Carbon sequestration scenarios in Portugal: which way to go forward?

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Abstract

Background: Assessing carbon storage and sequestration is key for defining effective conservation actions to mitigate climate change. Forest species changes have direct impacts on carbon stocks and may lead to undesirable climate trade-offs. In this paper, we measure aboveground biomass (AGB) and the impact of forest changes on climate regulation through three land policy scenarios by 2030 in continental Portugal.

Results: We found that a High intervention scenario, supported by an important increase in “Other coniferous trees” class, will provide 29.5% more of carbon sequestration, whereas a Low intervention scenario, in which there is a moderate increase in all forest classes, will result in an increase of 5.7%. A business as usual (BAU) scenario, supported by an increase in eucalyptus forests and a decrease in autochthonous species, will decrease carbon sequestration (-2.7%), particularly Lisboa, Algarve and Norte regions. Economic valuation shows that the High intervention scenario will generate the highest economic outcome for climate regulation by 2030.

Conclusion:

This study provides a spatial-based methodology for monitoring carbon sequestration and new insights about the impact of policies for Green House Gas (GHG) mitigation, supporting the 2030 Sustainable Development Goals achievement.

Background

The increase of carbon dioxide (CO₂) in the atmosphere is one of the main causes of global warming [1]. Under the United Nations Framework Convention on Climate Change (UNFCCC 2015), some national governments revised their environmental policies to reduce the emission of GHG by controlling the consumption of fossil fuels and by encouraging consumers to use renewable energies instead. Following the Paris Agreement and the United Nations 2030 Agenda for Sustainable Development, the GHG mitigation strategy aims to maintain the global average rise of the temperature below 2° C [2].

The aboveground biomass (AGB) of forests is an indicator of productivity, carbon stock and sequestration caused by land use and land cover (LULC) and climate change in forest ecosystems [3, 4]. Thus, its precise measurement is important for assessing the carbon budget of terrestrial biomes [5, 6]. The most accurate method for measuring AGB is through ground measurements which are very costly and difficult to implement, especially, if the study area is very wide [7]. Remote sensing methods are one credible and advantageous alternative to estimate AGB [3]. These can use free open imagery data and be combined with several methods, such as machine learning and others, to provide accurate AGB estimates [8, 9]. AGB can also be estimated from existing LULC data using simpler models [10, 11].

Forest conversions by forestry, agriculture and anthropogenic LULC changes have direct impacts in climate regulation by altering atmospheric CO₂ concentrations [12, 13]. Measuring spatiotemporal

distributions of terrestrial carbon stocks subject to LULC changes is key to Greenhouse Gas (GHG) estimates and mitigation [14]. Estimates of LULC changes are responsible for 12.5% of global carbon emitted by human activities [5]. Particularly, the agriculture and forestry sectors play a major role in the GHG mitigation strategy [15]. Studies about LULC changes and its impacts on ecosystem services (ES) contribute with helpful information in defining effective sustainable policies [10, 16]. These studies may provide relevant information to engage stakeholders in the decision processes involving ES approaches [17].

Over the past decades, studies on ES have been quite intensive [18–21] regardless the nature of their functions: provisioning, regulation, supporting or cultural (MEA 2005). The integration of these assessments with scenarios of LULC enables the quantification of the impacts of different land use policies and trade-offs on ES [10, 23]. Geographic Information Systems (GIS) tools and spatiotemporal analysis are usually used alongside the scenarios projection in ES assessments [20, 24].

The carbon storage and sequestration by forests is a complex regulation ES (MEA 2005) and is strongly influenced by internal conditions, such as plant species, phenology, density of the settlement and the landscape structure [25]. It is also influenced by external conditions like human activities set out by LULC management [26]. The inclusion of these conditions in spatially explicit ES approaches is relevant for designing effective strategies to mitigate climate change through the reduction of CO₂ emissions [27]. The incorporation of development scenarios make ES assessments useful in a science-policy interface perspective [28, 29]. These scenarios can be expected at regional and national scales to support the relationship between sustainable development and global environmental changes [30].

Valuation processes are crucial for the decision makers' perspective in management actions [31]. The valuation methods consist, in a broad sense, to "assigning importance" to what should represent the diversity of the dimensions of nature values aiming long-term sustainable strategies that evaluate the trade-offs between nature and human well-being [32]. Economic valuation techniques bring a monetary perspective to ES studies and provide information that may help organizations to define policies for effective management of resources, particularly, over the LULC sector (Daily et al, 2013).

Carbon stocks' assessments based on LULC changes have been carried out worldwide at local and national levels [33]. Fernandes et al. (2020) assessed and valued carbon sequestration for a semiarid region in Brazil using scenarios. Leh et al. (2013) modelled several ES including carbon sequestration based on land cover changes for two countries in West Africa. In a comprehensive review on forest models of sustainable land use management, Mäkelä et al. (2012) show a spatial relation between forest resources and their contribution to the carbon dynamic cycles. Under a European perspective, some studies highlight the vulnerability of forest ecosystems to land use and climate changes [37–39]. In this context, Sil et al. (2017) have analysed carbon sequestration and storage dynamics in a mountain landscape based on land cover changes in Portugal. Additional studies were also carried out in other parts of the country [41–44].

