Research Article

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Maritime pine land use environmental impact evolution in the context of life cycle assessment

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Abstract: Between 2005 and 2015, the forest area occupied by maritime pine trees in Continental Portugal decreased by about 10.6%, and the existing volume decreased by about 18.4% mainly due to fires and pests (e.g., nematode) that occurred during this period. The purpose of this study was to study the evolution of the land use environmental impact of 1 m^3 of maritime pine, standing in Portuguese forest, during that period using the model by Milà i Canals based on soil organic matter measured by soil organic carbon. Results show that the land use impact category increased from 16,812 kg C deficit in 2005 to 18,423 kg C deficit in 2015. Land transformation to forest roads is the main contribution for land use impact representing 54% of the total value followed by land occupation as forest that represents about 40%.

Keywords: forest, land occupation, land transformation, soil organic carbon, soil organic matter

1 Introduction

The new EU forest strategy for 2030 [1] recognises that “forests and the forest-based sector is an essential part of Europe’s transition to a modern, climate neutral, resource-efficient and competitive economy.” If at least three billion additional trees will be planted across Europe by 2030 as proposed in the strategy, forests will play a vital role in making Europe the first climate neutral continent by 2050 and for meeting the European Green Deal objectives (reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels). To fit this objective, a new proposal [2] sets out the overall Union target of net greenhouse gas removals in the land use, land use change, and forestry (LULUCF) sector to 310 million tonnes of CO_2 equivalent (CO_{2eq}) in 2030 and determines the Union target of climate neutrality for 2035 in the land sector (which combines the LULUCF sector and the non-CO_2 agricultural sector).

Portugal has committed internationally with the goal of a net-zero carbon footprint (labelled “carbon neutrality”) by 2050 [3]. It means that its greenhouse gas emissions should be reduced so that the balance between emissions and removals from the atmosphere, namely using forests, will be zero.

In Portugal, greenhouse gas emissions without LULUCF, including indirect emissions of CO_2, were estimated at about 70.7 Mt of CO_{2eq} in 2017 [4] and 67.4 Mt of CO_{2eq} in 2018 [5], corresponding to a decrease of 4.7% in the total emissions between 2017 and 2018. Greenhouse gas emissions of LULUCF were estimated at 7.3 Mt CO_{2eq} in 2017, and it was estimated as a sink sector in 2015 with −8.5 Mt CO_{2eq} and an average sink of −7.34 Mt CO_{2eq} in the period 1990–2015 with a tendency for increasing net-sequestration over time [6]. According to the same source, the main contributors for this increase have been an increase in removals in forest land and in other land and reductions in emissions in cropland and grassland.

Accomplishing carbon neutrality in Portugal implies reducing greenhouse gas emissions by more than 85%, compared to 2005, and ensuring an agricultural and forestry carbon sequestration capacity of around 13 Mt [7]. The year 2005 is considered because it was the time when a decoupling trend between greenhouse gases (GHG) emissions per unit of gross domestic product started, resulting from decarbonization of the economy, that is, an economy with less carbon emitted for each unit of produced wealth that is being maintained. Unfortunately, between 2005 and 2015, Portuguese maritime pine (*Pinus pinaster* Ait.) forest presented a larger reduction in area (−84,700 ha) and in volume (about −15 mm^3) [8]. This decrease in land use area and growing wood volume was mainly due to fires and pests (e.g., nematode).

Life cycle assessment (LCA) is one of the best technics to better understand and address the impacts associated

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with products, both manufactured and consumed [9–12], that aim to contribute to sustainability over chains of production, consumption, and waste management processes [13]. LCA is the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle, that is, from raw material acquisition or generation from natural resources to final disposal (from cradle to grave). Data is collected for each unit process that is included within the system boundary and then related with a functional unit (FU). Validated data per FU is then aggregated in the inventory table. Data from the inventory table are assigned to the selected impact categories, such as global warming and acidification (classification), and the category indicator results are calculated using the characterization factors (CFs; characterization) in the life cycle impact assessment (LCIA) step. Results from LCIA can be normalized in the optional element of normalization that is the calculation of the magnitude of the category indicator results relative to some reference information to better understand the relative magnitude of each indicator result of the product system under study.

