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.

Keywords: Global change, Ecosystems Services; Land Use Land Cover; InVEST model; Climate regulation; Aboveground biomass

Background

The increase of carbon dioxide (CO_2) in the atmosphere is one of the main causes of global warming (IPCC 2014). 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 bellow 2º C (UNFCCC 2015).

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 (Baccini et al. 2017; Zhang et al. 2019). Thus, its measurement is important for assessing the carbon budget of terrestrial biomes (Houghton et al. 2012; Keith et al. 2009).

AGB can be measured through ground measurements which are costly and difficult to implement, especially, in wide areas (Chave et al. 2014). Remote sensing methods are an alternative to estimate AGB (Zhang et al. 2019). These can use free open imagery data and combined with several methods, such as machine learning and others, to provide accurate AGB estimates (Li et al. 2020). AGB can also be estimated from existing LULC data using simpler models (Cabral et al. 2016; Nelson et al. 2010).

Estimates of LULC changes are responsible for 12.5% of global carbon emitted by human activities (Houghton et al. 2012). Particularly, the agriculture and forestry sectors play a major role in the GHG mitigation strategy (European Council 2014). Studies about LULC changes and its impacts on ecosystem services (ES) contribute with helpful information in defining effective sustainable policies (Posner et al. 2016). Forest conversions by forestry, agriculture and anthropogenic LULC changes have a direct impact in climate regulation by altering atmospheric CO_2 concentrations (Martin et al. 2020; Sleeter et al. 2018). Thus, measuring spatiotemporal distributions of terrestrial carbon stocks subject to LULC changes is key to Greenhouse Gas (GHG) estimates and mitigation (Ma et al. 2020).

The carbon storage and sequestration by forests is a complex regulation ES (MEA 2005). It is strongly influenced by internal conditions, such as plant species, phenology, density of the settlement and the landscape structure (Smith et al. 2008). It is also influenced by external conditions like human activities set out by LULC management (Pellikka et al. 2018). The inclusion of these conditions in spatially explicit ES approaches is relevant for designing effective strategies to mitigate climate change through the reduction of CO_2 emissions (H. T. Tallis et al. 2018). The incorporation of development scenarios make ES assessments useful in a science-policy interface perspective (de Andrade et al. 2017; Nicholson et al. 2019). These scenarios can be expected at regional and national scales to support the relationship between sustainable development and global environmental changes (Martinez-Harms et al. 2017).

Valuation processes are crucial for the decision makers´ perspective in management actions (Daily et al. 2013). 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 (Jacobs et al. 2016). 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 at local and national levels (Duveiller et al. 2020). 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 (EGGERS et al. 2008; Lindner et al. 2010). 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 carried out in other parts of the country (Alegria et al. 2019; P. M. Fernandes and Loureiro 2013; Fonseca et al. 2019; Nunes 2019).

In Portugal, the GHG strategies are defined by the National Low-Carbon Roadmap (APA and CECAC 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 (Presidência do Conselho de Ministros 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 (Presidência do Conselho de Ministros 2015). However, a national assessment of the carbon storage and sequestration based on LULC using a scenario approach is still missing for Portugal. This paper proposes a combined approach of Geographic Information Systems (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, different forest classes are included to estimate expected trends of carbon variation according to three different land use scenarios by 2030. Results 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 (Caetano et al. 2017; Direcção-Geral do Território 2018), mostly occupied by forests (39%) and agricultural areas (26.3%) (Direcção-Geral do Território 2018). The artificial surfaces represent 5.1% and are mainly located near the coast (Fig. 1a).