In Portugal, the GHG strategies are defined by the National Low-Carbon Roadmap (APA, 2012), which aims to implement a low carbon economy by increasing the consumption of the renewables sources rather than fossil fuel. Another important instrument is the National Forest Strategy (PCM, 2015), which stands for the development of the forest sector at social-economic and environmental levels. Alongside with this strategy, it is also important to mention the Common Agricultural Policy (CAP) that supports the economic viability of rural communities through rural development measures. Landscape planning from CAP assumes that the support for sustainable and climate-friendly land use must include the development of forest areas and sustainable forest management. Moreover, agricultural areas fall within existing policy instruments with impact on the forest sector generating relevant benefits for climate change mitigation, such as increasing soil carbon and improving soil health (Rosenstock et al. 2019). Therefore, the forestry measures to be implemented in Portugal through the European Agricultural Fund for Rural Development (EAFRD) should contribute to the implementation of the forestry strategy for the EU (PCM, 2015).

Despite the existence of several policy instruments for GHG mitigation and studies, a national assessment of the carbon storage and sequestration based on LULC using a scenario approach is still missing for Portugal. This paper aims at filling this gap and proposes a combined approach of GIS and ES modelling tools to measure the AGB and study the impact of future scenarios on carbon storage and sequestration and trade-offs. In our analysis, we include different forest classes to estimate expected trends of carbon variation according to three different land use scenarios by 2030. Results are expected to provide new insights for national authorities acting on GHG mitigation strategies within the existing Sustainable Development Goals (SDGs).

Materials And Methods

Study Area

The study was focused in continental Portugal, which is divided in five regions (NUTS II) (Fig. 1). According to the national land cover map (COS), continental Portugal has an area of 8 910 220 hectares (DGT, 2018), mostly occupied by forests (39%) and agricultural areas (26.3%) (DGT, 2018). The artificial surfaces represent 5.1% and are mainly located near the coast (Fig. 1a).

In the Centro and Norte regions, a rugged landscape where the relief reaches altitudes of 1993 meters, creates natural conditions for the forest expansion. The Alentejo region, in the southern part of the country, has favourable conditions for anthropic activities, such as agroforestry systems over large plane areas. It is also important to mention the existence of other LULC classes, although there is no evident spatial pattern in their distribution, i.e. complex cultivation patterns (18%), scrubs and open spaces (12%) and the pastures (7%).

Figure 1b describes the spatial distribution of the main forest classes in continental Portugal according to COS 2015 (DGT, 2018). The “Forests of other coniferous species” (31.2%, 1087367 ha) represent the

major part of the forest being mostly located in Centro region. Alongside this class, the “Eucalyptus forests” class has a large distribution in the country (25.4%, 882087 ha), and its spatial distribution follows approximately the same pattern of the “Forests of other coniferous species” class. The Portuguese forest complex is also characterized by large forest stands of cork oak (17.6%, 611111 ha) associated to agroforest exploitations, mostly in Alentejo region. Other forest classes have less expression in the territory, such as the stone pine (5.8%, 202308 ha), the holm oak (5.8%, 201739 ha), other oaks (6.1%, 213942 ha) and some other species that are grouped in broad-leaved forests (8%, 280169 ha) (Caetano et al, 2018).

Modelling Carbon Storage and Sequestration

The InVEST Carbon Storage and Sequestration model [27] was used to assess the influence of forests on climate regulation scenarios in continental Portugal. This modelling approach estimates the amount of carbon stored in a landscape and values the amount of sequestered carbon over time [27]. The model requires LULC maps and an input lookup table providing the amount of carbon that may be stored by each LULC class, according to four pools: i) the above-ground biomass (AGB), which includes the living vegetation, woody and herbaceous, above the soil; ii) below-ground biomass, characterized by the live roots; iii) dead wood, where the all non-living wood is concentrated; and iv) dead wood and litter and the soil organic matter, that includes organic carbon in mineral soils.

The Portuguese National Forestry Inventory report (ICNF, 2010) has published the official values of carbon stored by each of the seven forest classes that exist in Portugal according to COS (Table 1). Since these values are only related to the AGB, the modelling process was limited to this pool.

Table 1
Carbon density in aboveground biomass for LULC classes in continental Portugal.

Carbon density (ton/ha)	LULC Class	References
35.2	Holm oak forests	(ICNF, 2010)
55.7	Cork oak forests	(ICNF, 2010)
79.8	Eucalyptus forests	(ICNF, 2010)
83.1	Stone pine forests	(ICNF, 2010)
60.5	Forests of other oaks	(ICNF, 2010)
69	Forests of other broad-leaved species	(ICNF, 2010)
92.2	Forests of other coniferous species	(ICNF, 2010)

The Portuguese LULC were obtained for the years 1995, 2007 and 2015 (DGT, 1995, 2007, 2018). GIS tools (ArcGIS 10.6.1) were used to convert these 1:25000 scale data from the original ESRI’s shapefile format into raster in ESRI’s GRID format with a cell size of 50 m. All data had an ETRS89 projection system. Since the datasets had a different number of classes (89, 225 and 48, respectively for the years

1995, 2007 and 2015) it was necessary to reclassify the classes to make the maps compatible between each other. The most detailed LULC (i.e. COS 2007 and COS 2010) describes the forest classes using a range of areas (e.g. pure forest stands, mixed forest stands with a dominant one, cuts and new plantations, and burnt areas). The less detailed LULC (i.e. COS 2015) groups all these classes, defining them as pure forest stands. Annex 1 provides the reclassification table used to make the classes of the LULC maps compatible. A total of 12 LULC classes were used in the modelling process: seven forest classes (Table 1) and five non-forest classes (Cultivated areas, Moors, heathland and bare soil, Pastures, Complex cultivation patterns, and Other areas).