LCA has been applied to forest products, namely maritime pine (*P. pinaster*) [14,15] and Brazilian pine (*Pinus oocarpa*) [16], to assess the environmental impacts they cause on the environment. González-García et al. [14] and Ferro et al. [16] estimated the environmental profile of the forest products considered as CFs from the ReCiPe method, whereas Ferreira et al. [15] used the CML-IA (baseline). Although the methods contain the category of land use impact (not comparable), none of the authors evaluated it.

LCA is the most widespread methods in the land use assessment identified by Perminova et al. [17], and several LCIA methods have emerged to enable the quantification of land occupation impacts and land transformation on biodiversity, biotic production, and additional soil quality-related indicators [17–19]. According to the European Commission, Joint Research Centre, Institute for Environment and Sustainability [20], the most appropriate among the existing methods for LCIA in the European context is the method by Milà ì Canals et al. [21] that has a focus on soil quality reflecting changes in soil organic carbon (SOC).

SOC is a measurable component of soil organic matter (SOM) that contributes to nutrient retention and turnover, soil structure, moisture retention and availability, degradation of pollutants, and carbon sequestration [22]. Sequestering carbon in SOC is seen as one way to mitigate climate change by reducing the atmospheric carbon dioxide [23,24]. Changes in SOC are largely determined by how much biomass is grown and retained above and below ground [25].

The goal of this study is to assess the evolution on the land use impact category of Portuguese maritime pine between 2005 and 2015 using the LCA methodology. The results could help the decision-makers in the land use planning process for national forests and the stakeholders to engage in a broad debate on the future of Portuguese forests.

2 Material and methods

The study was performed with the methodology recommended in the ISO14040 [9] and ISO14044 [10] standards for LCA. It includes four phases: goal and scope of the study – where the intended application and audience, reasons for carrying out the study, function of the product system, FU, system boundary, allocation procedures, and assumptions are described; inventory analysis – where data collected from the unit processes are treated and related with the FU, and the inventory table is built; impact assessment – the results of the inventory table are translated into environmental impact scores; and interpretation (or conclusion).

2.1 Goal and scope of the study

The intended application of the study is in the improvement of forest land use, and the results are to be communicated to the decision-makers, that is, those organizations and individuals along the forest management chain. The study was carried out in the context of research that the authors performed in their research centre and funded by it.

The FU was 1 m^3 of maritime pine, standing in forest, and the function of the system is to produce maritime pine trees for different uses. All inputs and outputs were allocated to trees (raw wood) although forests are multifunction systems that provide materials, food, clean water, medicines, and more. It was assumed that transformation of land takes place, and all impacts are allocated to the first harvest.

The process included in the system boundary is related to the natural regeneration of maritime pine trees in the forest. The inputs and outputs of the system are represented in Figure 1. Land occupation and transformation are the only inputs that contribute to the land use impact category, so CO_2 assimilated by the trees were not considered. The output is maritime pine standing in forest.

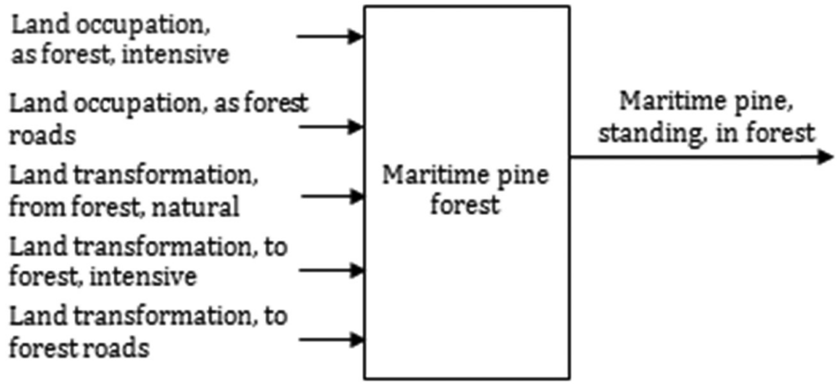

Figure 1: Gate-to-gate system boundary.

2.2 Inventory analysis

The inventory analysis was based on data from the National Forest Inventory (IFN5 and IFN6) provided by the Institute for Nature and Forest Conservation [8] and other sources as described below.