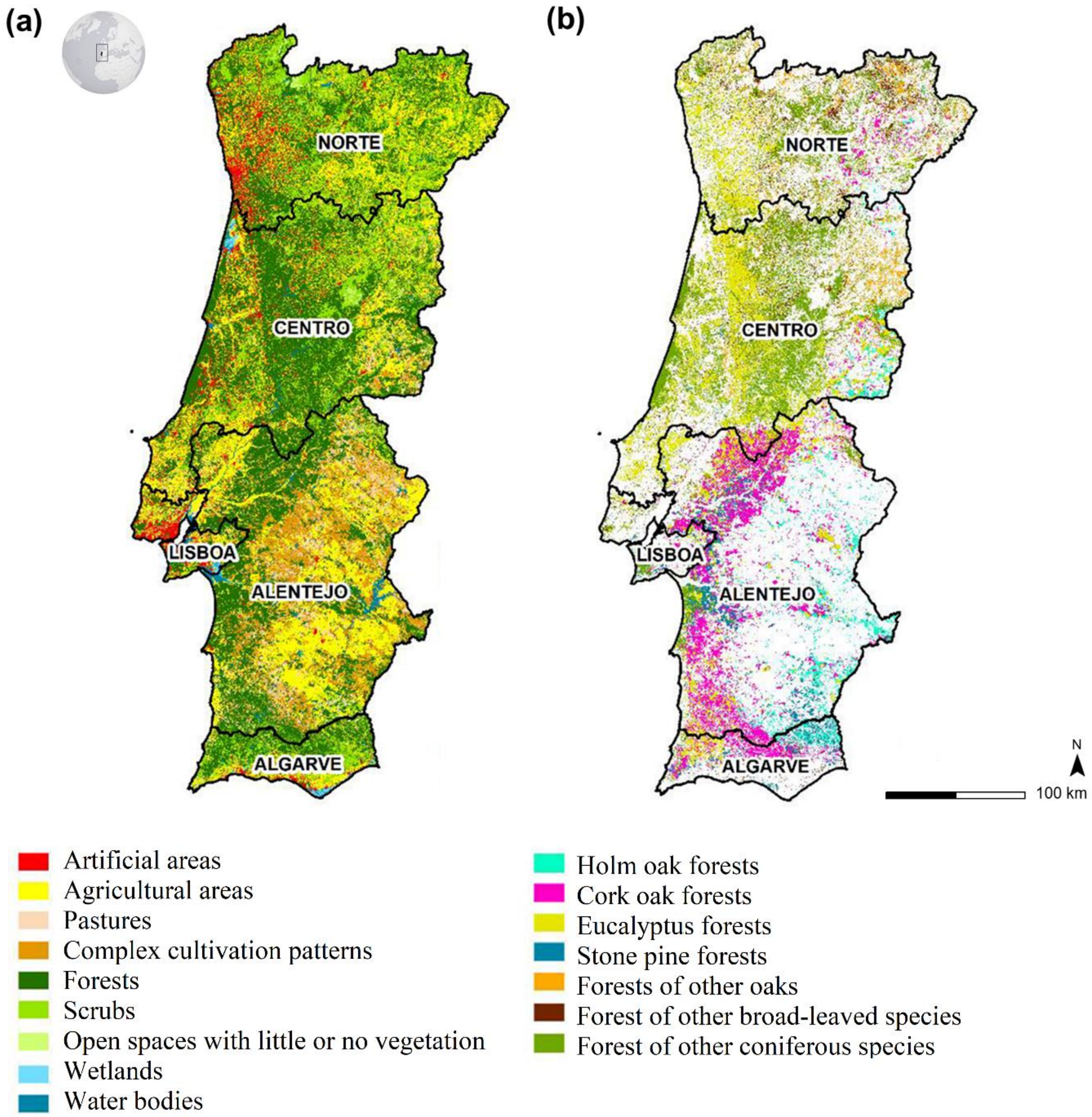

Fig. 1. Land Use and Land Cover (1a) and Forest species distribution (1b) in continental Portugal in 2015. Data Source: DGT, 2018.

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%).

Fig. 1b describes the spatial distribution of the main forest classes in continental Portugal according to COS 2015 (Direcção-Geral do Território 2018). The "Forests of other coniferous species" (31.2%, 1,087,367ha) 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%, 882,087ha), 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%, 611,111ha) associated to agroforest exploitations, mostly in Alentejo region. Other forest classes have less expression in the territory, such as the stone pine (5.8%, 202,308ha), the holm oak (5.8%, 201,739ha), other oaks (6.1%, 213,942ha) and some other species that are grouped in broad-leaved forests (8%, 280,169ha) (Caetano et al. 2018).