Scenario Modelling Analysis and Valuation

Two types of scenarios were used in this study [23]: (i) Intervention scenarios, also called policy scenarios, which are used to identify effective and equitable interventions to meet policy goals; and (ii) Business-as-Usual (BAU) approach, for assessing current policies' future consequences.

The intervention scenarios are the best way to achieve a future that is idealized by stakeholders [52]. In other words, this approach is useful to represent how politics or other interventions are projected in the future and to foresee its consequences [23]. In this analysis, two possible intervention scenarios were considered for continental Portugal: Low intervention scenario and the High intervention scenario. These scenarios represent stakeholders' vision, particularly, the 2030 National Strategy for the Forests goals (PCM, 2015). This strategy includes the environmental function of the forest, where the carbon sequestration is present, as well as the social-economic aspect. The main goal for the forest sector in the Low intervention scenario is to improve by 3% the forest areas. The High intervention scenario produces an increase of 12%. Both scenarios are designed to consider trade-offs between foreign species (e.g. eucalyptus) and autochthonous species (e.g. oak, stone pine and maritime pine). Most of all, the key for a regulated forest, according to the National Forest Strategy (PCM, 2015), is the expansion of forest stands instead of the deforested areas. Aiming at measuring the future effect of the current policies for the forest sector, the BAU is used when the objective is to establish a baseline that depicts the current situation [23]. This scenario points to a situation without any kind of intervention or changes unlike in the other scenarios; it can be based on historical trends or stakeholder expectations.

Carbon storage and sequestration are highly dependent of the LULC changes [53]. Thus, modelling representative future scenarios for this ES involves the analysis of the trade-offs among the LULC classes [54]. To model the intervention and BAU scenarios, we used the InVEST – Scenario Generator: Ruler Based model [27]. This tool works as a multi-criteria process, for which it is necessary to assign weights for the trade-offs between classes. The weights are given in the scenario generator model by a transition likelihood matrix. The matrix must submit the trade-offs between classes, given by a weight varying from 1 to 9. Additionally, it should be complemented with the percentage of growth for each class. Each scenario approach is based on a table selected for the evaluation. Annex 2 provides the transition matrixes used for each scenario.

To quantify LULC changes, we calculated the variations in a period of 20 years (Eq. 1).

$$VAR_{1995-2015} = \left[\frac{(LULC_{2015} - LULC_{1995})}{LULC_{1995}} \right] \times 100 \quad (\text{Eq. 1})$$

where $VAR_{1995-2015}$ is the total variation (%) between the LULC for 2015 ($LULC_{2015}$), and LULC for 1995 $LULC_{1995}$.

We considered that the LULC changes trend observed in the period between 1995 and 2015 is going to be the same until 2030. Using this information, LULC was projected for the next 15 years until 2030 (Eq. 2).

$$LULC_{2030} = x \times (1 + t)^2 \quad (\text{Eq. 2})$$

where $LULC_{2030}$ corresponds to the year of the goals set by the National Strategy for the Forest sector (PCM, 2015) and by the EU [15].

The European Union Member states and the European Parliament set a price of €85/tCO₂ for year 2030 to encourage clean investments in line with the Paris climate goals [55]. For each scenario, we will multiply the quantity of carbon stored of the forest species classes by this monetary value to obtain an estimate of the economic value of the carbon stored.

Results

Land Cover Changes

In Fig. 2 are presented the changes (%) in land cover from 1995 to 2015 and from 2015 to 2030 according to the 3 scenarios. The “Forest of other coniferous species” have decreased their area importantly (-18.9%) between 1995 and 2015. In this period, the stone pine (34.3%), eucalyptus (21.1%) and other broad-leaved species (18.7%) forests have expanded their area. Forest of other oaks have also grown, although less importantly (8.6%). All non-forest classes, with the exception of “Other areas” (23.6%) have lost area being pastures (-11.7%) and complex cultivation patterns (-11.2%) the ones which decreased most importantly.

The results of the intervention scenarios suggest a very ambitious goal for the forest sector in continental Portugal. These strategies will increase the autochthonous species since the main goal is a suitable development for the forest sector. To accomplish the stakeholder goals, the main expected changes indicate an increase of “Forest of other coniferous species” in 35% in the High intervention scenario and, in the Low intervention scenario, an increase of 6.4%. It is also expected a high growth of the stone pine forests in the High intervention scenario (24.8%), and in the low intervention scenario (13%). Eucalyptus

will increase 5.2% in the High intervention scenario and 3% in the Low intervention scenario. The Forest National Strategy supports the development of the forest sector in deforested areas and, for this reason, it is expected an important decrease of the “Moors, Heathland and bare soil” class (-40% and - 27.7%, respectively, for High and Low intervention scenarios), since the deforested areas are part of this class.

