Environmental Boundaries
The Intergenerational Impacts of Natural Resource Use

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CALOUSTE GULBENKIAN FOUNDATION

FUTURE FORUM

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PREFACE

The Gulbenkian Foundation, through the Future Forum, aims to contribute to the identification, study and discussion of the fundamental challenges of society's future. We aim to promote critical mass about these topics and to entail the reflection about today's public policies based on the challenges ahead.

With these objectives in mind, an initiative is being carried out to introduce Intergenerational Justice on the public agenda and to encourage the different public representatives to answer the Intergenerational impact of public policies.

These are complex and ambitious objectives: on the one hand, because the focus is on covering the rights of people that, in many cases, are not yet born and, for this reason, still don't have a voice in the public space; on the other hand, because we attempt to counter what the Spanish political philosopher Daniel Innenarity named short-termism in public policies design, whose benefits are frequently dominated by the short-term interests.

One of the key elements of this initiative is a set of studies that aims to evaluate the impact of the different public policies among generations. That is the only way to measure all the costs and benefits of these public policies. This is particularly important in structural and long term areas with high impact on people's lives: housing, public finances, labour market and environment.

This study in particular – "Environmental Boundaries - The Intergenerational Impacts of Natural Resource Use" – aims to calculate the impact of the natural resources use by different generations in Portugal and to relate the amount of resources used to the planetary environmental boundaries, as well as identifying the legacy (or the burden) left to the next generations.

We would like to thank the authors Tiago Domingos, Ricardo da Silva Vieira and their team for the work done, as well as to all the experts that contributed with their comments and revisions.

We believe that the Intergenerational Justice initiative, along with Foresight Portugal 2030 and other projects in the pipeline, can provide an important contribution to the reflection on the great future challenges that the country faces and to the strategical options to address it on the long term.

Miguel Poiares Maduro
President of the Future Forum Scientific Committee

Luís Lobo Xavier
Coordinator of the Intergenerational Justice Project

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ACRONYMS AND ABBREVIATIONS

#	number
APA	Agência Portuguesa do Ambiente (Portuguese Environment Agency)
As	Arsenic
BaP	Benzo-(a)-Pyrene
Cd	Cadmium
CFCs	Chlorofluorocarbons
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents (unit of measure for GHG)
DU	Dobson Units (unit used as measurement for the ozone layer thickness)
E/MSY	Extinction rates per million species a year
EU	European Union
FAOSTAT	Statistics from the Food and Agriculture Organisation
FCG	Calouste Gulbenkian Foundation (Fundação Calouste Gulbenkian)
GHG	Greenhouse gases
HANPP	Human Appropriation of Net Primary Production
IPCC	Intergovernmental Panel on Climate Change
MSW	Municipal solid waste
N	Nitrogen
N_2O	Nitrous oxide, a GHG and an ozone depleting substance
NG	Natural gas
NH_3	Ammonia
Ni	Nickel
NIR	National Inventory Report
NMVOC	Non-methane volatile organic compounds
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NPP	Net primary production
Nr.	number
O_3	Ozone (used here to refer to tropospheric ozone)
P	Phosphorus
Pb	Lead
PM_{10}	Particulate matter with diameter less than 10 mm
$PM_{2.5}$	Particulate matter with diameter less than 2.5 micrometres (mm)
ppm	Parts per million
PT	Portugal
SINIERPA	Sistema Nacional de Inventário de Emissões e Remoções de Poluentes Atmosféricos (National System for the Inventory of Emissions and Removals of Air Pollutants)
SO_2	Sulphur dioxide
SO_x	Sulphur oxides
SSW	Sectoral solid waste
WHO	World Health Organization

EXECUTIVE SUMMARY

1.
INTRODUCTION AND OBJECTIVES

Human development patterns and economic activities have resulted in sustainability challenges of unprecedented scale and urgency, e.g., in terms of climate change and global biodiversity loss. This worrying development gives rise to the critical question of whether or not human-induced pressures now approach or exceed planet Earth's environmental limits. Are current pressures on the Earth system in terms of, for example, levels of greenhouse gas (GHG) emissions, ecosystem degradation or global resource use jeopardising the stability of the Earth system? How many biophysical resources and services (and environmental problems) are past and present generations leaving for new and yet to come generations?

The planetary boundaries framework identified nine processes that regulate the stability and resilience of the Earth system — 'Earth life-support systems'. The framework proposes precautionary quantitative planetary boundaries within which humanity can continue to develop and thrive, referred to as a 'safe operating space'. It suggests that crossing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes that could turn the Earth system into a state that is detrimental for human development.

Discussions around environmental stability, given its long-run perspective, are intimately linked with considerations about Intergenerational Fairness, due to the asymmetric distribution of current and long-run costs and benefits associated with changes in current practices. The work presented in this report aims to contribute to this debate by promoting the development of scientific evidence on the contribution of different generations to the pressure on planetary boundaries during the latest decades in Portugal.

This study developed for the *Calouste Gulbenkian Foundation* aimed to: (1) Estimate the impact of biophysical resource use by different generations in Portugal and to relate the amount of resources used to planetary environmental boundaries; (2) Provide explanatory hypotheses to rationalise the trends observed in biophysical resource use; (3) Estimate how many biophysical resources each generation received from the previous generation and the resources it left to the next. To achieve these, four steps were conducted, building on each other:

- The first step explored how to define the Portuguese shares of the global safe operating space. Such a definition of shares inevitably involves normative choices. This report studied the equality principle, which assumes the basic idea of equal rights for all humans on Earth, independently of any specific planetary boundary. This principle was used to calculate Portuguese limits for eight boundaries.
- The second step was to evaluate the extent to which Portuguese environmental footprints are compatible with the Portuguese limits as calculated for the eight boundaries. These footprints were estimated as far back in time as data allowed (1960 onwards, for most cases). The report calculates Portuguese footprints and compares them with the calculated Portuguese limits to assess whether or not Portugal is living within its environmentally safe operating space.
- The third step provided overarching explanatory hypotheses to the observed patterns in the footprints analysed. This involved a literature review and a series of tests on the data to find relationships between the environmental footprints analysed and socio-economic variables.
- The fourth step an Intergenerational analysis is presented, allocating the Portuguese environmental footprints and limits to each generation to understand how much each generation is leaving to the next generations. The allocation of Portuguese footprints and limits to generations (birth cohorts) was conducted based on the age of the head of the household and assumed that the family consumption can be allocated to the head of the household.

The analysis covered the current Portuguese territory (mainland Portugal and Azores and Madeira autonomous regions). It excluded regions that are not part of Portugal nowadays, but they were at some point during the period of analysis (1960-2018), such as Angola, Cape Verde, East Timor, Goa, Guinea Bissau, Mozambique, and São Tomé e Principe. The report addresses eight planetary boundaries: climate change, stratospheric ozone depletion, Pressure on ecosystems (to represent land-system change and changes to biosphere integrity), Water pollution by nitrogen (N) and phosphorus (representing the biogeochemical cycles), freshwater use, and two new categories: air pollution and solid waste production and disposal.

2. OVERVIEW OF RESULTS

The results from this study show that:

- Portugal is within the boundaries for only one environmental category (although very close to the boundary) – pressure on ecosystems (since 2014). Pressure on ecosystems represents here the appropriation by humans of net primary production, linked with freed up areas for nature (forests and shrubland). For the remaining environmental categories, Portugal is outside the boundary for the whole category or for some of the sub-categories.
- Within these, the most pressing environmental areas for Portugal are climate change, water pollution by phosphorus and the freshwater use. This is because: (1) climate change and water pollution are the two indicators that present the highest distance between their footprint and their limit for the latest year (deficit), or (2) water pollution by phosphorus and freshwater use both present the highest growth rate, which means that the situations on these indicators will get worse quicker.
- GDP growth is the main cause for transgressing the boundaries. This is valid for most of the indicators analysed (except for the agriculturally linked indicators such as water pollution (by N and P) and

freshwater use) and assumes particular relevance for the waste production and disposal indicators. For water pollution and freshwater use, agricultural policy was the main driver, particularly, the transition period to the EU policies on agriculture (from 1986).

- Partial decoupling of the biophysical indicators from GDP has been obtained through policies promoting the decarbonisation of electricity; energy efficiency (for industry and buildings); cleaner vehicles and fuels; regulating the production and consumption of ozone depleting substances; policies on waste valorisation.
- Older generations have higher impacts than the remaining generations in terms of pressures on ecosystems, N and P flows. For the remaining environmental categories, all generations present at a certain point in their lives (age) higher impacts than the remaining generations. This was because the impacts of generations depend on two factors: (1) the age of the head of the household (different age groups have different probability of being a head of a household; this probability changes over time) and (2) the trends observed in the biophysical indicators, whose trend varies for each environmental indicator. The combination of these two factors results in the variety of the patterns observed in terms of the impacts of each generation in each biophysical indicator.
- Most of the generations analysed had their impacts above the boundary. Apart from a few exceptions, Generation Z (born from 2000 onwards) is the only one that is within or almost within the boundary in all the environmental categories, which can be explained by the fact that this generation has not yet had the time to have many heads of households.

These aspects are explored in more detail below.

3.
THE IMPACT OF BIOPHYSICAL RESOURCE USE IN PORTUGAL

The current situation of Portugal in terms of the pressure exerted on the biosphere from the activities happening within the Portuguese territory is summarised in Table 1. In this table, “the risk zone” refers to: or (1) variables that have more than one boundary and are currently over one of these boundaries and within other boundaries; or (2) variables that have only one boundary and where the variable is over the boundary, but close to the boundary, and with a decreasing trend (i.e., a trend that is getting closer to the boundary). The areas of concern are climate change, ozone layer depletion (for the latitudes between 30N-30S and between 60S-30S, for the ozone hole latitudes, although improving, it is still in the risk zone (over the boundary)), Water pollution (by nitrogen and phosphorus), freshwater use (in dry years), air pollution (for emissions from non-methane volatile organic compounds (NMVOC) and ammonia (NH_3); and for $PM_{2.5}$, PM_{10} and O_3 concentrations) and waste production and disposal (for municipal solid waste and total solid waste).