Methods

The overall methodology used in this study is presented on Fig. 2 and described afterwards.

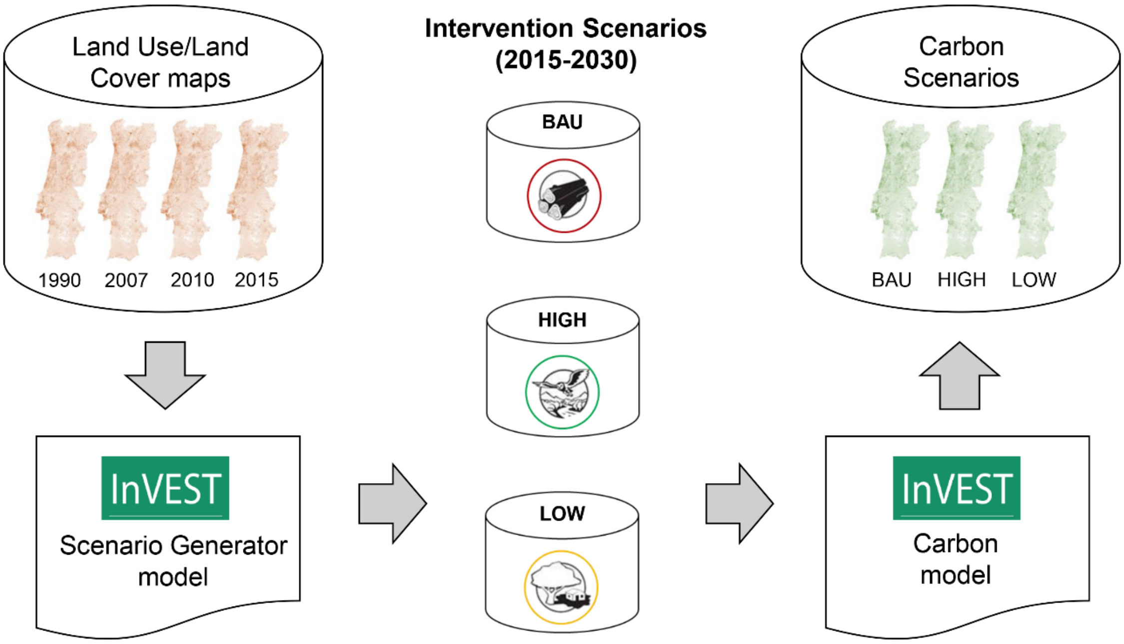

Fig. 2. Workflow of this study

Modelling Carbon Storage and Sequestration

The InVEST Carbon Storage and Sequestration model (H. T. Tallis et al. 2018) 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 (H. T. Tallis et al. 2018). 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 - Instituto da Conservação da Natureza e das Florestas 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 (ICNF - Instituto da Conservação da Natureza e das Florestas 2010).

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

The Portuguese LULC were obtained for the years 1995, 2007 and 2015 (Direcção-Geral do Território 1995, 2007, 2018). These maps have a positional accuracy of less than 5.5m and a global thematic accuracy of 85.13% with an error of 2% for a 95% confidence level. GIS tools (ArcGIS 10.6.1) were used to convert these 1:25,000 scale data from the original ESRI’s shapefile format into raster in ESRI’s GRID format with a cell size of 50m.

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) 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 (Mckenzie et al. 2012): (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 (Schaefer et al. 2015). In other words, this approach is useful to represent how politics or other interventions are projected in the future and to foresee its consequences (Mckenzie et al. 2012). 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 (Presidência do Conselho de Ministros 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 (Presidência do Conselho de Ministros 2015), is the expansion of forest stands instead of the deforested areas. In Table 2, are presented the High and Low scenarios developed by the Portuguese government for 2030. This information was then included in the matrix used as input of the scenario generator tool of the Invest software.