The BAU model projects by 2030 the tendency in LULC observed in the 1995–2015 period. Results emphasise the decline of “Forest of other coniferous species” (-16.5%), and a slight decline of “Moors, Heathland and bare soil” (-3.4%). Furthermore, BAU results highlight the improvement of the stone pine (20.5%), the eucalyptus (13.7%) and the other broad-leaved (12.3%) forest classes. Agricultural areas (-5.1%), scrub and/or herbaceous (-2.6%), pasture (-9.7%) and complex cultivation pattern (-9.2%) will decrease in this scenario.

Forest Classes and Carbon Storage and Sequestration

Fig. 3 shows the quantity of carbon in gigatons (GtC) stored by each forest class between 1995 and 2015 and for each scenario by 2030. It is possible to observe that the “Forests of other coniferous species” is the only class decreasing the quantity of carbon stored between 1995 and 2015. This class represented 38% of total carbon stored by all forest classes in 2015. All the other classes increased their values in this period. For 2030, this class will increase in both intervention scenarios and will keep the value in the BAU scenario. The stone pine forests will increase in both intervention scenarios. However, this class will decrease importantly if the BAU is adopted for 2030, i.e. from 16.8 GtC in 2015 to 5.3 GtC, respectively.

Regional (NUTS II) Carbon Storage and Sequestration

In 2015, Lisbon had only 24% of its area occupied by forests, being the region with the lowest percentage of forests. The Centro region had in 2015 the highest percentage of forests (48.5%), followed by Algarve (37.8%), Norte (35.6%), and Alentejo (31.9%).

Carbon sequestration projections for the development scenarios show that the intervention scenarios positively impact this ES (Fig. 4). However, the BAU presents some decrease in all the territory for all the scenarios. In Fig. 5 it is possible to observe the changes (%) in carbon sequestration for each NUTS II region over time.

The Centro region had the highest carbon density value (40.5 ton/ha) (Table 2). The impact of the scenarios on this value follows the same logic of the one observed in carbon storage and sequestration, i.e. it will increase in High and Low scenarios, and it will decrease in the BAU scenario in all regions. In 2015, Alentejo and Lisboa regions, had the lowest carbon density, respectively 18.4 ton/ha and 19.2 ton/ha. In Alentejo, this may be explained by the existence of extensive agricultural land and only 31.9% of forests. In Lisbon, there is a greater extent of urban areas when compared to the other regions.

Algarve, Lisbon, and Centro regions are positively impacted with a growth higher than 20% in carbon storage between 2015 and 2030 for the High intervention scenario. This fact is strongly related to the

high concentration of deforested areas in these regions which will be, according to the model, converted into forests.

Table 2
– Carbon density in NUTS II (ton/ha).

NUTS II	Area (Ha)	1995	2007	2015	High	Low	BAU
Norte	2128588	28.6	29.8	29.6	33.9	32.7	28.2
Centro	2819934	40.5	40.7	40.5	49.9	42.0	39.9
Lisboa	301524	19.4	19.4	19.2	24.2	20.7	18.3
Alentejo	3160491	18.4	20.4	20.6	22.8	21.2	20.1
Algarve	499679	21.5	25.4	25.5	41.1	28.9	24.2
MEAN		25.7	27.1	27.1	34.4	29.1	26.2

3.4. Carbon Sequestration and Economic Valuation

Carbon sequestration has increased 4.5% between 1995 and 2007 (Fig. 6). However, between 2007 and 2015 there was a small decrease (-0.2%). According to our model, a High intervention scenario is expected to increase carbon sequestration from 261.3 GtC in 2015 to 337.7 GtC in 2030 (29.5%). The increase will be more modest in the case of the Low intervention scenario (5.7%). The BAU will result in a loss of carbon sequestration by forest classes of -2.7% when compared to 2015.

One important reason for the better performance of the High intervention scenario when compared to the other scenarios is the higher decrease in the “Moors, Heathland and bare soil” class (-40%) which will be replaced by classes with higher levels of carbon density, such as the “Forests of other coniferous species” (92.2 ton/ha) and the “Forests of other oaks” (60.5 ton/ha) classes.

In the Low intervention scenario, the “Moors, Heathland and bare soil” class will also decrease (-27.7%) although less importantly. All the forest classes will increase less than 15%, but less than in the High scenario.

The BAU scenario presents an important decrease of high carbon density forest, such as “Forests of other coniferous species” (92.2 ton/ha) class. All the other forest classes increase their occupation, being the stone pine the one with the highest value (20.5%).

Considering the price of carbon for year 2030 set to €85/tCO₂, the High intervention scenario is the one with the highest value of carbon among the three scenarios, i.e. 28707 M€. The Low and BAU scenarios store lower values, respectively, 23442 M€ and 21564 M€.

Discussion

Our study contributes with a methodology using the Portuguese national land cover map (COS) to monitor the carbon sequestration in Portugal. This temporal series of land cover maps had to be harmonised for comparison purposes is the basis for designing several national policies including environmental planning instruments at municipal levels (ICNF, 2010). Its technical characteristics, such as scale, minimum mapping unit and the number of classes make it more advantageous than using other datasets, such as CORINE land cover [56], which does not have forest classes in such detail. The results presented in this paper are innovative for Portugal and may help Portuguese policymakers achieving United Nations 2030 Sustainable Development Goals [57].

