, maritime pine, holm cork, and holm oak, which comprise 85% of Portuguese forest cover (Pereira et al. 2009). More recently, the Roteiro scenarios projected a total forest area decrease of 4–5% between 2015 and 2030 and 1.5–6% between 2015 and 2050. These projections include afforestation initiatives of 8 kha annually (APA 2019), which was not part of the PT-SSP assumptions. Notably, afforestation, in the PT-SSPs, is equivalent to the new forest due to the restoration policy that was implemented in the model but does not comprise an expansion of the total forest area (Table 1).

Projections in the Portuguese GHG emissions inventory assume a forest increase of 2% (from 4118 to 4215 kha) between 2021 and 2025 (APA 2020). According to World Bank estimates (for Portugal Mainland, Azores, and Madeira), there has been an almost unchanged forest cover from 2015 to 2020 (WB 2023b). On the one hand, it shows the difficulties in scenario developments and, thus, the importance of implying various plausible future outcomes. On the other hand, it underlines the extent to consider long-term trends (decades) rather than short-term variability (5 years) when developing future scenarios (Pedersen et al. 2021; van Vuuren et al. 2010).

Table 3 shows differences in forest species composition in PT-SSP1 and Roteiro's GHG neutrality scenario. Although the Roteiro and SSP scenarios are not directly comparable because of the difference in starting points, comparing our model's results with Roteiro's expectations is relevant. Similar tendencies exist, such as maritime pine and eucalyptus decreasing in both scenario series' sustainability scenarios (PT-SSP1 and Yellow Jersey) and projecting overall forest decline.

Future forest cover depends on various factors, including wildfire, climate change, and policies. Expecting that climate change impacts will likely increase (IPCC 2022; UNEP 2022), our model addresses policy efforts and strategies of various ambition levels. Considering existing policies, the National Forest Strategy of 2015 (GoP 2020) has the ambition of retaining the forest cover of 2010 by 2030, not excluding the ambition of the previous National Forest Strategy of 2006 of 3500 kha, the largest forest area ever in Portugal (GoP 2020). However, several constraints were identified in these two policies, particularly fires and climate change (see the "Policy opportunities" section). Our results indicate that only a combination of efforts at all levels is able to cope with increasing fire and climate change impacts. Without climate change adaptation (P3), considering redistributing stands according to the most optimal ecological and climate zones, eucalyptus and maritime pine are projected to vanish from Portugal between 2075 and 2100, and other species will suffer significant declines (Fig. 4). Without efficient fire and forest management policies (P1 and P2) and increasing efforts to restore degraded land (P4), forest cover in Portugal at the end of the century can be less than half of today's cover (Fig. 4, Table 2). The results of the scenario simulations indicate that to maintain the current forest cover in the future, it is required that forest burned areas are reduced to 50–70% of the average of the last decades, tree mortality in burned forest stands is lower than 20%, mortality due to climate change is less than 0.5% per year, and that the same or twice the forest area lost to fires is afforested annually.

Portuguese commitments and targets

Portugal's EU LULUCF effort sharing commitment of 5.8 Mt CO_2/year by 2030 (EC 2018) is within the range of the three PT-SSPs by 2030. The scenarios project a decline of sequestration rates to 84–88% of 2015 levels by 2030. The target allows Portuguese carbon sequestration to drop to 53% of 2015 levels (from 10.9 to 5.8 Mt CO_2/year) based on the scenario estimates.

To reach the Portuguese the net zero target (NZT) of 13 Mt CO_2/year by 2050 (APA 2019)[3]sequestration needs to increase by around 120% (from 10.8 to 13 Mt CO_2/year). PT-SSP1 and PT-SSP2 break the curve of declining sequestration rates around 2040, diminishing the loss in sequestration rates to 92% and 87% by 2050, respectively. On the contrary, with continuation of current policies (PT-SPP3) carbon sequestration is projected to decline to 63% by 2050.

Policy opportunities

Our results show a need to revise current policies and implement changes promptly to ensure the long-term stability of Portugal's forests. By leveraging existing policy instruments, resources, and economic incentives, Portugal may stabilize forest cover and carbon sequestration and contribute to a more sustainable future society. The opportunity lies in timely and comprehensive action, combining scientific knowledge, innovation, and societal support for successful forest management and climate mitigation. We suggest protecting highly productive landscapes (a), restoring areas affected by fires (b), and managing naturally expanding forests (c).