Table 2 - 2030 National Strategy for Forests goals (in 10^3 ha) (Presidência do Conselho de Ministros 2015).

Species	**2010**	**%**	**2030 (Low)**	**% 2030 (Low)**	**Variation (%)**	**2030 (High)**	**% 2030 (High)**	**Variation (%)**
Holm oak forests	331	11	331	10	0%	346	10	5%
Cork oak forests	737	23	748	23	1%	835	24	13%
Eucalyptus forests	812	26	812	25	0%	812	23	0%
Stone pine forests	176	6	202	6	15%	233	7	32%

Forests of other oaks	108	3	122	4	13%	152	4	41%
Forests of other broad-leaved species	195	6	217	7	11%	238	7	22%
Forests of other coniferous species	787	25	807	25	3%	903	26	15%
Total	**3146**	**100**	**3239**	**100**		**3519**	**100**	

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 (Mckenzie et al. 2012). 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 (Deng et al. 2016). Thus, modelling representative future scenarios for this ES involves the analysis of the trade-offs among the LULC classes (Bryan et al. 2016). To model the intervention and BAU scenarios, we used the InVEST – Scenario Generator: Ruler Based model (H. T. Tallis et al. 2018). 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 in InVEST – Scenario Generator.

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

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

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).

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

where $LULC_{2030}$ corresponds to the year of the goals set by the National Strategy for the Forest sector (Presidência do Conselho de Ministros 2015) and by the EU (European Council 2014), x is carbon sequestered in ton/ha in each year (*t*).

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 (Carbon Market Watch 2017). 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. 3 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.