Table 1
Portuguese biophysical status compared to the biophysical boundaries

<table>
<tr><th>Category</th><th colspan="4">Status</th></tr>
<tr><td>Climate change
(1961-2016)</td><td colspan="4">Over the boundary
Since at least 1989. Trend: decreasing since 2005.</td></tr>
<tr><td>Ozone layer depletion
(1979-2019)</td><td>Over the boundary
For lower latitudes (30S-30N)</td><td colspan="2">In the risk zone
For the ozone hole (although improving) and mid-south latitudes (60S-30S)</td><td>Within the boundary
For mid and higher north latitudes</td></tr>
<tr><td>Pressure on ecosystems
(1961-2016)</td><td colspan="4">Within the boundary
In the last 2 years. Trend has been decreasing (improving) since 1990.</td></tr>
<tr><td>Water pollution by nitrogen
(1961-2016)</td><td colspan="4">Over the boundary
Since 1971. Trend: increasing significantly since 2011</td></tr>
<tr><td>Water pollution by phosphorus
(1961-2016)</td><td colspan="4">Over the boundary
During the whole period analysed. Trend: decreasing (improving).</td></tr>
<tr><td>Freshwater use
(1961-2016)</td><td colspan="2">Over the boundary
In dry years, since 2008. Trend: increasing.</td><td colspan="2">Within the boundary
For an average year and for wet years. Trend is increasing.</td></tr>
<tr><td>Air Pollution
(1990-2018[a]; 2003-2018[b]; 1995-2018[c])</td><td>Over the boundary
For NH_3 emissions, and for concentrations of $PM_{2.5}$ (daily values) and O_3 (8-hour values, WHO) [d]</td><td colspan="2">In the risk zone
For concentrations of $PM_{2.5}$ (annual values) PM_{10}, SO_2 (daily values, WHO) [d]</td><td>Within the boundary
For emissions of $PM_{2.5}$, SO_x, NO_2, NMVOC and for concentrations of CO, NO_2, SO_2 (daily values EU) [d] and O_3 (8-hour values, EU) [d]</td></tr>
<tr><td>Waste production and disposal
(1960-2018[e]; 2008-2018[f])</td><td colspan="2">Over the boundary
Total waste produced, with an increasing trend.</td><td colspan="2">In the risk zone
Waste disposal (due to municipal solid waste)</td></tr>
</table>

In the risk zone refers to: or (1) variables that have more than one boundary and are currently over one of these boundaries and within other boundaries; or (2) variables that have only one boundary and where the variable is over the boundary, but close to the boundary, and with a decreasing trend (i.e., a trend that is getting closer to the boundary).

Notes to the table: a. For emissions; b. For $PM_{2.5}$ concentrations; c. For remaining air pollutants concentrations, d. O_3 and SO_2 concentrations have two boundaries with different statuses: The World Health Organisation guidelines (based on the health effects of exposure to pollutant concentrations) and the Portuguese Decree Law No. 102/2010), less strict values; e. For municipal solid waste only; f. for sectoral and total solid wastes.

Within these, the most pressing environmental areas for Portugal are climate change, water pollution by phosphorus and the freshwater use. This is because: (1) climate change and water pollution are the two indicators that present the highest distance between their footprint and their limit for the latest year (deficit), or (2) water pollution by phosphorus and freshwater use both present the highest growth rate, which means that the situations on these indicators will get worse quicker.

The particular case of freshwater use, while globally the planet was within the boundary in 2010 (Steffen et al. 2015), this study shows that Portugal already crossed this boundary within its territory for dry years. Although 2010 was not a dry year in Portugal (and therefore, Portugal was within the boundary on the year), when Portugal is over the boundary, this might not be visible globally because there are countries who are within the boundary in the indicator, balancing the fact the Portugal has crossed the boundary for the indicator.

In fact, for the whole analysis, local impacts are diluted as impacts are analysed in national terms. This is particularly relevant for water (where regional water scarcity (e.g., in the south) is diluted with regions with less scarcity) and air pollution, in particular, traffic related air pollution, where limits might be transgressed locally, but not when national averages are analysed.

Lesser areas of concern are pressure on ecosystems, the ozone layer for the latitudes between 90S-60S (the ozone hole latitude), 60N-30N and 90N-60N, air pollution from $PM_{2.5}$ SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 and NO_2 hourly concentrations, solid sectoral waste disposal. This is because these indicators:

- are in the safe zone and their current trend will keep them in the safe zone (for ozone layer depletion for the latitudes between 90N-30N, $PM_{2.5}$, SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 hourly concentrations, solid sectoral waste disposal),
- although still in the uncertainty zone of the boundary, show an improving trend (for ozone layer depletion for the latitudes between 90S-60S, NO_2 hourly concentrations).

4. CAUSES LEADING TO THE CURRENT ENVIRONMENTAL STATUS

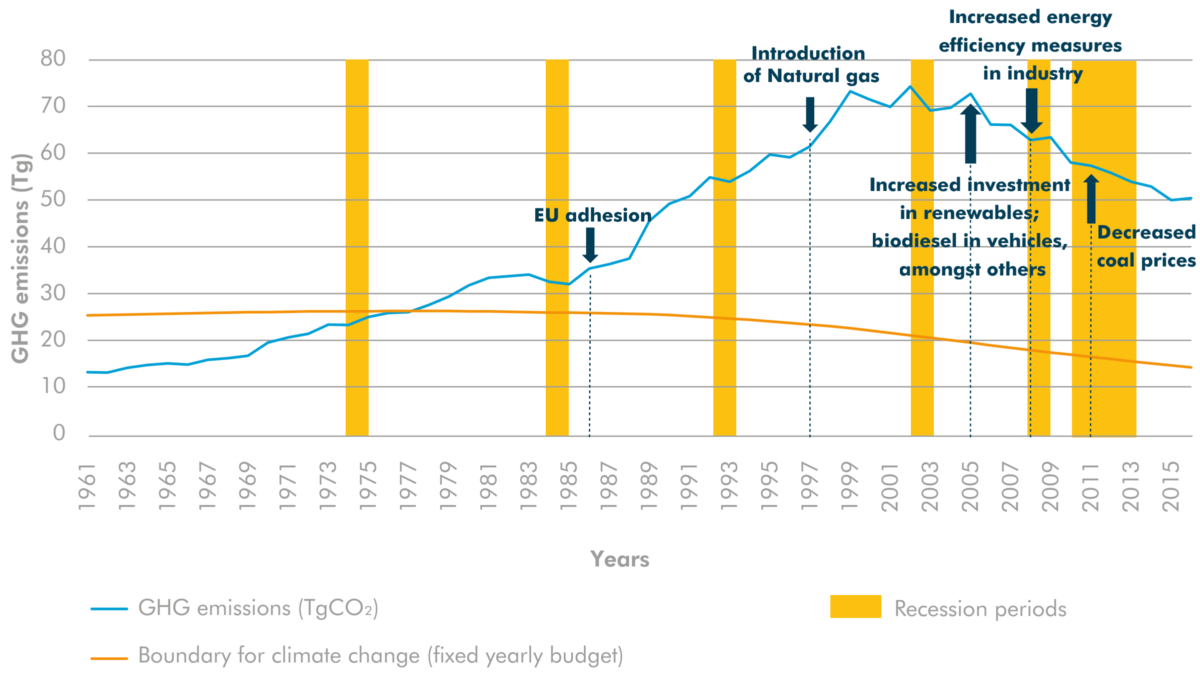
The main factors identified in this report, leading to the observed trends in the indicators analysed were:

- GDP dynamics,
- Partial decoupling of the biophysical indicators from GDP has been obtained through many policies implemented from the 1990s onwards.
- The agricultural policies associated to entering the EU (from 1986).

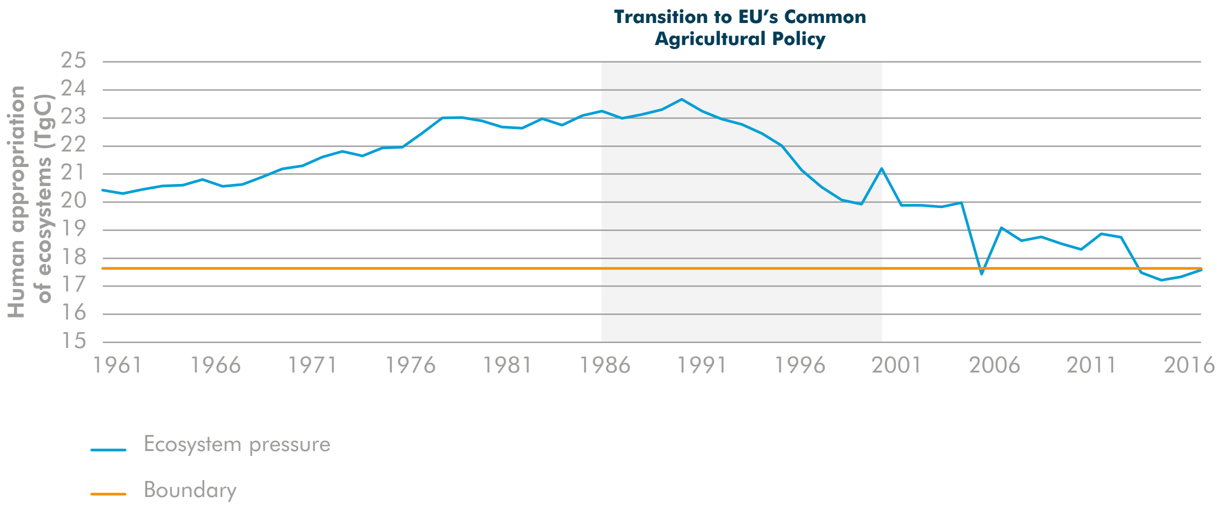
Figure 1 presents an example of how these factors shaped the dynamics of different indicators. The indicators presented are climate change and pressure on ecosystems. GDP affected GHG emissions. When Portugal joined the EU, this affected all the indicators directly and indirectly. GHG emissions were affected due to an economic boost coming from joining the EU. Pressure on ecosystems was affected by the EU agricultural policies, which led to an abandonment of agricultural land and an intensification of remaining agricultural land. This contributed to a release of land for pastures and shrubland, decreasing the pressure on ecosystems. The shift to the EU also influenced water, nitrogen, and phosphorus use, promoting an increase in the use of water and decreases of fertiliser use.