(a) Protect and maintain high-productivity forest regions dominated by maritime pine and eucalypt, as they are crucial in carbon sequestration, economic value, and social importance. Implement policies to ensure their productivity remains optimal by adapting management to changing climate conditions and is easily implementable due to the existence of policy instruments and resources (e.g., land use data, regional forest plans, Cork Oak Protection Law, PRR) (RP, 2023, 2022, 2006) and economically attractive to local owners and industries. Proper selection and management, considering climate changes, should maintain these areas' stability from 2022 to 2100 and target changes in the distribution of the species to respond to changes in environmental envelopes. However, maintaining optimal productivity will depend on industry capacity and effective public policies.

(b) Establish timely and extensive restoration measures for areas affected by fires, especially in high-hazard regions with recurrent fire incidents. Utilize funding opportunities like the Landscape Transformation Program (PTP) (with PRR support) for large-scale restoration of degraded areas and adopting agroforestry systems with high carbon sequestration potential.

(c) Embrace new forest cover established naturally in abandoned farmland or disturbed forestland as opportunities for climate action. Encourage rural development paradigms that combine scientific training and innovative practices to ensure effective carbon sequestration. Leverage conservation associations and qualified young professionals to shape forests in such areas while maintaining traditional activities and sustainable forest use. In addition, afforestation policies in current farmlands.

Policy changes and challenges

Plausible policy changes are illustrated in PT-SSP2 and PT-SSP1. In the PT-SSP1 and PTSSP2 scenarios, burnt forest areas are reduced by 45% and 9%, respectively, in the 2045–2050 period compared to 2015–2020. On the contrary, forest fires increase by 9% PT-SSP3. In PT-SSP1, strong fire management policies (P1) and forest management policies (P2) result in a declining burnt forest area number of fires from around 61 kha (2015–2020) to about 34 kha (2045-2050). In PT-SSP3, the number of fires is projected to increase by approximately 74 kha annually. In PT-SSP1, projected forest stands are about 3100 kha in 2050, near 2015 levels (3224 kha), while PT-SSP3 projects a decline to 2400 kha by 2050.

To ensure a relatively stable future forest area in Portugal, we suggest strengthening policies in fire (P1) and forest management (P2), introducing climate adaptation policies (P3) to protect forest stands, and additionally improving restoration actions to rewild burnt areas (P4). The PT-SSP1 considers expansion in forest cover as part of restoration policies and may also result from rewilding in abandoned land burnt areas. Furthermore, Roteiro introduced afforestation as a fifth policy option, which could be included in future PT-SSP elaborations. In our model, rewilding represents a spontaneous expansion of forest cover in the country, resulting in woodlands. Although this is not a policy option in the model, its implementation could be favored by rewilding policies, at least in part of the country. Other research states that wild forest has higher energy efficiency (e.g., lower day temperatures) than human-managed forests (Norris et al. 2011), which may increase climate change and fire resilience against rising temperatures (Moomaw et al. 2019; Moreira et al. 2020).

[3] Notably the NZT implies also and uses (agriculture, urban areas, wetlands or swamps), not considered in the PT-SSPs.

Policy challenges

There are several obstacles in forest management in Portugal to consider in policy designs, including:

1. Climate change: Portugal is facing increasing risks of wildfires due to climate change, with hotter and drier conditions making it more challenging to prevent and control fires (UNEP 2022). Thus, adaptation measures are to be integrated into forest management policies.
2. Forest fires: Portugal is the country in Europe with the highest number of fires and the largest burned area as a percentage of the country area (Effis 2023; San-Miguel-Ayanz et al. 2022). Although the number of fires has decreased over the last 5 years, fire is still a significant factor affecting forests in Portugal. This risk might increase due to climate change and depends on the land-use changes implemented (Turco et al. 2019).
3. Forest management challenges:

   a. The resources allocated to forest management in Portugal are often inadequate to cover the costs of implementing effective forest management practices, such as fuel management. Several privately owned plots miss incentives, economic resources, and skills to effectively manage the forest and reduce fire risks (Marques et al. 2020).
   b. Only 2% of Portuguese forests are under public ownership and management control, which differs from the European and World averages of 46% and 73%, respectively (florestas.pt; 2021). This situation increases the difficulty of forest management. It may help to explain why Portugal has a higher percentage of burnt area compared with countries with similar forest cover and climatic challenges (Cloke and Da Costa 2021; Costa et al. 2020; OECD 2023).
   c. Forest land in Portugal is often fragmented into small parcels, creating economic viability problems. Most of the private forests in Portugal belong to small landowners (florestas.pt; 2021), making it challenging to implement effective forest management policies over large areas. Fragmentation can lead to conflicting priorities among a wide range of forest owners, including large and small forest owners, forest managers, public authorities, and fire-fighting agencies. The lack of stakeholder cooperation and coordination has led to ineffective forest management (Marques et al. 2020).