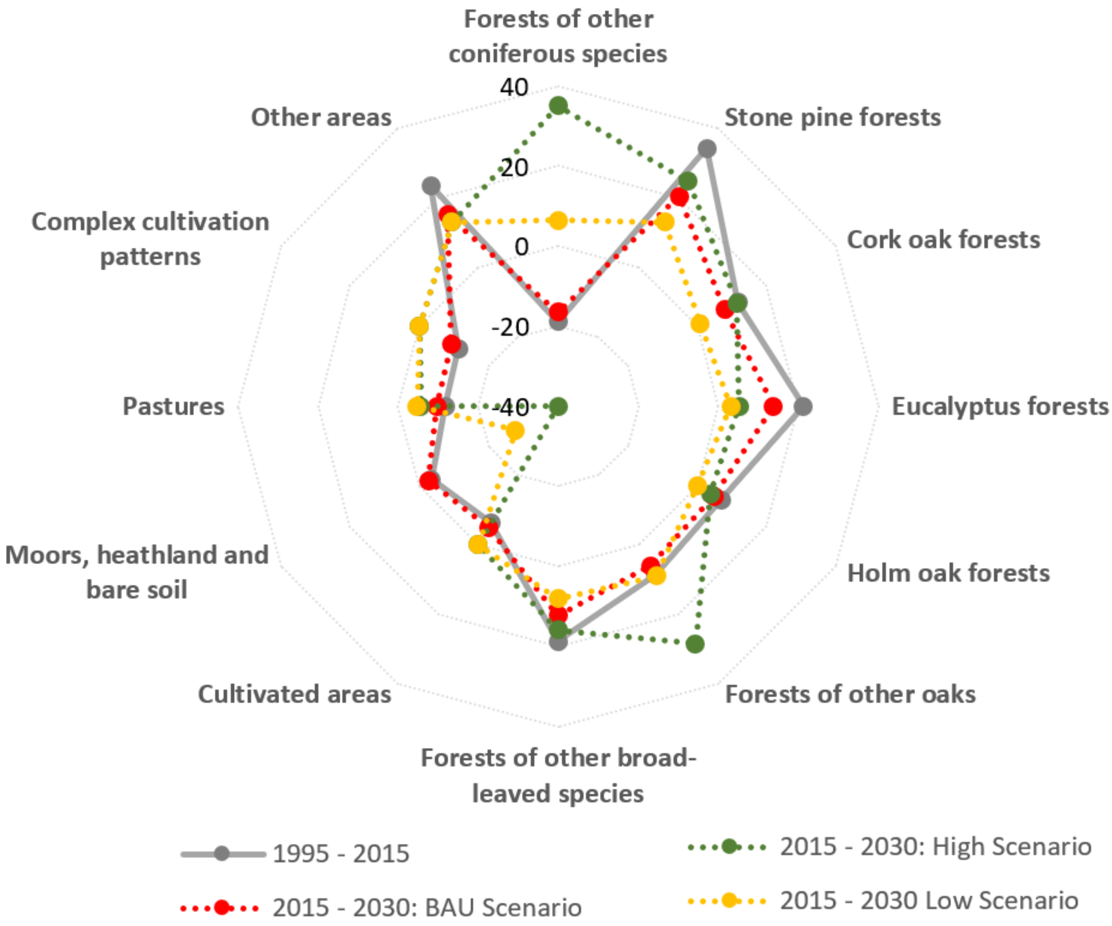

Fig. 3. LULC changes between 1995 and 2015, and according to each scenario by 2030 in continental Portugal (2015-2030).

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. In Annex 3, are provided the values obtained for the class changes.

Forest Classes and Carbon Storage and Sequestration

Fig. 4 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.

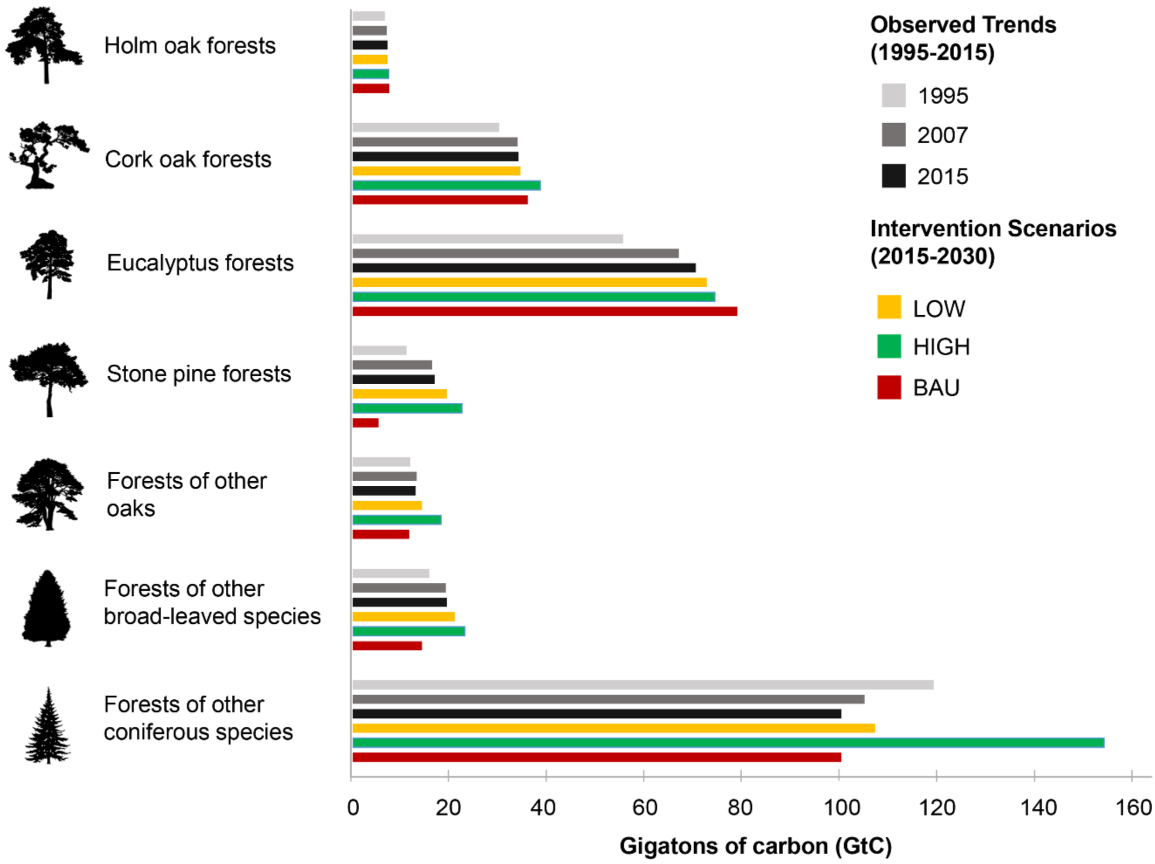

Fig. 4. Carbon storage of forest classes in carbon gigatons (GtC) in continental Portugal.