Figure 1
Footprints, boundaries, and explanatory factors for selected indicators

Climate change



Ecosystems pressure



4.1. GDP growth as the main cause of boundary transgression

GDP dynamics (growth and recession) affect indirectly the biophysical indicators by affecting the economic activities and providing family income which leads to increased energy demand, road transport, production activities (industrial activity), consumption (of products but also of water) and waste production. GDP was the main contributor for transgressing the boundaries in most of the biophysical indicators analysed. This is valid for most of the indicators analysed (except for agriculturally linked indicators such as the pressure on ecosystems, water pollution and freshwater use) and assumes particular relevance for the waste production and disposal indicators.

GDP influences almost all variables analysed in certain interval periods. We have found a strong relationship between GDP and (1) GHG emissions from energy industries until 2005, when decarbonisation policies started influencing electricity production; (2) industry energy demand until 2002; (3) households and services until 2005; (4) road transport emissions until 2004; (5) waste production in all years analysed (1960-2018); and (6) waste disposal until 2000 (date when recycling rates started becoming significant and incineration was introduced).

4.2. Contribution of policies to decouple GDP from biophysical indicators

Many policies have been implemented since the 90s that have had a contribution to the biophysical indicators analysed. We are referring to policies promoting the decarbonisation of electricity, road transport and waste disposal; energy efficiency measures (for industry and buildings); policies promoting cleaner vehicles and fuels; policies regulating the production and consumption of ozone depleting substances (ODS); policies on waste valorisation.

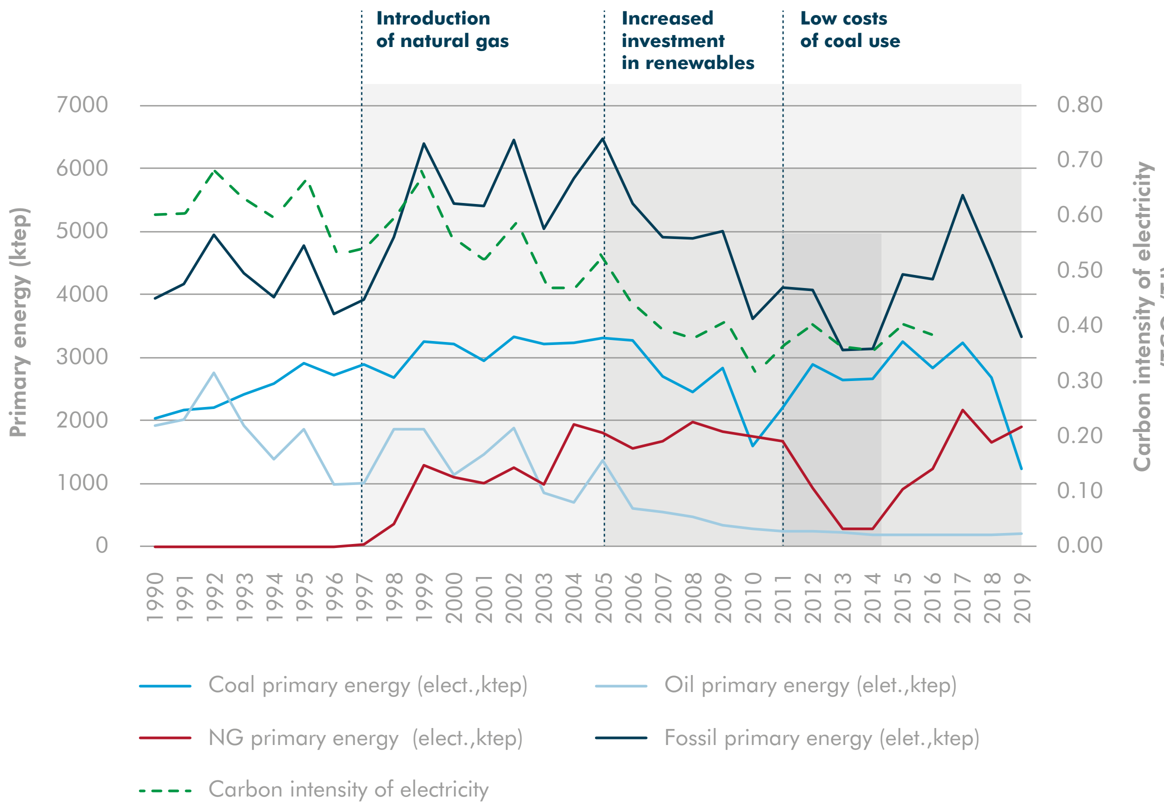
We have found that:

- Decarbonisation policies had a strong effect on air pollution from 1997 and on GHG emissions (from energy industries) from 2005 with the introduction of natural gas and investment in renewable sources of electricity,
- Energy efficiency measures had a strong effect in terms of GHG emissions from manufacturing industries from 2002 onwards, when these policies started to have a significant effect; and on building energy efficiency from 2005,
- Policies for cleaner fuels and transport have had a strong effect on air pollutants from road transport from 2004 onwards,
- Waste policies, in particular the ones promoting recycling and incineration, have had a significant effect from 2000 onwards on waste disposal.

One example of such policies, and that had a great deal of relevance, was the introduction of natural gas in Portugal, in 1997, which had a transversal effect in the environmental indicators, affecting climate change and a series of air pollutant concentrations. Natural gas replaced oil in electricity generation (Figure 2), butane gas in household and services, and influenced the manufacturing industry. This affected positively GHG emissions (overall, and in particular GHG emissions from electricity production – where the carbon intensity of electricity started to decline when oil use for power generation started to decrease due to the use of natural gas) and air pollutant emissions in terms of PM_{10}, SO_2, NO_2, NMVOC, and NH_3 (Figure 3).

Figure 2

Fuels used in power generation and carbon intensity of electricity



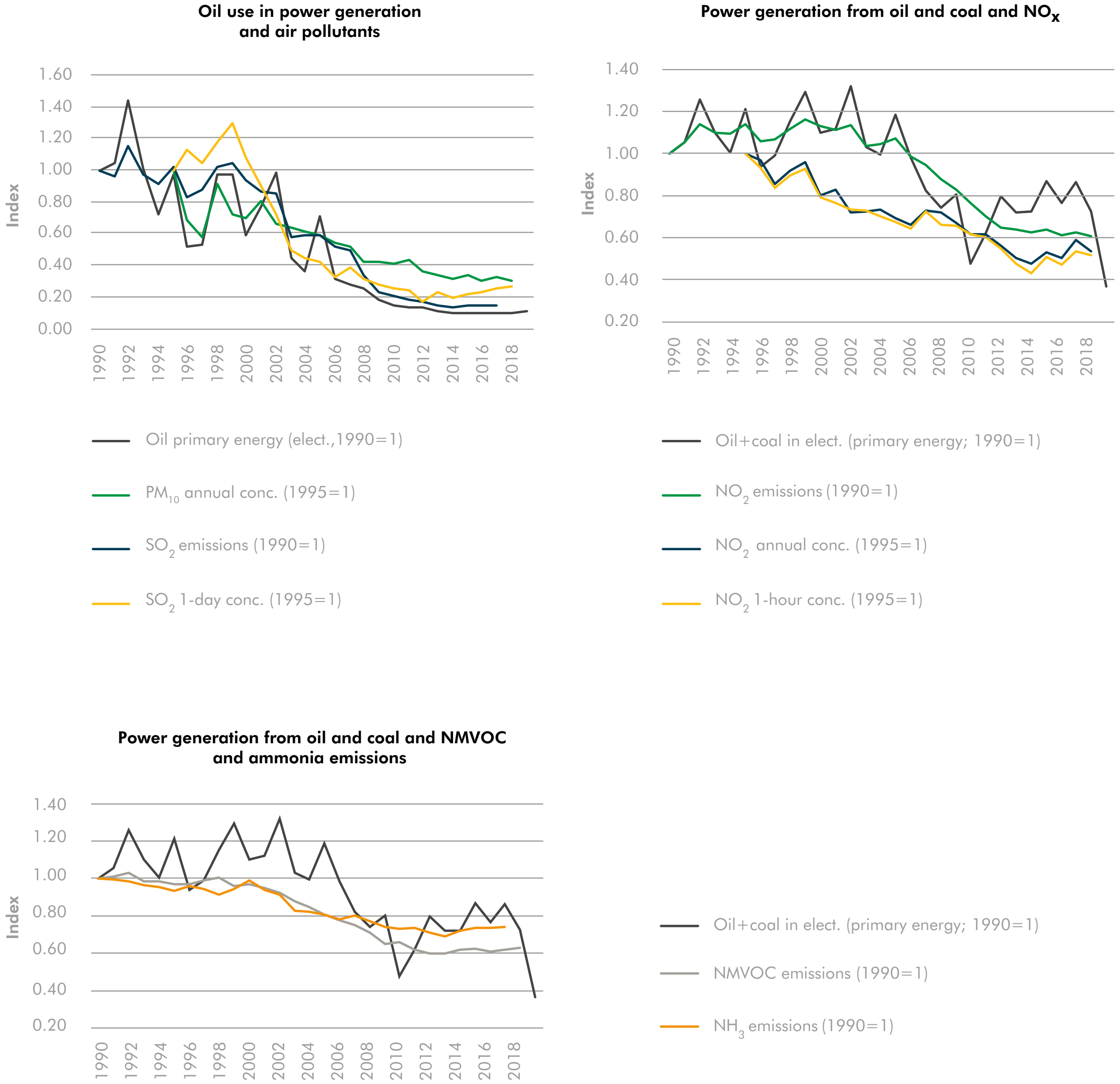
Data sources: fossil fuels (in kilo tonnes of oil equivalent) – national energy balances from DGEG; carbon intensity of electricity (in tonnes of carbon dioxide equivalent by Tera-Joules) – Felício et al. (2019).

4.3. EU policy on agriculture

Prior to Portugal joining the EU, there was a growing intensification of agriculture with increased use of fertilisers and machinery and lead to a generalised increase in animal production (Figure 4). This was mainly a result of agricultural policies implemented during the 60s to improve agricultural income, resulting in the intensification of agriculture (Branco 2015). The result was a slow increasing trend in in GHG emissions from agriculture, pressure on ecosystems (Figure 5) and fertiliser use (N and P flows).