According to Portuguese Institute for Nature Conservation and Forests (ICNF) [8], in 2005, the land occupation of maritime pine in Continental Portugal was 798.0×10^3 ha and the volume (growing) of $81.558 \times 10^6\,m^3$. In 2015, these values were 713.3×10^3 ha for land occupation and $66.52 \times 10^6\,m^3$ for volume (growing). So, the average standing volume of maritime pine per hectare (yield including forest road) was very low ($102.2\,m^3\,ha^{-1}$ in 2005 and $93.26\,m^3\,ha^{-1}$ in 2015) with a still decreasing tendency. The lower land-use efficiency is a result of lower management intensity (e.g., no fertilizer or pesticide use) and is due to the multiple benefits for which forests are also managed (e.g., water supply and recreation). The time from birth/plantation to final tree harvest (rotation length) was assumed to be 35 years [26].

For the forest road, a length of $71.3\,m\,ha^{-1}$ [27] and a width of 3.5 m [28] was considered, which means a forest road area of $0.024955\,m^2$ of forest.

With previous data, the inventory table was built as illustrated in Table 1, considering the following expressions:

Land occupation as forest ($m^2\,year\,m^{-3}$) = [Land occupation × (1 – Forest road area)/Volume (growing)] × Rotation length

Land occupation as forest roads ($m^2\,year\,m^{-3}$) = [Land occupation × (Forest road area)/Volume (growing)] × Rotation length

Land transformation from forest ($m^2\,m^{-3}$) = Land occupation/Volume (growing)

Land transformation to forest ($m^2\,m^{-3}$) = Land occupation × (1 – Forest road area)/Volume (growing)

Land transformation to forest roads ($m^2\,m^{-3}$) = Land occupation × Forest road area/Volume (growing)

The occupation and transformation of land per cubic meter of maritime pine increased about 9.5% between 2005 and 2015 (Table 1), reflecting the decrease in the average standing volume in this period.

2.3 LCIA

LCIA is the phase where the substances derived from the inventory table are assigned to the land use impact category. They are converted into indicators using CFs calculated by impact assessment models. These CFs reflect pressures per unit substance used (or consumed) in the context of the impact category.

The model by Milà i Canals et al. [21] based on SOM was used for this LCIA. This model is considered by the European Commission-Joint Research Centre the most appropriate in the European context [20].

SOM often measured by SOC can be used as an indicator for soil quality, that is, the ability of soil to sustain life support functions such as biotic production, substance cycling and buffer capacity, or climate regulation [29]. Reflecting changes in SOC, the indicator results are expressed as kilogram C deficit [20,30]. The model can be represented by the following mathematical expression:

$$\text{Land use impact} = \sum_i \text{CF}_i \times \text{SQ}_i, \qquad (1)$$

where land use impact – represents the impact on land use expressed in kg C deficit;

CF_i – is the characterization factor for the land of type (1) in kg C deficit $m^{-2}\,year^{-1}$ or kg C deficit m^{-2}; and SQ_i – represents the quantity of substance (land) of type (1) (occupation or transformation) in m^2 year or m^2.

Table 1: Inventory table (FU = 1 m^3 of maritime pine, standing, in forest)

Substance	Unit	Maritime pine, standing, in forest (2005)	Maritime pine, standing, in forest (2015)
Land occupation as forest	m^2 year	3339.2	3659.3
Land occupation as forest roads	m^2 year	85.46	93.65
Land transformation from forest	m^2	97.852	107.226
Land transformation to forest	m^2	95.41	104.55
Land transformation to forest roads	m^2	2.442	2.676

Table 2: CFs for occupation flows from Milà i Canals et al. [29]

Substance	Unit	Substance name as in Milà i Canals et al. (2007)	CF kg C deficit m^{-2} year^{-1}
Land occupation as forest	m^2 year	Occupation, forest (OF)	2
Land occupation as forest roads	m^2 year	Occupation, traffic area, road embankment (OTA)	12

CFs for land use flows in the background system were provided from Milà i Canals et al. [29] and illustrated in Table 2 for land occupation and in Table 3 for land transformation. These CFs are based on Ecoinvent land use flows, which were further adapted to the International Reference Life Data System inventory flows and were considered for the global application of the model [31].