This research also contributes to a case study which reflects different and realistic policy options and their impact on a climate regulation ES. Scenario projections make possible to understand the political influences under the LULC management in future visions. The study presents effective results of the demonstration of how useful the scenarios approaches could be in the construction of national strategies that include ES and LULC policies (e.g. APA, 2012). It also underlines the importance of the scenarios projections over the definition of the current policies. The BAU development scenario is conditioned by the constraints set by the Forest National Strategy (PCM, 2015) since it blocks the evolution of foreign species (i.e. eucalyptus) favouring the development of autochthonous ones (i.e. oak, pine). The increase of autochthonous species based on the occupation of the deforested areas by species with better adaptation to the soil and climate conditions are the main guideline for this strategy (PCM, 2015).

This study evaluates the performance of current policies and new strategies for LULC management that may impact carbon storage and sequestration with the use of open data and free modelling tools. Modelling ES implies the generalization of a complex ecosystem, such as the carbon cycle [27]. Thus, it is necessary to take some precautions with the InVEST carbon model and scenario generator tools, which have some limitations [27]. The LULC scenarios are static, conditioning the modelling processes to the hypothesis of LULC short-period changes. Furthermore, the model results are highly dependent on the LULC inputs, and the conversion of the carbon classes should be carefully processed, since it may induce to wrong results [27]. Thus, results should be carefully considered to avoid wrong interpretations. Another limitation is related to the data collection guidelines of the carbon model which recommend making a literature review for this process. There are several options in what concern the scenarios projections, although this type of analysis should be adopted considering data scarcity and scale [27].

To emphasize the impact of the analysis provided by this research over the land use management decisions that affect the forest sector, it is crucial to apply a valuation method for the regulating ES, such as carbon sequestration dynamics [32]. The valuation has an important role in the implementation for the decision-makers' perspective to take account the ES in management actions [58]. These methods assess the balance between multiple dimensions, which can improve several human and natural well-being indicators [28, 59]. Although variations (%) on carbon storage and sequestration should not have been impacted importantly, we are aware that the quantities and economic values obtained for each scenario are underestimated since only one carbon pool was considered (i.e. AGB).

We believe that the best approach to represent the stakeholders' vision, according to the scale of this project is through a national strategy specifically developed for LULC management. Further LULC-based assessments would provide a better understanding on how different stakeholders' perception is from the modelling results [60]. Nevertheless, a future scenario approach should promote a stakeholders' intervention, where the parts should integrate not only the government sector but also economic and environmental actors (Harrison et al., 2018). Future developments of this study will benefit from the consultation of stakeholders and also from the study of other ES and trade-offs [61].

Conclusions

This study measures AGB and assesses the impact of policies on carbon storage and sequestration for Portugal using GIS, ES modelling tools and open data. Results show that the Portuguese forests will improve its capacity for carbon storage and sequestration if High and Low intervention scenarios are followed for 2030. These scenarios will provide the highest levels of carbon storage and sequestration and economic value. A BAU scenario is expected to decrease this ES in the country and mainly in the Norte, Lisboa and Algarve regions. Overall, this spatially explicit approach leads to new insights that may help the discussion and delineation of sustainable forest policies regarding the GHG strategy goals by 2030.

Declarations

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

JC and PC equally contributed to the review conception, data gathering, analyses and writing. FC contributed to writing, review conception and analyses. JD and RP contributed to the review conception and analyses. All authors read and approved the final manuscript.

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References

1. IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer, editors]. Geneva, Switzerland; 2014.
2. UNFCCC. Adoption of the Paris Agreement: Proposal by the President to the United Nations Framework Convention on Climate Change. Conf Parties. 2015;21932:1–32.
3. Zhang R, Zhou X, Ouyang Z, Avitabile V, Qi J, Chen J, et al. Estimating aboveground biomass in subtropical forests of China by integrating multisource remote sensing and ground data. *Remote Sens Environ* [Internet]. 2019;232:111341. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0034425719303608>.
4. 10.1126/science.aam5962
Baccini A, Walker W, Carvalho L, Farina M, Sulla-Menashe D, Houghton RA. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science* (80-) [Internet]. 2017;358:230–4. Available from: <https://www.sciencemag.org/lookup/doi/10.1126/science.aam5962>.
5. Houghton RA, House JI, Pongratz J, van der Werf GR, DeFries RS, Hansen MC, et al. Carbon emissions from land use and land-cover change. *Biogeosciences* [Internet]. 2012;9:5125–42. Available from: <https://www.biogeosciences.net/9/5125/2012/>.
6. 10.1073/pnas.0901970106
Keith H, Mackey BG, Lindenmayer DB. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. *Proc Natl Acad Sci* [Internet]. 2009;106:11635–40. Available from: <http://www.pnas.org/lookup/doi/10.1073/pnas.0901970106>.
7. <http://doi.wiley.com/10.1111/gcb.12629>
Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, et al. Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob Chang Biol* [Internet]. 2014;20:3177–90. Available from: <http://doi.wiley.com/10.1111/gcb.12629>.
8. Li Y, Li M, Li C, Liu Z. Forest aboveground biomass estimation using Landsat 8 and Sentinel-1A data with machine learning algorithms. *Sci Rep* [Internet]. 2020;10:9952. Available from: <http://www.nature.com/articles/s41598-020-67024-3>.
9. Lu D. Aboveground biomass estimation using Landsat TM data in the Brazilian Amazon. *Int J Remote Sens* [Internet]. 2005;26:2509–25. Available from: <https://www.tandfonline.com/doi/full/10.1080/01431160500142145>.
10. <https://dx.plos.10.1371/journal.pone.0014327>