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. 5). However, the BAU presents some decrease in all the territory for all the scenarios. In Fig. 6 it is possible to observe the changes (%) in carbon sequestration for each NUTS II region over time.

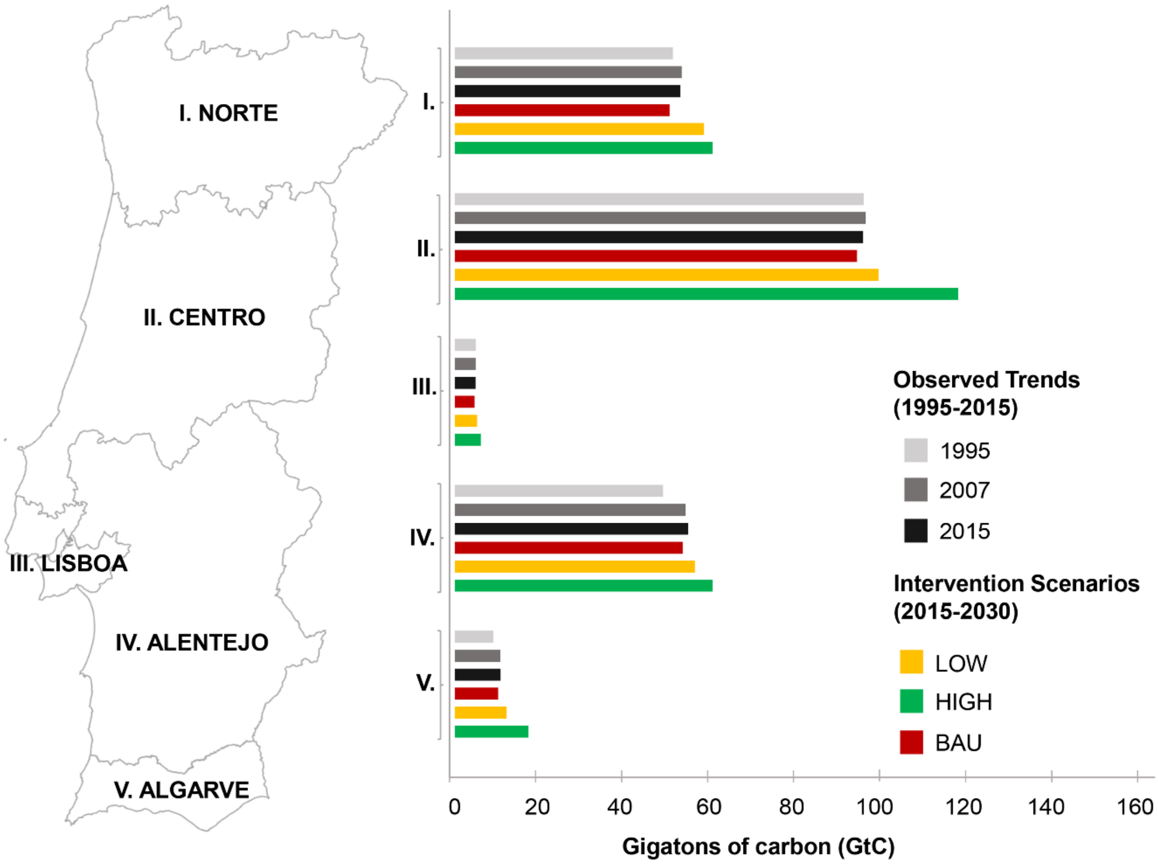

Fig. 5. Carbon stored (GtC) in each NUTSII region between 1995 and 2015, and according to each scenario by 2030.