Portugal joined the EU in 1986. The Portuguese transition period to the EU Common Agricultural Policy (CAP, between 1986-2000) and the internationalisation of the EU agricultural market (in 1993) led to first a decrease in agricultural production followed by an intensification of agriculture (namely seen in the increased N input per unit area) in the more productive and irrigated areas and extensification or abandonment elsewhere. Agricultural areas and animal production decreased (Figure 4). The exception is for more intensive forms of animal production such as non-dairy cattle which increased (and, later, swine production also increased). The result is a decreased trend in pressure on ecosystems, fertiliser use in total, NH_3 and NMVOC emissions (due to manure management, grazing and fertilisation) and PM_{10} concentrations (due to grazing and ploughing) (Figure 5).

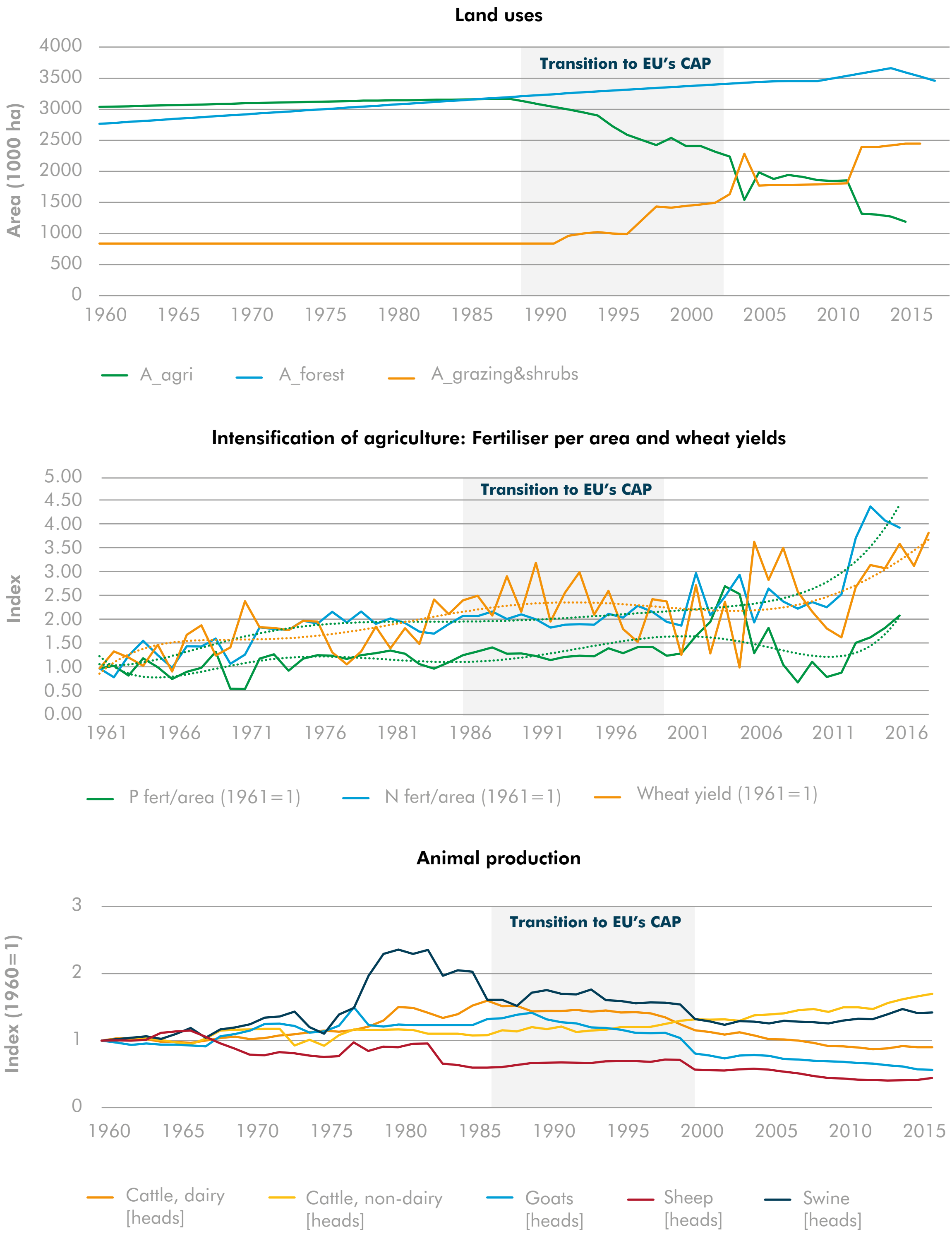
Figure 3
Air pollution (PM_{10}, SO_x, NO_x, NH_3, NMVOC), oil and coal use in power generation



Data sources: Primary energy from oil (in tonnes of oil equivalent) from the national energy balances from DGEG; SO_x, NO_x, NH_3 and NMVOC emissions (in kilo-tonnes of pollutant) from APA (2019a); SO_x 1-day concentrations, NO_x concentrations and PM_{10} annual concentrations (in micrograms per cubic meter) from own calculations based on the national air quality monitoring network data.

Figure 4

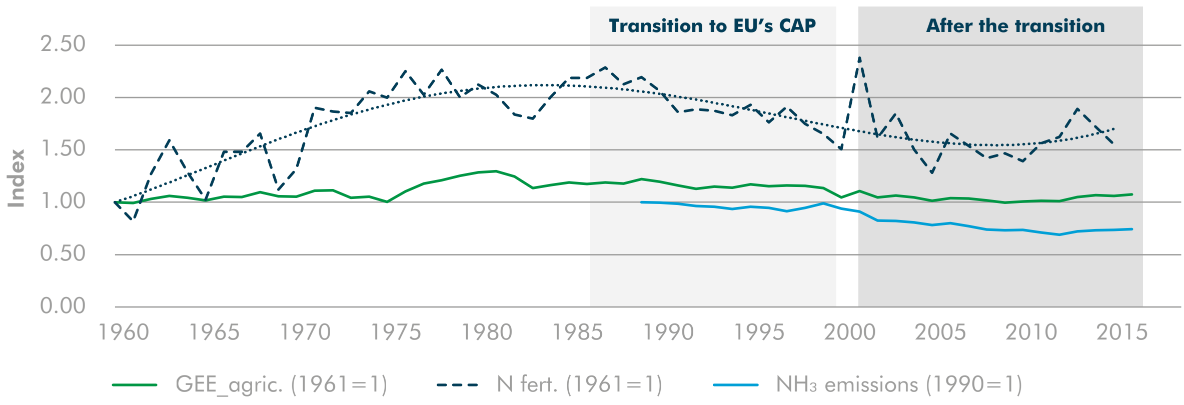
Trends in land use, fertiliser, and animal production in Portugal



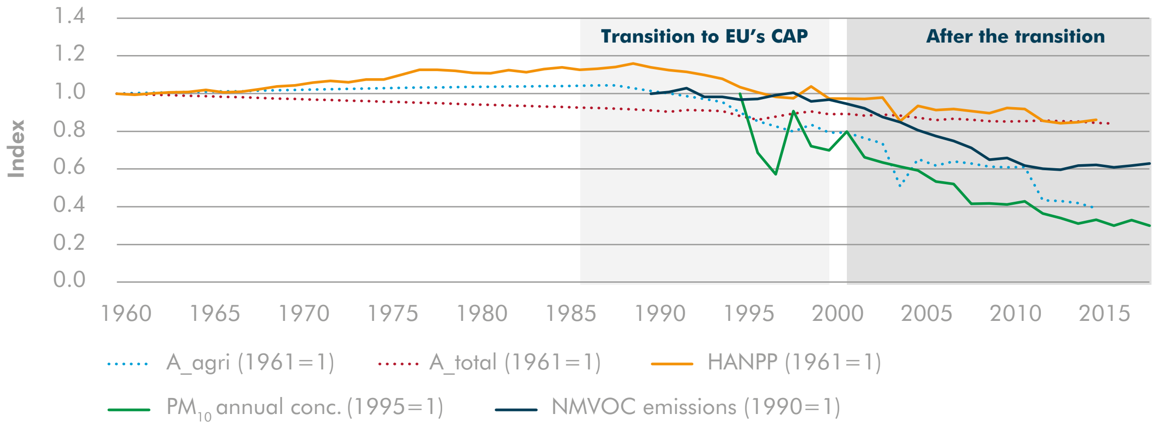
Source of data: Forest area: COS; Remaining variables: FAOSTAT.
Note that agricultural and grazing areas remain fairly constant until the 80s, which could be due to low quality of the data available. Grazing areas include shrubland and pastures.

Figure 5
Agricultural policy shifts and environmental indicators, 1960-2018

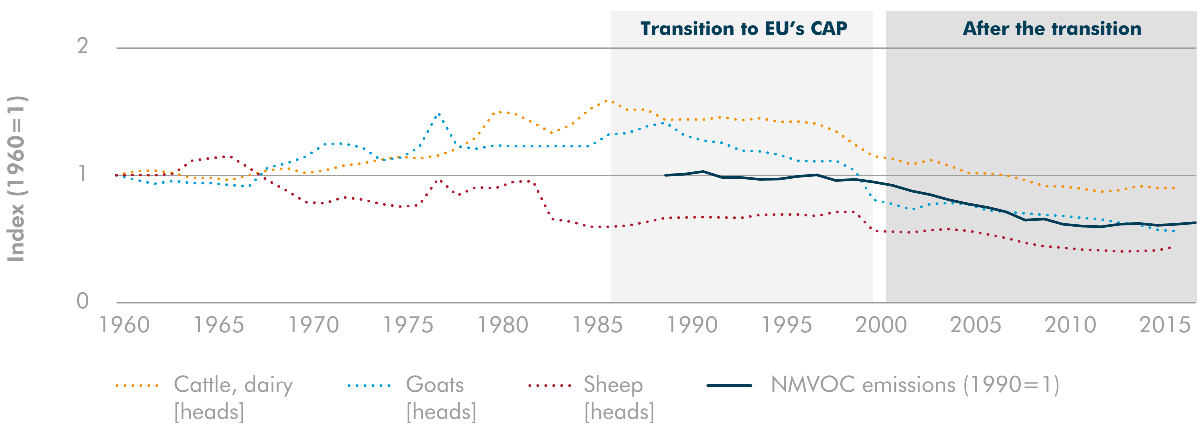
Nitrogen fertiliser use, GHG and ammonia emissions



Agricultural area pressure on ecosystems (HANPP), NMVOC emissions and PM_{10} concentrations



Grazing: grazed animals and NMVOC emissions



5.
INTERGENERATIONAL ANALYSIS

To explore how much each generation has used in terms of biophysical resources and how much it is leaving to the next generations, annual impacts were allocated to the population using an age-based consumer profile per year. For this, birth-cohorts and generations were used. 25 birth cohorts were defined, based on 5-year intervals, covering all cohorts living between 1960 and 2020. To make it easier for the interpretation of results, the nomenclature for birth-cohorts was the following: "C" from cohort, and "number" reflecting the age of the youngest member of the cohort in 2020. Given the period of analysis (1960-2020), this means that not all cohorts are complete; in fact, only the cohorts C56 to C41 are complete. Generations, as used here, are aggregations of birth-cohorts. Five generations were considered: Pre-WWII divided in the groups C121-C101 and C96-C81, Baby Boomers (C76-C61), Generation X (includes birth cohorts C56-C41), Generation Y (includes birth cohorts C36-C21) and Generation Z (includes birth cohorts C16-C01).