- Nelson E, Sander H, Hawthorne P, Conte M, Ennaanay D, Wolny S, et al Projecting Global Land-Use Change and Its Effect on Ecosystem Service Provision and Biodiversity with Simple Models. Merenlender AM, editor. PLoS One [Internet]. 2010;5:e14327. Available from: <https://dx.plos.org/10.1371/journal.pone.0014327>.
11. Cabral P, Feger CC, Levrel H, Chambolle MM, Basque D. Assessing the impact of land-cover changes on ecosystem services: A first step toward integrative planning in Bordeaux, France. *Ecosyst Serv* [Internet]. Elsevier; 2016;22:318–27. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S2212041616302182>.
 12. 10.1111/conl.12740
Martin DA, Osen K, Grass I, Hölscher D, Tschardt T, Wurz A, et al. Land-use history determines ecosystem services and conservation value in tropical agroforestry. *Conserv Lett* [Internet]. 2020; Available from: <https://onlinelibrary.wiley.com/doi/abs/10.1111/conl.12740>.
 13. <https://iopscience.iop.org/article/10.1088/1748-9326/aab540>
Sleeter BM, Liu J, Daniel C, Rayfield B, Sherba J, Hawbaker TJ, et al. Effects of contemporary land-use and land-cover change on the carbon balance of terrestrial ecosystems in the United States. *Environ Res Lett* [Internet]. 2018;13:045006. Available from: <https://iopscience.iop.org/article/10.1088/1748-9326/aab540>.
 14. Ma W, Domke GM, Woodall CW, D'Amato AW. Contemporary forest carbon dynamics in the northern U.S. associated with land cover changes. *Ecol Indic* [Internet]. 2020;110:105901. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S1470160X19308969>.
 15. European Council. Conclusions adopted by the European Council meeting. EUCO 169/14 On the 2030 Climate and Energy Policy Framework. 2014.
 16. Posner S, Verutes G, Koh I, Denu D, Ricketts T. Global use of ecosystem service models. *Ecosyst Serv*. 2016;17:131–41.
 17. Mascarenhas A, Ramos TB, Haase D, Santos R. Participatory selection of ecosystem services for spatial planning: Insights from the Lisbon Metropolitan Area, Portugal. *Ecosyst Serv* [Internet]. 2016;18:87–99. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S2212041616300341>.
 18. Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, et al. The value of the world's ecosystem services and natural capital. *Nature*. 1997;387:253–60.
 19. De Groot RS. Evaluation of Nature in Environmental Planning, Management and Decision Making. Groningen: Wolters-Noordhoff; 1992.
 20. De Groot RS. Environmental functions and the economic value of natural ecosystems. In: Johnsson A, M H, Folke C, Constanza R, editors. *Invest Nat Cap Ecol Econ Approach to Sustain*. Washington D.C.: Island Press; 1994. pp. 151–68.
 21. De Groot RS, Wilson MA, Boumans RMJ. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecol Econ*. 2002;41:393–408.
 22. Millennium Ecosystem Assessment. Ecosystems and human well-being: A framework for Assessment. Ecosystems. Washington D.C.: Island Press; 2005.

23. McKenzie E, Rosenthal A, Bernhardt J, Girvetz E, Kovacs K, Olwero N, et al. Developing Scenarios to Assess Ecosystem Service Tradeoffs: Guidance and Case Studies for InVEST Users. *Environ Monit Assess*. 2012.
24. Levrel H, Cabral P, Feger C, Chambolle M, Basque D. How to overcome the implementation gap in ecosystem services? A user-friendly and inclusive tool for improved urban management. *Land use policy* [Internet]. 2017;68:574–84. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0264837716307633>.
25. Faias S, Morais P, Dias S, Morão S, Salas R, Tomé M, et al. Uma rede europeia de zonas piloto para avaliação de critérios e indicadores de gestão florestal sustentável – Relatório final do projecto FORSEE. Lisboa; 2007.
26. <https://royalsocietypublishing.org/doi/10.1098/rstb.2007.2184>
Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, et al. Greenhouse gas mitigation in agriculture. *Philos Trans R Soc B Biol Sci* [Internet]. 2008;363:789–813. Available from: <https://royalsocietypublishing.org/doi/10.1098/rstb.2007.2184>.
27. Tallis H, Ricketts T, Guerry A, Wood S, Sharp R, Nelson E, et al. InVEST 3.6 User's Guide: Integrated Valuation of Environmental Services and Tradeoffs [Internet]. The Natural Capital Project; 2018. Available from: http://ncp-dev.stanford.edu/~dataportal/invest-releases/documentation/current_release/.
28. Nicholson E, Fulton EA, Brooks TM, Blanchard R, Leadley P, Metzger JP, et al. Scenarios and Models to Support Global Conservation Targets. *Trends Ecol Evol* [Internet]. 2019;34:57–68. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0169534718302519>.
29. [10.1186/s13021-017-0074-0](https://doi.org/10.1186/s13021-017-0074-0)
de Andrade RB, Balch JK, Parsons AL, Armenteras D, Roman-Cuesta RM, Bulkan J. Scenarios in tropical forest degradation: carbon stock trajectories for REDD+. *Carbon Balance Manag* [Internet]. 2017;12:6. Available from: <https://cbmjournal.biomedcentral.com/articles/10.1186/s13021-017-0074-0>.
30. Martinez-Harms MJ, Bryan BA, Figueroa E, Plischoff P, Runtting RK, Wilson KA. Scenarios for land use and ecosystem services under global change. *Ecosyst Serv*. 2017;25:56–68.
31. Daily GC, Kareiva PM, Polasky S, Ricketts TH, Tallis H. Mainstreaming natural capital into decisions. *Nat Cap*. 2013.
32. Jacobs S, Dendoncker N, Martín-López B, Barton DNDN, Gomez-Baggethun E, Boeraeve F, et al. A new valuation school: Integrating diverse values of nature in resource and land use decisions. *Ecosyst Serv* [Internet]. 2016 [cited 2016 Dec 9];22:213–20. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S221204161630479X>.
33. Duveiller G, Caporaso L, Abad-Viñas R, Perugini L, Grassi G, Arneth A, et al. Local biophysical effects of land use and land cover change: towards an assessment tool for policy makers. *Land use policy* [Internet]. 2020;91:104382. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0264837718311554>.