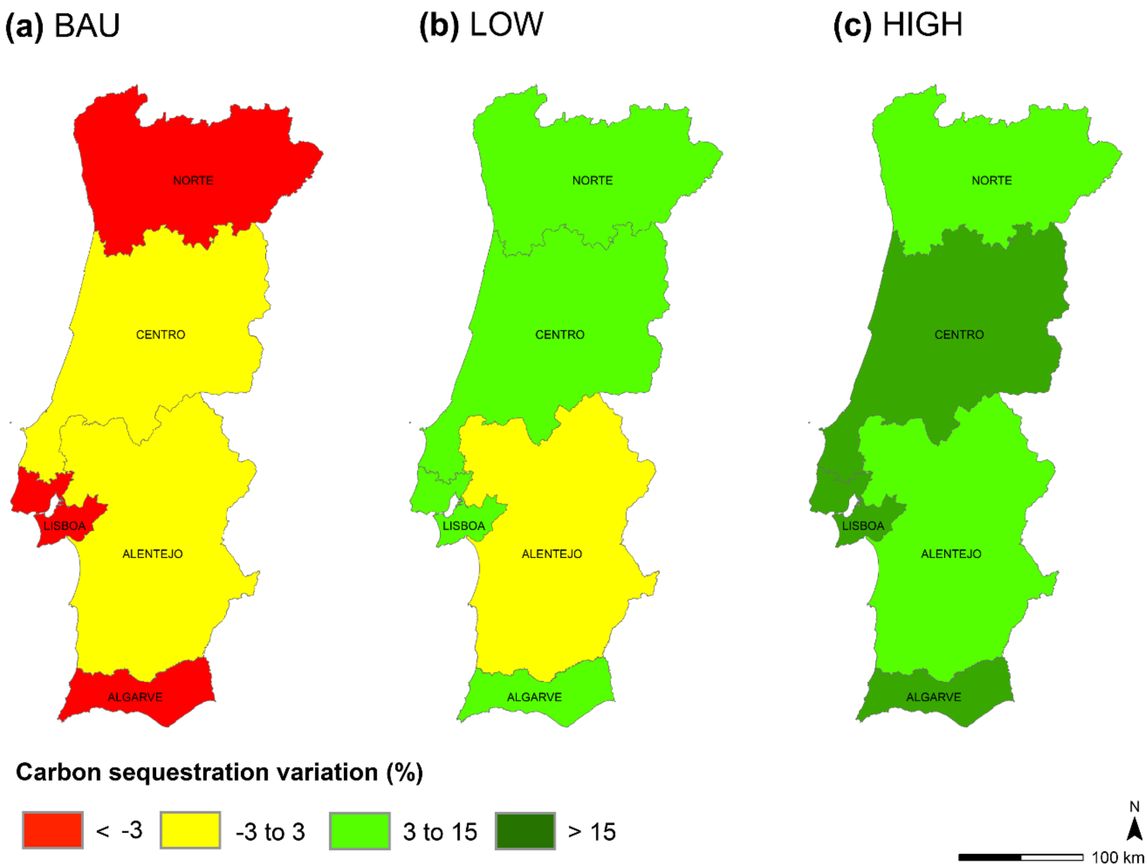

Fig. 6. Changes (%) in carbon sequestration by NUTSII region between 2015 and by 2030 (user defined classes).

The Centro region had the highest carbon density value (40.5 ton/ha) (Table 3). 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 3 – Carbon density in NUTS II (ton/ha).

NUTS II	Area (Ha)	1995	2007	2015	2030: High	2030: Low	2030: 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. 7). 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.