A consumption profile per age was determined based on the age distribution of the household heads through time. The value of the biophysical indicators for each year were allocated to each birth-cohort of the household heads in each year. With this, the impacts of each birth-cohort of household heads per age group (or per year) were obtained.

From the results of this project, the impacts of generations depend on two factors: (1) the consumption profiles assumed based on the age-distribution of the household heads (consumption per age group) and (2) the trends observed in the biophysical indicators (impact in each year). The combination of these two factors results in the variety of the patterns observed in terms of the impacts of each generation in each biophysical indicator. This made the results very different for each environmental indicator:

- Older generations have higher biophysical impacts per capita than younger generations for the biophysical indicators pressure on ecosystems and N and P flows (see Figure 6, for the pressure on ecosystems).
- For the remaining environmental indicators, all generations have an age interval where their impacts were the highest across generations (Figure 7).
- This age interval has been happening earlier and earlier in time, so for older generations this happened later in their life and for younger generations, this happened earlier in life.

Figure 6
Impacts per generation and per age group for pressures on ecosystems

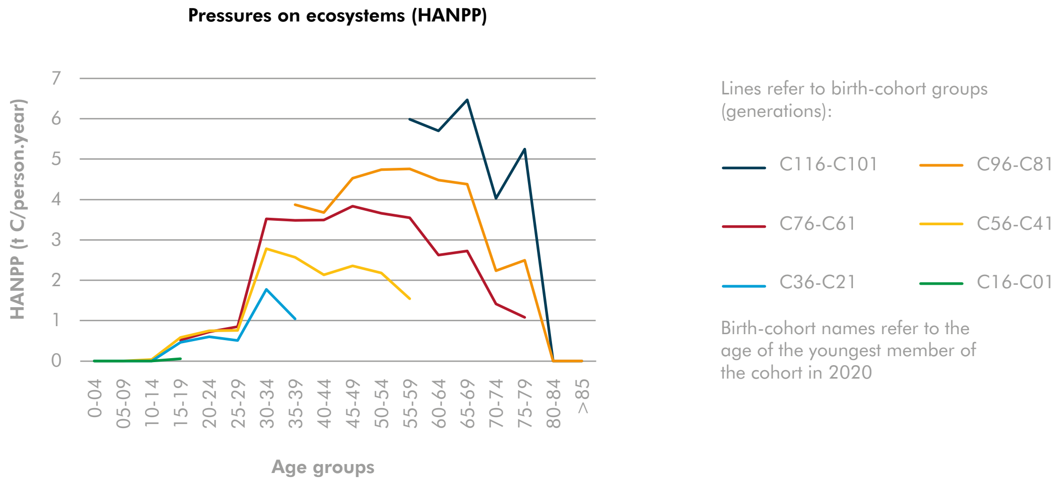
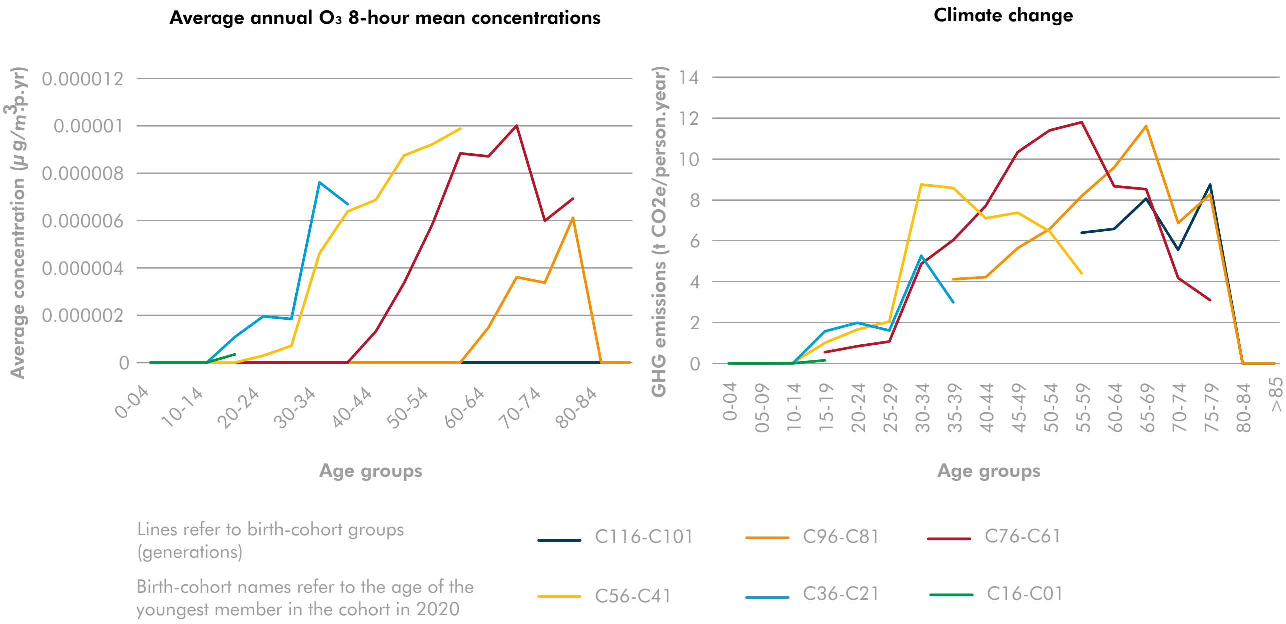


Figure 7
O_3 concentrations and climate change per capita, by age group



Most of the generations analysed had their impacts above the boundary. Apart from a few exceptions, Generation Z (C16-C01) is the only one that is within or almost within the boundary in all the biophysical indicators, as this generation has not yet reached the ages allocated with the highest consumption levels.

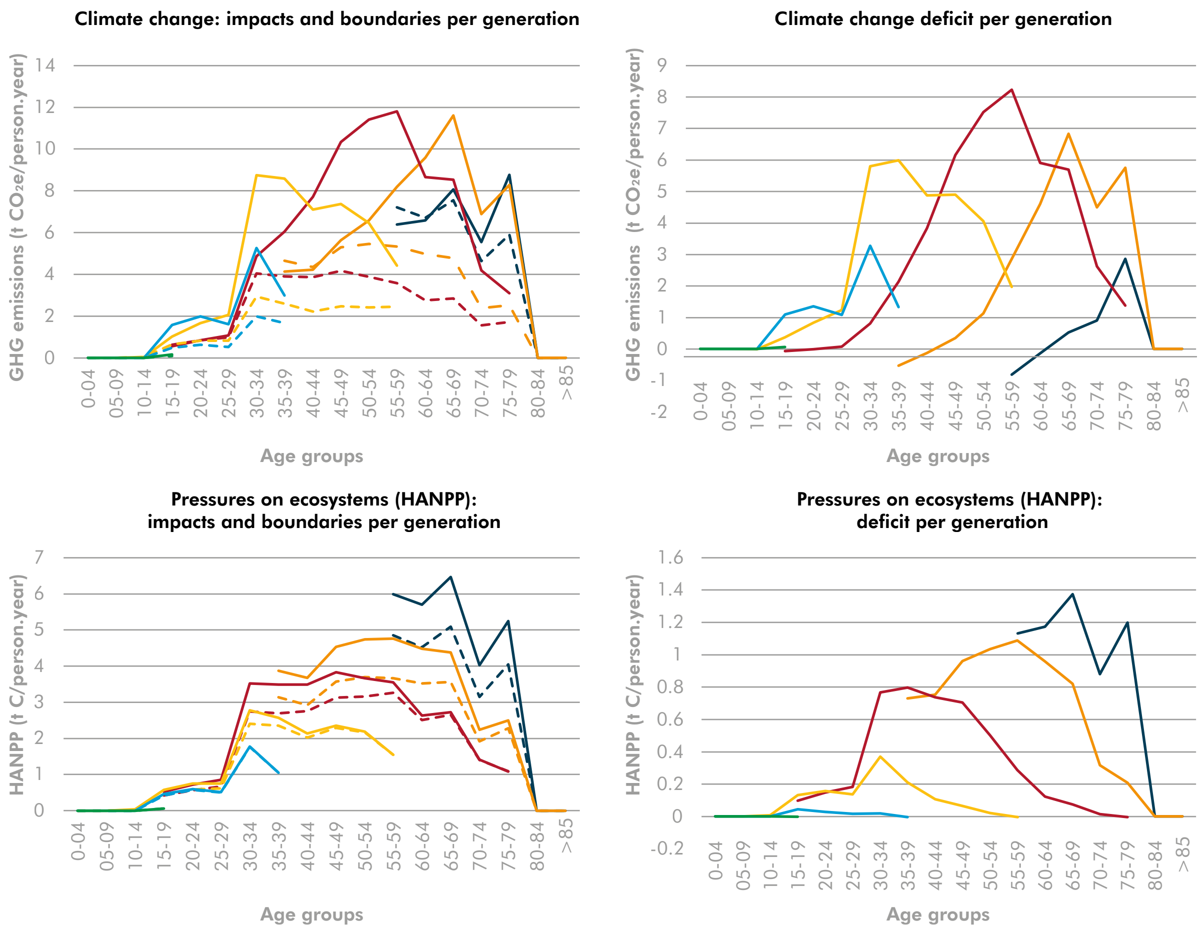
Figure 8 presents an example of this for climate change and pressure on ecosystems. In these examples the generation boundary refers to the boundary per capita allocated to each age group according to their consumption profile (in the same way as conducted for attributing the biophysical impacts per generation). This generation boundary represents the maximum impact each generation in each age could do without trespassing the boundary (i.e., without damaging the environment).