34. Fernandes MM, Fernandes MR, de M, Garcia, Matricardi JR, de Almeida EAT, Pinto AQ AS, et al. Assessment of land use and land cover changes and valuation of carbon stocks in the Sergipe semiarid region, Brazil: 1992–2030. *Land use policy* [Internet]. 2020;99:104795. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0264837719320344>.
35. Leh MDK, Matlock MD, Cummings EC, Nalley LL. Quantifying and mapping multiple ecosystem services change in West Africa. *Agric Ecosyst Environ* [Internet]. 2013;165:6–18. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0167880912004343>.
36. Mäkelä A, Río M, del, Hynynen J, Hawkins MJ, Reyer C, Soares P, et al. Using stand-scale forest models for estimating indicators of sustainable forest management. *For Ecol Manage* [Internet]. 2012;285:164–78. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0378112712004549>.
37. 10.1007/s10021-007-9028-9
Zaehle S, Bondeau A, Carter TR, Cramer W, Erhard M, Prentice IC, et al. Projected Changes in Terrestrial Carbon Storage in Europe under Climate and Land-use Change, 1990–2100. *Ecosystems* [Internet]. 2007;10:380–401. Available from: <http://link.springer.com/10.1007/s10021-007-9028-9>.
38. <http://doi.wiley.com/10.1111/j.1365-2486.2008.01653.x>
EGGERS J, LINDNER M, ZUDIN S, LISKI ZAEHLES. J. Impact of changing wood demand, climate and land use on European forest resources and carbon stocks during the 21st century. *Glob Chang Biol* [Internet]. 2008;14:2288–303. Available from: <http://doi.wiley.com/10.1111/j.1365-2486.2008.01653.x>.
39. Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, et al. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *For Ecol Manage* [Internet]. 2010;259:698–709. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0378112709006604>.
40. 10.1080/21513732.2017.1297331
Sil Â, Fonseca F, Gonçalves J, Honrado J, Marta-Pedroso C, Alonso J, et al. Analysing carbon sequestration and storage dynamics in a changing mountain landscape in Portugal: insights for management and planning. *Int J Biodivers Sci Ecosyst Serv Manag* [Internet]. 2017;13:82–104. Available from: <https://www.tandfonline.com/doi/full/10.1080/21513732.2017.1297331>.
41. Fernandes PM, Loureiro C. Fine fuels consumption and CO₂ emissions from surface fire experiments in maritime pine stands in northern Portugal. *For Ecol Manage* [Internet]. 2013;291:344–56. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S037811271200713X>.
42. Alegria C, Pedro N, do Carmo Horta M, Roque N, Fernandez P. Ecological envelope maps and stand production of eucalyptus plantations and naturally regenerated maritime pine stands in the central inland of Portugal. *For Ecol Manage* [Internet]. 2019;432:327–44. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0378112718313513>.
43. Fonseca F, de Figueiredo T, Vilela Â, Santos R, de Carvalho AL, Almeida E, et al. Impact of tree species replacement on carbon stocks in a Mediterranean mountain area, NE Portugal. *For Ecol Manage*