According to Milà i Canals et al. [29], an increase in SOM due to the soil management practices implies a benefit (negative sign of CF), whereas any decrease in SOM is accounted as damage from the system (positive sign of CF).

3 Results and discussion

Using equation (1) and CFs from Tables 2 and 3, the substances derived from the inventory table (Table 1) were converted into indicators of the land use impact category for the FU. The results are listed in Table 4, and the evolution of land use impact per substance is illustrated in Figure 2.

The results shown in Table 4 and illustrated in Figure 2 refer to the impacts from activities on forest to produce 1 m^3 of maritime pine (FU) considering a rotation time of 35 years, and that all impacts are allocated to the first harvest. The activities considered were land (forest and forest road) occupation, land transformation from and to forest, and land transformation to forest road.

The total carbon deficit attributed to FU increased from 16,812 kg C deficit in 2005 to 18,423 kg C deficit in 2015. It means that, in this period, the deficit in carbon increase of approximately 9.6% and covered all substances.

TTTA with 9,157 kg C deficit in 2005 and 10,034 kg C deficit in 2015 presents the highest value representing 54% of the total land use impact. OF with 6,678 kg C deficit in 2005 and 7,319 kg C deficit in 2015 is the second most important result, representing about 40% of the total impact followed by the TTF that accounts for about 11.3%. OTA represents about 6% of the total deficit in SOM.

It should be noted that land use impacts from land transformation are much higher than impacts from land occupation. Similar results were obtained by Sandin et al. [32] in the cotton and wood-based fibre study.

Land TFF account for an increase in SOM of 1,908 kg C (–1,908 kg C deficit) in 2005 and 2,091 kg C (–2,091 kg C deficit) in 2015.

In Table 5 data of inventory items for maritime pine (this study) are compared with spruce and Poland pine provided by Lewandowska et al. [33].

As stated in Table 5, the inventory data for all types of land occupation and land transformation are higher for Portuguese maritime pine than for spruce and Poland pine. Consequently, land use impact of maritime pine (16,812 kg C deficit in 2005 and 18,423 kg C deficit in

Table 3: CFs for transformation flows from Milà i Canals et al. [29]

Substance	Unit	Substance name as in Milà i Canals et al. (2007)	CF (kg C deficit m^{-2})
Land transformation from forest	m^2	Transformation, from forest (TFF)	–20
Land transformation to forest	m^2	Transformation, to forest (TTF)	20
Land transformation to forest roads	m^2	Transformation, to traffic area, road embankment (TTTA)	3,750

Table 4: Land use impact for the FU (1 m^3 of maritime pine, standing, in forest)

Substance	Unit	Maritime pine, standing, in forest	
		2005	2015
OF	kg C deficit	6,678	7,319
OTA	kg C deficit	1,026	1,124
TFF	kg C deficit	−1,957	−2,145
TTF	kg C deficit	1,908	2,091
TTTA	kg C deficit	9,157	10,034
Total	kg C deficit	16,812	18,423

TTTA – transformation, to traffic area, road embankment; TTF – transformation, to forest; TFF – transformation, from forest; OTA – occupation, traffic area, road embankment; and OF – occupation, forest.

2015) is higher than spruce (2,195 kg C deficit) and Poland pine (5,758 kg C deficit) if the Equation 1 and CFs from Tables 2 and 3 are applied to the substances listed in Table 5. This is mainly due to a very small yield of maritime pine (102.2 $m^3 ha^{-1}$ in 2005 and 93.26 $m^3 ha^{-1}$ in 2015) when compared with spruce (1,337 $m^3 ha^{-1}$) and Poland pine (651 $m^3 ha^{-1}$).

When compared with other forest species, land use impact of maritime pine is about 3 times higher than Poland pine and 7.7 times higher than spruce mainly due to a very small yield of maritime pine.

The increase in the carbon deficit of Portuguese maritime pine means a decrease in SOC, which consequently decreases the growing and retained biomass above and below ground as suggested by Nave et al. [25].