For climate change, all generations present impacts above the boundary, including the youngest ones. Generation X (C56-C41), Baby Boomers (C76-C61) and Pre-WWII (C116-81) have the highest differences between the boundary and their actual impacts. For the pressure on ecosystems, the oldest generations present the highest differences between their impacts and the boundary, but all the generations, with exception of the youngest one (Generation Z - C16-C01), present values above the boundary.

For the particular case of climate change, in 2016 Portugal emitted more GHG than the annual GHG budget, which resulted in a progressive reduction of this limit (becoming less available to be emitted until 2100). This results in a citizen (or an age group) in 2016 having a lower emission budget than a citizen of the same age in previous years: -31% compared to a citizen of the same age in 2000, -43% compared to a citizen in 1980 of the same age, -41% compared to a citizen in 1961 of the same age.

Figure 8

Estimated impacts vs generation boundaries for climate change and pressure on ecosystems



C116-C101	C96-C81	C76-C61	C56-C41	C36-C21	C16-C01
C116-C101 (boundary)	C96-C81 (boundary)	C76-C61 (boundary)	C56-C41 (boundary)	C36-C21 (boundary)	C16-C01 (boundary)

On the left: impacts estimated, by generation (full lines), and generation boundaries: boundary for each generation, using the same allocation procedures (consume profiles) as for determining the impacts for generation (dashed lines).
On the right: difference between estimated impacts and the boundary for each generation. Positive values refer to impacts above the boundary. Negative values refer to impacts below the boundary.

Older generations, although not within the boundaries in many biophysical indicators, have contributed to the implementation of policies that led to a reduction in these indicators, leaving their own generation and younger generations with lesser impacts.

6. POLICY IMPLICATIONS

We have found that GDP growth, as it is linked with production and consumption activities, is the main cause of transgressing the boundaries in the biophysical indicators analysed. This is valid for most of the indicators analysed (except for the agriculturally linked indicators such as pressure on ecosystems, water pollution and freshwater use) and assumes particular relevance for the waste production and disposal indicators. For pressure on ecosystems, water pollution and freshwater use, agricultural policy was the main driver, particularly, the transition period to the EU policies on agriculture (from 1986), which lead to an intensification of agriculture.

However, policies implemented from the 1990s onwards had their contribution in partially decoupling the biophysical indicators from GDP. This shows the relevance of policies on promoting the decarbonisation of electricity, energy efficiency (for industry and buildings); cleaner vehicles and fuels; regulating the production and consumption of ozone depleting substances; policies on waste valorisation.

The results from this study show that there are many environmental areas of concern as Portugal is completely within the boundary for only one environmental category out of eight. This means that there are several areas that can be tackled. These areas are:

- Reduction of GHG emissions,
- Reduction in the use of nitrogen and phosphorus fertilisers (e.g., through more efficient agriculture),
- Ensuring water availability in particular for dry years (e.g., efficient use of water and re-use of grey waters),
- Ensure that at least the national limits are achieved, in particular in terms of emissions of ammonia and NMVOC, and concentrations of pollutants such as particles ($PM_{2.5}$ and PM_{10}), sulphur oxides and ozone,
- Reduction of waste production and increase waste treatment, in particular for municipal solid wastes.

1. INTRODUCTION

With the objective of increasing scientific knowledge on Intergenerational justice, the *Calouste Gulbenkian Foundation* (FCG) aims to support the production of high-quality research, focusing on a multidisciplinary approach and incorporating demographic, economic, social, environmental, political, and ethical perspectives. In Portugal, the number of studies on Intergenerational justice is still very small, particularly in areas of public policy where a given policy measure may have different impacts depending on the generation under consideration.

One of the public policy areas that has been increasingly expanding in the latest decades is the regulation of human processes that affect the environment. These efforts range from new standards of production technology and natural resources usage, to changes in consumer habits, via public information campaigns, new legislation, and taxation. The evolution of public perceptions and government policies has led to, among other multinational agreements, the 2030 Agenda for Sustainable Development set by the United Nations General Assembly in 2015.

Against this backdrop, there is an active field of research that studies important boundaries related to critical Earth-system processes (e.g., biosphere integrity, biogeochemical flows, climate change, and land-system change). It is argued that these boundaries define limits to the stability of Earth's ecosystems. Another strand of the literature focuses on the development and estimation of environmental footprint indicators for biophysical resource flows. These indicators link levels of consumption of goods and services to the corresponding environmental effects (greenhouse gas emissions, freshwater usage, etc.). More recently, researchers have been bridging the two approaches. This effort enables the estimation of the contribution of current consumption choices and production methods to the existing pressure on and possible transgression of planetary boundaries.

Discussions around environmental stability, given its long-run perspective, are intimately linked with considerations about Intergenerational Fairness, due to the asymmetric distribution of current and long-run costs and benefits associated with changes in current practices. The work conducted in this project aims to contribute to this debate by promoting the development of scientific evidence on the contribution of different generations to the pressure on planetary boundaries during the latest decades in Portugal. This allows us to answer the call from the *Calouste Gulbenkian Foundation* (FCG) for a study with the following goals:

- To develop a method to quantify the contribution of each generation for the environmental footprint indicators and their corresponding impact on the Portuguese share of the planetary environmental boundaries.
- To propose explanatory hypotheses (technological change, renewable energy use, etc.), supported by the data, that can rationalize the observed trends.
- Given the trends in footprint indicators, to compute what each generation received (from the previous) and left to the next generation, in terms of biophysical resources and respective flows.

The objectives of this report were to:

1. estimate the impact of biophysical resource use by different generations in Portugal and relate the amounts of resources used to global environmental boundaries,
2. provide explanatory hypotheses to rationalise the trends observed for the biophysical resource use,
3. estimate what each generation received from the previous generation and left to the next.

The report is structured as follows. Chapter 2 provides an overview of the planetary boundaries framework (Section 2.1) and explains which planetary boundaries have been included in the analysis the limits as used in this report (Section 2.2). The chapter also calculates the environmental footprints for Portugal (Section 2.3), presenting the results of this analysis (Section 2.4). Chapter 3 identifies and explores explanatory hypotheses for the observed trends in the footprint indicators from Chapter 2. This chapter starts with a description of the approach taken to identify the explanatory hypotheses (Section 3.1), followed by a presentation of the results from the analysis (Section 3.2). The chapter ends with an overview of the results (Section 3.3). The results are then detailed. Chapter 3.3 provides the Intergenerational analysis, describing first the approach followed (section 4.1), the detailed results (Section 4.2), and ending with a summary of the main points (Section 4.3). Chapter 5 summarises the main points from this report.

2.

IMPACT OF BIOPHYSICAL RESOURCE USE IN PORTUGAL

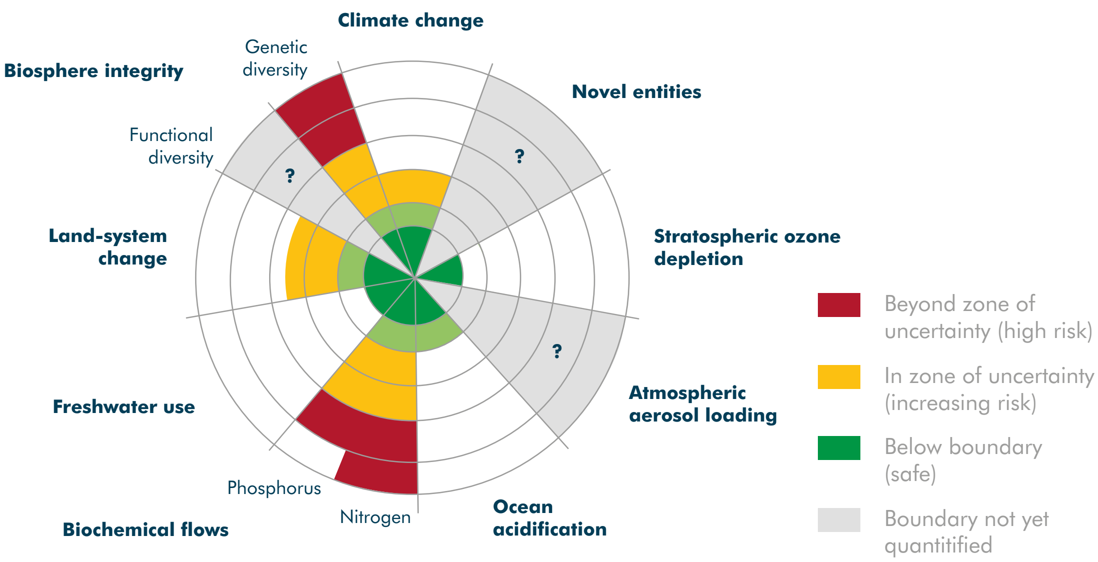
Our aim in this Chapter is to present the quantification of the impacts in the biosphere from the Portuguese territory using the planetary boundaries framework. We have estimated a series of biophysical indicators from as far back as the data allowed it to the present (which was never before 1960). The indicators were grouped into eight environmental categories. For each of the indicators, we have also quantified the Portuguese share of the planetary boundaries (thresholds / ceilings) for the same period. The results show us the current biophysical situation of Portugal, by comparing the indicators with their boundaries. The results also show the evolution of the indicators through time, giving an indication on their trends. The results from this Chapter will feed into the results from the next two Chapters (provision of explanatory hypotheses for the trends observed in the biophysical indicators and allocation of the impacts per generation).

2.1 THE PLANETARY BOUNDARIES FRAMEWORK

The planetary boundaries framework identifies nine planetary life-support systems. These were first introduced by Rockström et al. (2009) and have subsequently been refined by others such as Steffen et al. (2015) and O'Neill et al. (2018).

For each of the planetary boundaries, so-called 'control variables' have been defined as proxies to measure whether or not they are transgressed on the global scale because of human activities (Rockström et al., 2009; Steffen et al., 2015). Steffen et. al. (2015) suggested that between 2010 and 2014, humanity had already transgressed the limits that define a safe operating space for four of the planetary boundaries: biogeochemical flows (nitrogen and phosphorus cycles) and biosphere integrity (genetic diversity component) (both in the red zone indicating high risk as shown in Figure 9), as well as climate change and land system change (both in the yellow zone indicating increasing risk as shown in Figure 9). Three planetary boundaries were still within the green zone (i.e., the safe operating space): freshwater use, ocean acidification and stratospheric ozone depletion. Some planetary boundaries have not yet been quantified: functional diversity (part of biosphere integrity), novel entities and atmospheric aerosol loading.