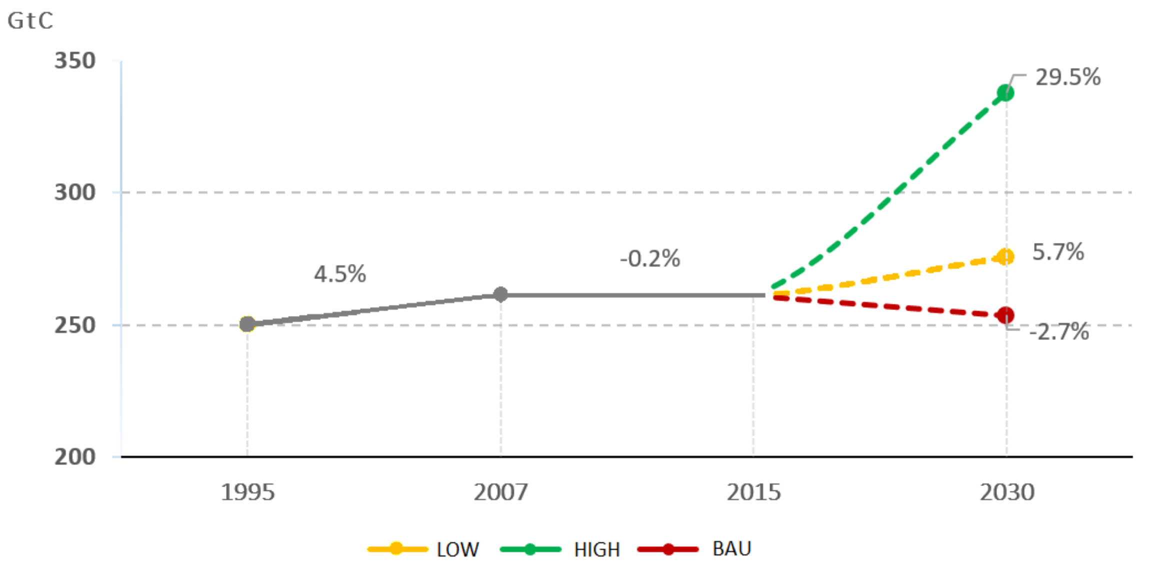

Fig. 7. Trends on carbon sequestration by forest classes between 1995 and 2015, and according to three intervention scenarios by 2030 in continental Portugal (GtC).

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/tCO_2, 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

This study contributes with a methodology using the Portuguese national land cover map (COS) to monitor the carbon sequestration in Portugal. A case study is provided which 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. The results presented in this paper are innovative for Portugal and may help Portuguese policymakers achieving United Nations 2030 Sustainable Development Goals (UN n.d.).

Nevertheless, there are some limitations which should be considered. For instances, the 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 - Instituto da Conservação da Natureza e das Florestas 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 (Copernicus 2018), which does not have forest classes in such detail.

Other limitation, is the generalization of a complex ecosystem, such as the carbon cycle (H. T. Tallis et al. 2018). The same consideration applies to LULC modelling which considers static scenarios, conditioning the modelling processes to the hypothesis of LULC short-period changes. Furthermore, the model results are highly dependent on the LULC inputs which were based on a literature review. The conversion of the carbon classes should be carefully processed, since it may induce to wrong results (H. T. Tallis et al. 2018). Thus, modelling results should be carefully considered to avoid wrong interpretations.

There are several options in what concern the scenarios, although this type of analysis should be adopted considering data scarcity and scale (H. T. Tallis et al. 2018). 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 (Jacobs et al. 2016). The valuation has an important role in the implementation for the decision-makers' perspective to take account the ES in management actions (H. Tallis and Polasky 2011). These methods assess the balance between multiple dimensions, which can improve several human and natural well-being indicators (Guisan et al. 2013; Nicholson et al. 2019). 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 think 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 (Burkhard et al. 2009). 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 (Naime et al. 2020).

Conclusions

This study measures AGB and assesses the impact of policies on carbon storage and sequestration for Portugal using GIS, ES free open modelling tools and data. The study demonstrates how useful scenario-based approaches can be in assisting the construction of national strategies that include ES and LULC policies. It also underlines the importance of scenarios over the definition of the current policies.

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. The BAU development scenario is conditioned by the constraints set by the Forest National Strategy 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.

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.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, J.C., upon reasonable request.

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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