4. Over-reliance on monoculture plantations: Historically, Portugal has relied heavily on monoculture plantations of fast-growing eucalyptus and maritime pine for commercial forestry (APA 2020). However, these plantations are highly vulnerable to wildfires, insect outbreaks, and diseases and can negatively impact biodiversity, ecosystem services, and climate resilience (Moomaw et al. 2019; Moreira et al. 2020; Norris et al. 2011).

Addressing these challenges will require a comprehensive approach to forest management, including improved forest governance, increased investment in forest management, and promotion of more sustainable and resilient forest management models and practices. The ongoing efforts of Portuguese authorities take many of these constraints into consideration. Still, only policies simultaneously addressing them will be able to tackle the expected trend of decreasing forest cover and carbon sequestration/storage in the long run.

Conclusions

This study modeled the Portuguese forest area, carbon storage, and sequestration under three policy scenarios 2015–2100 to assess the current Portuguese carbon sequestration targets. The three scenarios comprise a no-change scenario with continuation of current policies (PT-SSP3), slow and moderately strengthened policy ambitions with introduction of a new climate adaptation policy (PT-SSP2), and a sustainability scenario with high ambition and long-term forest policies (PT-SSP1). Policy improvements in PT-SSP2 and PT-SSP1 are assumed implemented between 2025 and 2035.

The projected Portuguese forest area declines in all three scenarios The current policies scenario (PT-SSP3) projects a rapid decrease in the Portuguese forest area to 76% in 2050 compared to the present (2015). The moderate (PT-SSP2) and high (PT-SSP1) policy ambition scenarios project declining forest areas to 93% and 96% of current levels by mid-century. Here, increasing wildfire risk is countered by a combination of improved fire management, forest management, and climate adaptation to reduce burnt areas. At the same time, strengthened restoration policies ensure regrowth in the burned areas.

Changes in forest area imply reduced annual carbon sequestration in all scenarios The PT-SSP3 projects reduced sequestration by almost 40% by 2050, meaning that serious policy improvements are needed for Portugal to continue contributing to the EU's Paris Agreement targets beyond 2030. With the improved forest policies in PT-SSP2 and PT-SSP1, carbon sequestration levels are projected to recover post-2035 reaching 87% and 98% of 2015 levels by the mid-century, and 88% and 102% by 2100, respectively.

In all three scenarios, Portugal is projected to reach its EU LULUCF effort-sharing commitment in 2030 (5.8 Mt CO_2/year), while Portugal's 2050 net zero target (13 Mt CO_2/year) is not met The EU commitment allows Portuguese carbon sequestration to drop to 50% in 2030 compared to 2015. The PT-SSP scenarios project declining sequestration rates to 84–88% by 2030 compared to 2015 levels. To reach the Roteiro target, carbon sequestration will need to grow to 118% in 2050 of 2015 levels. The scenarios project a decline in sequestration to 63% in case of no policy changes (PT-SSP3) and to 92% in case of high policy ambitions (PT-SSP1). The NZT LULUCF target appears impossible even under high policy ambitions. However, including a fifth policy (afforestation) may increase the changes.

A fundamental policy change is needed to provide a stable Portuguese carbon sink in the long term. A critical factor is introducing structural reforms into forest management policy Recent data indicate an increasing trend in burnt areas. Inadequate land use planning and climate change have increased fire hazards, challenging the Portuguese forest. Fire-resistant forest cover, landscape-scale fire, forest management, and climate change adaptation are mandatory to overcome this challenge. The presented policy mix must be implemented to fulfill Portugal's EU effort sharing and 2030/2050 mitigation targets (Policy 1–4). Current policies of fire management (P1), forest management (P2), and restoration of burnt areas (P4) should be strengthened. Furthermore, a new climate change adaptation policy should be implemented that redistributes forest species geographically according to changing climatic conditions (P3).

We aim to continuously refine and update the model as new data and knowledge become available to ensure the model remains relevant and robust. In addition, we aim to repeat the process periodically and adjust the model for other geographical contexts, e.g., to support decision-making in Global South countries.

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Data Availability Additional data analyses, figures, and datasets generated and analyzed during the current study are available from the corresponding author at reasonable request.

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