Figure 9
Global status of the planetary boundaries



Source: Steffen et al. (2015).

There are ongoing scientific discussions on Earth's system processes, and the control variables, therefore, the planetary boundaries represent only estimates based on currently available scientific knowledge. Some of the control variables originally proposed in Rockström et al. (2009) were subsequently refined in Steffen et al. (2015), and further refined by O'Neill et al. (2018), amongst others. Current control variables and limits are therefore likely to be further refined as knowledge evolves. There is currently no scientific evidence on the magnitude of the impact for some of the issues, coupled with the capability of humanity to be able to reach a Holocene like planetary boundary.

For example, for climate change, evidence has accumulated to suggest that the zone of uncertainty for the CO_2 control variable should be narrowed from 350 to 550 ppm (in Rockström et al. 2009) to 350 to 450 ppm CO_2 (in Steffen et al. 2015). However, due to inertia in human energy systems, and in the Earth-system response to decarbonisation, it is generally regarded as unlikely that atmospheric CO_2 can be brought below 350 ppm in the 21st century; even the most optimistic integrated assessment scenarios considered in the IPCC's Fifth Assessment Report (AR5) foresee only a range of 420–440 ppm by 2100. To have an actionable target, O'Neill et al (2018) proposed that a new (non-Holocene) climate state must be accepted—one that avoids the worst impacts of a changing climate but allows for a reasonable chance for societies to decarbonise. In this sense, O'Neill et al (2018) proposed to use the 2ºC temperature stabilisation goal emphasised in the Paris Agreement.

As mentioned in Steffen et al. (2015), planetary boundaries cover phenomena with varying spatial scopes. By applying a classification based on biophysical aspects, some can be characterised as global phenomena (e.g., climate change, as it is the total amount of greenhouse gas (GHG) emissions that is important, not the location of the emissions), while others are local or regional phenomena the impacts of which can accumulate to a global level (e.g., freshwater use).

To better consider the aggregated processes on a local/regional scale and to prevent the transgression of sub-global boundaries that would 'contribute to an aggregate outcome within a planetary-level safe operating space', Steffen et al. (2015) propose complementing the global limits with sub-global limits for five planetary boundaries: functional diversity, (as part of biosphere integrity), phosphorus (as part of biogeochemical flows), land system change, freshwater use, and atmospheric aerosol loading.

Table 2 presents a summary of the nine planetary boundaries defined by Steffen et al. (2015).

Table 2
Brief overview of the nine planetary boundaries

Biophysical indicator	Description
Climate change (assessed in this report)	It results from the emission of GHG to the atmosphere, mostly due to burning fossil fuels, but also with contributions from industrial processes, agriculture (and animal production) and waste management. Recent evidence suggests that the Earth, now passing 390 ppm (volume) CO_2 in the atmosphere, has already transgressed the planetary boundary, and is approaching several Earth system thresholds (Steffen et al. 2015). The result is the increase in global mean annual temperature at the Earth's surface, increased frequency and severity of extreme climatic events and sea level raise.
Change in biosphere integrity (partially assessed in this report)	This category includes both genetic diversity (biodiversity) and functional diversity (ecosystem services).
Stratospheric ozone depletion (assessed in this report)	The stratospheric ozone layer filters out ultraviolet (UV) radiation from the sun. If this layer decreases, increasing amounts of UV radiation will reach ground level. This can cause a higher incidence of skin cancer in humans as well as damage to terrestrial and marine biological systems. The appearance of the Antarctic ozone hole was evidence that increased concentrations of anthropogenic ozone-depleting chemical substances (ODS), interacting with polar stratospheric clouds, had passed a threshold and moved the Antarctic stratosphere into a new regime. This category is linked with the ozone layer thickness.
Ocean acidification (not assessed in this report)	Acidification of the oceans due to, mostly, carbon dioxide. Acidification of oceans impacts on the solubility/saturation of several compounds in the water, some of the vital for aquatic species, such as aragonite, essential component for shellfish to maintain their shells (Steffen et al. 2015).
Biogeochemical flows (assessed in this report)	Biogeochemical flows, which include the flows of nitrogen and phosphorus to the environment. It affects climate change (due to nitrogen release to the environment), freshwater availability (due to water pollution) and biodiversity and human life.
Land-system change (assessed in this report)	Land-system change is linked with anthropogenic changes to pristine forest cover. This boundary was meant to account for deforestation. It is linked with biosphere integrity, but also to climate change and freshwater use, amongst others.
Freshwater use (assessed in this report)	Global water use (withdrawal) by humans (from the environment).
Atmospheric aerosol loading (not assessed in this report)	Aerosols, in particular, $PM_{2.5}$ (suspended particulate matter with diameter below 2.5 μm) affects cloud formation, impacting on climate (influencing radiative balance), water availability (influencing the monsoons), biosphere integrity and human health (by inhaling the particles themselves, but also the heavy metals associated to these).
Introduction of novel entities (partially assessed in this report)	This boundary accounts for the introduction of novel entities to the environment. These are, for example, emissions of toxic and long-lived substances such as synthetic organic pollutants, heavy metal compounds and radioactive materials.

2.2 DEFINING A SAFE OPERATING SPACE FOR PORTUGAL

2.2.1 Selection of control variables for the analysis

For the purpose of measuring Portuguese performance against planetary boundaries (i.e., comparing Portuguese limits with Portuguese footprints), the biophysical control variables for some of the planetary boundaries proposed by Steffen et al. (2015) have been amended for this study to make them compatible with Portuguese footprint data. Some of the names of the control variables in this report are different from those proposed by Steffen et al. (2015) to represent this change of perspective. This also means that the global performances computed are different from the performances reported in Steffen et al. (2015).

In general terms, this study considered eight environmental categories. Changes in biosphere integrity were combined with land-system change and measured using the Human Appropriation of Net Primary Production (HANPP), in resemblance to O'Neill et al. (2018). This combined indicator is referred to, in the present report, as pressure on ecosystems. Biogeochemical flows will be referred to as "water pollution" in the remaining of the report and nitrogen and phosphorus flows will be treated as two separate indicators (water pollution by nitrogen and water pollution by phosphorus). Introduction of novel entities was analysed in terms of air pollution only and this category was named "air pollution". Atmospheric aerosol loading was not considered, although $PM_{2.5}$ emissions and concentrations were included within "air pollution". One additional category was introduced: waste production and disposal.

Oceans' acidification, suggested in Steffen et al. (2015), was not included in the present work because the main source of the pressure on ocean acidification is caused by CO_2 emissions, already covered in the climate change Earth-system process. The ecological footprint (suggested in O'Neill et al., 2018) was also not included. Although the ecological footprint is a valuable indicator for communication, this indicator has been a target of criticisms in the scientific literature (see O'Neill et al. 2018) to the point that alternative scientific approaches such as the Planetary Boundaries framework have emerged, covering all the areas the ecological footprint claims to cover.

2.2.2 Defining the biophysical boundaries for Portugal

Table 3 summarises the control variables and the global limits used as the basis for the present study. The following paragraphs provide the rational and describe how these limits were defined.

Table 3
Summary of the control variables and global limits in this report

Environmental category	Control variables in this study
Climate change	Atmospheric CO_2e emissions **Global emission budget 1960-2100:** 2 $GtCO_2e$ (Same approach as in O'Neill et al. 2018).
Pressure on ecosystems	Maximum potential net primary production to be appropriated by humans without causing harm to ecosystems. **Global limit:** 17.64 t C, corresponding to 33% of net primary production in Portugal appropriated by humans (Same as in O'Neill et al. 2018).
Stratospheric ozone depletion	Stratospheric O_3 concentration (DU). **Global limit:** <5% reduction from preindustrial level of 290 DU (5%–10%, between 275.5 and 319 DU), assessed by latitude (Same as in Steffen et al. 2015)
Water pollution: nitrogen flows	Industrial release of N per year. **Global limit:** 94.1 Tg N yr^{-1}. (Same as in Steffen et al. 2015 and O'Neill et al. 2018)
Water pollution: phosphorus flows	Regional P flow from fertilisers to erodible soils. **Regional limit:** 9.4 Tg yr^{-1} (Same as in Steffen et al. 2015 and O'Neill et al. 2018)
Freshwater use	Blue water withdrawal as % of mean monthly river flow. **Limit:** for dry years: 25% (4192 Mm^3); for intermediate years: 30% (9595 Mm^3); and for wet years: 55% (26 891 Mm^3).
Air pollution	Global limits only for specific substances, based on WHO guidelines. See Table 4 for details.
Waste production and disposal	No global limit defined (only local) based on national targets • Boundary on solid waste production: 20% reduction on total waste production from 2009 to 2020: 11 089 kt of waste produced by 2020. • 62% reduction from 2009 to 2020 on solid waste disposed (in landfill): maximum of 2055.6 kt of waste/year sent to landfill.

Climate change

In Steffen et al. (2015), the boundary is defined to be the maximum concentration of CO_2 in the atmosphere of 350 ppm, a value that would likely preserve the climate in a Holocene-like state.

However, it is generally regarded as unlikely that atmospheric CO_2 can be brought below 350 ppm in the 21st century. Even the most optimistic integrated assessment scenarios considered in the IPCC's Fifth Assessment Report (AR5) only achieve a range of 420–440 ppm by 2100. As an alternative boundary to 350 ppm, O'Neill et al. (2018) proposed the 2ºC temperature stabilisation goal emphasised in the Paris Agreement, approximately 1.61 t CO_2 per capita.

In this study, we have followed a similar approach to O'Neill et al. (2018), considering the 2ºC temperature stabilisation goal by 2100, estimating the GHG emissions budget available from 1960-2100 to ensure that goal is not surpassed. In 2010, the IPCC estimated that for this goal, the world could still emit 1 $PtCO_2$. This means that in 1960 the world could emit until 2100 the GHG emissions verified from 1960 to 2009 plus the world budget from 2010 to 2100. We have estimated these emissions to be 2 $PtCO_2$.