- [Internet]. 2019;439:181–8. Available from:
<https://linkinghub.elsevier.com/retrieve/pii/S0378112718323624>.
44. Nunes AN. Mudanças na paisagem e serviços dos ecossistemas. Abandono agrícola e variação no carbono orgânico dos solos. *Cad Geogr* [Internet]. 2019;7–16. Available from: https://impactum-journals.uc.pt/cadernosgeografia/article/view/39_1.
45. Agência Portuguesa do Ambiente (APA). Roteiro Nacional de Baixo Carbono 2050. Alterações Climáticas. 2012.
46. Presidência do Conselho de Ministros. Resolução do Conselho de Ministros n.º 6-B/2015, Diário da República, 1.ª série - N.º 24 – 4 de Fevereiro de 2015. *Diário da República*. 2015. p. 692-(2)-692-(92).
47. Direcção-Geral do Território. Carta de Uso e Ocupação do Solo – 2015. 2018.
48. A ocupação e uso do solo em 2015 e dinâmicas territoriais 1995-2007-2010-2015 em Portugal Continental
Caetano M, Marcelino F, Igreja C, Girão I. A ocupação e uso do solo em 2015 e dinâmicas territoriais 1995-2007-2010-2015 em Portugal Continental. *Estud. Dinâmicas Territ. - COS – 1995-2007-2010-2015*. 2018.
49. ICNF -. Instituto da Conservação da Natureza e das Florestas. 5.º Inventário Florestal Nacional. 2010.
50. Direcção-Geral do Território. Carta de Uso e Ocupação do Solo – 1995. 1995.
51. Direcção-Geral do Território. Carta de Uso e Ocupação do Solo – 2007. 2007.
52. 10.1073/pnas.1420500112
Schaefer M, Goldman E, Bartuska AM, Sutton-Grier A, Lubchenco J. Nature as capital: Advancing and incorporating ecosystem services in United States federal policies and programs. *Proc Natl Acad Sci* [Internet]. 2015;112:7383–9. Available from:
<http://www.pnas.org/lookup/doi/10.1073/pnas.1420500112>.
53. Deng L, Zhu G, Tang Z, Shangguan Z. Global patterns of the effects of land-use changes on soil carbon stocks. *Glob Ecol Conserv* [Internet]. 2016;5:127–38. Available from:
<https://linkinghub.elsevier.com/retrieve/pii/S2351989415300226>.
54. Bryan BA, Nolan M, McKellar L, Connor JD, Newth D, Harwood T, et al. Land-use and sustainability under intersecting global change and domestic policy scenarios: Trajectories for Australia to 2050. *Glob Environ Chang* [Internet]. 2016;38:130–52. Available from:
<https://linkinghub.elsevier.com/retrieve/pii/S0959378016300231>.
55. Carbon Market Watch. Beyond the EU ETS: Carbon Market Watch Policy Briefing, December 2017 [Internet]. 2017. Available from: <https://carbonmarketwatch.org/publications/beyond-eu-ets/>.
56. Copernicus CORINE, Land Cover. [Internet]. 2018 [cited 2019 Jan 20]. Available from:
<https://land.copernicus.eu/>.
57. UN. Sustainable Development Goals: Sustainable Development Knowledge Platform [Internet]. [cited 2020 Jun 25]. Available from: <https://sustainabledevelopment.un.org>.
58. 10.1093/acprof:oso/9780199588992.001.0001/acprof-9780199588992-chapter-3

Tallis H, Polasky S. Assessing multiple ecosystem services: an integrated tool for the real world. *Nat Cap* [Internet]. Oxford University Press; 2011. p. 34–50. Available from: <http://www.oxfordscholarship.com/view/10.1093/acprof:oso/9780199588992.001.0001/acprof-9780199588992-chapter-3>.

59. <http://doi.wiley.com/10.1111/ele.12189>

Guisan A, Tingley R, Baumgartner JB, Naujokaitis-Lewis I, Sutcliffe PR, Tulloch AIT, et al Predicting species distributions for conservation decisions. Arita H, editor. *Ecol Lett* [Internet]. 2013;16:1424–35. Available from: <http://doi.wiley.com/10.1111/ele.12189>.

60. Burkhard B, Kroll F, Müller F, Windhorst W. Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments. *Landsc Online*. 2009;15:1–22.

61. Naime J, Mora F, Sánchez-Martínez M, Arreola F, Balvanera P. Economic valuation of ecosystem services from secondary tropical forests: trade-offs and implications for policy making. *For Ecol Manage* [Internet]. 2020;473:118294. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S037811272031063X>.

Figures

Figure 1

LULC (a): 1. Artificial areas; 2. Agricultural areas; 3. Pastures; 4. Complex cultivation patterns; 5. Forests; 6. Scrubs; 7. Open spaces with little or no vegetation; 8. Wetlands; 9. Water bodies. LULC (b) Forest species distribution: 1. Holm oak forests; 2. Cork oak forests; 3. Eucalyptus forests; 4. Stone pine forests; 5. Forests of other oaks; 6. Forest of other broad-leaved species; 7. Forest of other coniferous species) in continental Portugal in the year 2015. Data Source: DGT, 2018.

Figure 2

LULC changes between 1995 and 2015, and according to each scenario by 2030 in continental Portugal (2015-2030).

Figure 3

Carbon storage of forest classes in carbon gigatons (GtC) in continental Portugal.

Figure 4

Carbon stored (GtC) in each NUTSII region between 1995 and 2015, and according to each scenario by 2030.

(a) BAU

(b) LOW

(c) HIGH

Figure 5

Changes (%) in carbon sequestration by NUTSII region between 2015 and by 2030.

Figure 6

Trends on carbon sequestration by forest classes between 1995 and 2015, and according to three intervention scenarios by 2030 in continental Portugal (GtC).

Supplementary Files

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