Fires and pests on maritime pine forest during the study period play an important role in SOC losses. As suggested by Nave et al. [34], fire may decrease SOC stocks quite severely and pest outbreaks, fuel accumulation, and tree mortality may increase the extent or severity of fires. According to these authors, the proactive management of fuels or stem density through prescribed under-burning or fell-and-burn stand restoration practices may help to restore ecosystems while preventing wildfires and attendant SOC losses.

Although the model used in this study (based on SOM) for the assessment of land use impact is considered by the European Commission-Joint Research Centre as the most appropriate in the European context [20], it

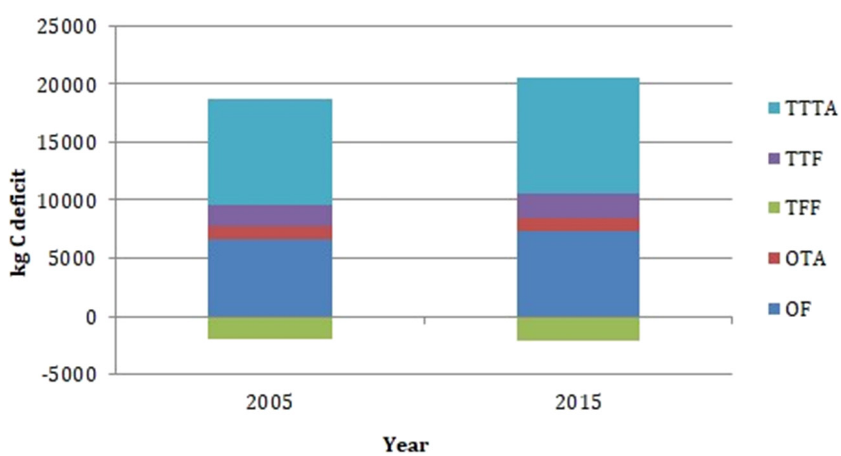

Figure 2: Evolution of land use impact of 1 m^3 of maritime pine, standing, in forest between 2005 and 2015. Acronyms: TTTA – transformation, to traffic area, road embankment; TTF – transformation, to forest; TFF – transformation, from forest; OTA – occupation, traffic area, road embankment; and OF – occupation, forest.

Table 5: Comparing inventory items of different species (FU = 1 m^3 of wood, standing, in forest)

Substance	Unit	Maritime pine (2005)[1]	Maritime pine (2015)[1]	Spruce[2]	Poland pine[2]
Land occupation as forest	m^2 year	3339.2	3659.3	888.0	1639.8
Land occupation as forest roads	m^2 year	85.46	93.65	9.7	54.15
Land transformation from forest	m^2	97.852	107.226	7.481	15.361
Land transformation to forest	m^2	95.41	104.55	7.4	14.91
Land transformation to forest roads	m^2	2.442	2.676	0.081	0.49

[1]Data from Table 1.
[2]Data from Lewandowska et al. [33].

was considered not fully satisfactory because important soil functions are disregarded (e.g., resistance to erosion, salinization, and compaction). Nonetheless, SOM is considered one of the most important indicators for the sustainability of cropping systems and plays a crucial role in supporting climate regulation and provisioning biotic production [35].

4 Conclusion

This article proposed to study the evolution of the land use impact category of Portuguese maritime pine between 2005 and 2015 using the method proposed by Milà i Canals et al. [21] based on SOM.

The main conclusion of this study is that the deficit in carbon per cubic meter of maritime pine, standing, in forest increased from 16,812 kg C deficit in 2005 to 18,423 kg C deficit in 2015 that means an increase of about 9.6% in this period. The most important contribution for land use impact is from land transformation to forest roads representing 54% of the total value followed by land occupation as forest that represents about 40%. Another conclusion is that the land use impact of maritime pine is about 3 times higher than land use of Poland pine and 7.7 times higher than spruce land use mainly due to a very small yield of maritime pine.

The evolution of land use impact of maritime pine was expected because during this period an average of about 45,000 ha per year of Portuguese forest were burnt by fires.

As future research, the model used in this study should be applied to other land cover types such as natural and mixed forest, cultivated land, and Eucalyptus plantation to compare the results. Newly developed models should be used too, mainly those that appear more robust and improved in terms of the scope completeness and geographical coverage.

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Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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