We have found four ways of operationalising the boundary linked with the Paris Agreement goals, based on how to distribute the total budget per year (equal or differentiated) and how to allocate the budget to each country (once in 1960 based on population numbers; or every year, based on population numbers). The results from these different approaches are detailed in the Technical Notes (section 7.1.2). In the remaining of this report, we have selected the boundary considering a fixed yearly budget, with the values downscaled to the country level in 1960. In this way, decreased in the budget relate only to the fact that Portugal has crossed the boundary (i.e., less available budget for the future).

Pressure on ecosystems

There are several sources for the pressures on ecosystems, habitat loss and degradation being one of the major causes (WWF 2020). This strong link between land-use changes and biodiversity loss led us to aggregate the two planetary boundaries biosphere integrity and land-system change into one single category and named this category of "pressure on ecosystems. For land-system change and biosphere integrity, O'Neill et al. (2018) used a proxy indicator, the Human Appropriation of Net Primary Production (HANPP). HANPP measures the amount of biomass harvested through agriculture and forestry, as well as biomass that is killed during harvest but not used, and biomass that is lost due to land use change (Kastner et al., 2015). HANPP includes land-system change and biosphere integrity but also freshwater use and water pollution to some degree. HANPP may be compared to the potential net primary production (NPP_{pot}) that would exist in the absence of human activities, to arrive at a useful planetary boundary. Running (2012) determined that in 2007 there was still 5 Gt C y^{-1} of NPP_{pot} available for the appropriation of humans worldwide. This means that the planetary boundary for HANPP would be the total NPP_{pot} already appropriated by humans (HANPP) in 2007 plus the remaining NPP_{pot} available for appropriation. According to O'Neill et al. (2018), the HANPP in 2007 represented 13.2 Gt C y^{-1}. Therefore, the boundary for HANPP is 18.2 Gt C y^{-1}, which represents roughly 33% of total NPP_{pot}.

O'Neill et al.'s (2018) approach was followed, using "human appropriation of net primary production" (HANPP) as a more nuanced indicator for both land-system change and biodiversity integrity.

Stratospheric ozone depletion

We have used the same boundary as in Steffen et al. (2015). This boundary aims to avoid the risk of large impacts for humans and ecosystems from the thinning of the extra-polar ozone layer. The control variable used was the stratospheric O_3 concentration, measured in Dobson Units (DU). One DU is 0.01 mm thick at standard temperature and pressure and relates to how thick the ozone layer would be if it were compressed in the Earth's atmosphere. The limit was set to less than 5% reduction from preindustrial level of 290 DU (5%–10%), assessed by latitude.

Water pollution by nitrogen and phosphorus

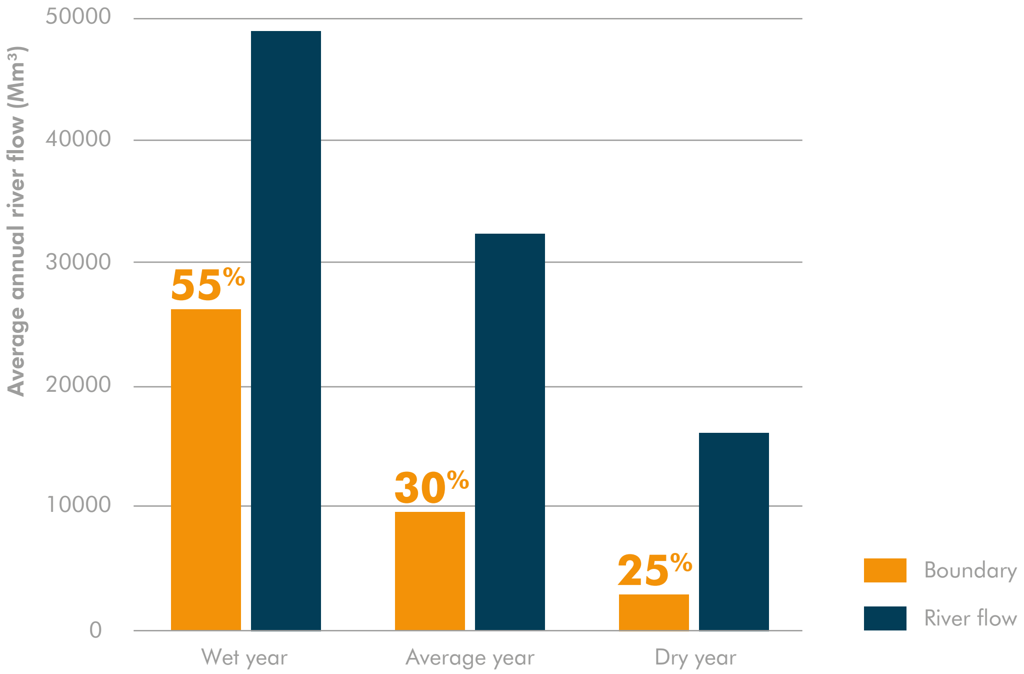
The boundaries per capita proposed in O'Neill et al. (2018) were used in this study.

Freshwater use

In the literature, the planetary boundary for freshwater use has been specified as a maximum global withdrawal of 4000 $km^3\ y^{-1}$ of blue water from rivers, lakes, reservoirs, and renewable groundwater stores (Rockström et al., 2009; Steffen et al., 2015; O'Neill et al., 2018). This boundary has been debated, given that the environmental impacts of freshwater use are primarily confined to the river-basin scale (Gerten et al., 2013; Heistermann, 2017). The boundary proposed here draws on the concept of minimum "environmental flow requirements" to maintain healthy riparian/coastal ecosystems, as suggested by Weiskel et al. (2014) and Steffen et al. (2015). We believe it is important to consider the spatial and temporal variation in freshwater availability, but this depends on the data availability. Data was only available at a yearly scale (no monthly variations).

The boundary used here draws from this minimum "environmental flow requirements" and represents the maximum yearly withdrawal as a percentage of mean river flow. To incorporate yearly water availability changes, we have considered the yearly hydraulicity index for Portugal (APA, 2019b), which classifies each year in terms of dryness-wetness and applied this index to determine how much water withdrawal could be made in each year to guarantee the minimum environmental flow requirements. For dry years it is 25%, for average years 30%, and for wet years 55% (percentages based on Steffen et al. 2015), see Figure 10.

Figure 10
Average river flow and freshwater boundary for Portugal



Air pollution

Steffen et al. (2015) considers the category introduction of novel entities, which includes air pollution as a subset. In Steffen et al. (2015) no control variable nor boundary were defined due to the diversity of this environmental category and the lack of a comprehensive control variable for it.

In the present study, we have considered the current legislated substances for which there is data available. These are: particulate matter ($PM_{2.5}$ and PM_{10}), Sulphur oxides (SO_x), Nitrogen oxides (NO_x), Nitrogen dioxide (NO_2), non-methane volatile organic compounds (NMVOC), tropospheric Ozone (O_3), Ammonia (NH_3) and Carbon monoxide (CO).

For these substances, some of the boundary values are available in terms of annual emissions and for others these are available in terms of concentrations. The approach followed for air pollutants is different depending on whether we are talking about emissions or concentrations. For substances with an emission boundary, the boundaries used are the limit values present in the Portuguese legislation, which is based on the EU ceilings directive. For substances with a concentration-boundary, we have used the World Health Organization (WHO) guidelines for human health protection. Additionally, we have also considered the Portuguese legislation (based on EU target values), which are less strict than the values from the WHO. The current targets and limit values used in this report are presented in Table 4.

Table 4

Definitions of the boundaries for air quality

Indicator		Boundary value	Origin of the boundary
$PM_{2.5}$	annual emissions	55 kt $PM_{2.5}$/year by 2020	Emission ceilings for 2020 (Decree-Law No. 19/2018)
	annual mean concentration	10 $\mu g/m^3$.year	WHO guidelines (WHO 2006)
		25 $\mu g/m^3$.year	Portuguese legislation (Decree Law No. 102/2010)
	1-day mean concentration	25 $\mu g/m^3$.day	WHO guidelines (WHO 2006)
PM_{10}	annual mean concentration	20 $\mu g/m^3$.year	WHO guidelines (WHO 2006); Portuguese legislation (Decree Law No. 102/2010)
	1-day mean concentration	3 days/year over 50 $\mu g/m^3$.day	WHO guidelines (WHO 2006)
		35 days/year over 50 $\mu g/m^3$.day	Portuguese legislation (Decree Law No. 102/2010)
SO_x	annual emissions	65.5 kt SO_2/year by 2020	Emission ceilings for 2020 - Decree-Law No. 19/2018
	1-day mean concentration	20 $\mu g/m^3$.day	WHO guidelines (WHO 2006)
		3 days/year over 125 $\mu g/m^3$.day	Portuguese legislation (Decree Law No. 102/2010)
	1-hour mean concentration	24 h/year over 350 $\mu g/m^3$.h	Portuguese legislation (Decree Law No. 102/2010)
NO_2	annual emissions	163.8 kt NO_2/year by 2020	Emission ceilings for 2020 - Decree-Law No. 19/2018
	annual mean concentration	40 $\mu g/m^3$.year	Portuguese legislation (Decree Law No. 102/2010)
	1-hour mean concentration	200 $\mu g/m^3$.h	WHO guidelines (WHO 2006)
		18h/year over 200 $\mu g/m^3$.h	Portuguese legislation (Decree Law No. 102/2010)
NMVOC	annual emissions	169.7 kt NMVOC/year by 2020	Emission ceilings for 2020 - Decree-Law No. 19/2018

Indicator		Boundary value	Origin of the boundary
NH_3	annual emissions	46.5 kt NH_3/year by 2020	Emission ceilings for 2020 - Decree-Law No. 19/2018
CO	8-hour mean concentrations	10 mg/m^3.8h	Portuguese legislation (Decree Law No. 102/2010)
	1-hour mean concentration	30 mg/m^3.h	WHO guidelines (WHO 2006)
O_3	8-hour mean concentrations	100 μg/m^3.8h	WHO guidelines (WHO 2006)
		25 8h periods/year (averaged over 3 years) over 120 μg/m^3.8h	Portuguese legislation (Decree Law No. 102/2010)

More information on the boundaries in section 7.1.7.
Acronyms used: $PM_{2.5}$ – particles with diameter less than 2.5 μm; PM_{10} – particles with diameter less than 10 μm; SO_x – Sulphur oxides; SO_2 – Sulphur dioxide; CO – carbon monoxide; NO_x – Nitrogen oxides; NO_2 – Nitrogen dioxide; NMVOC – non-methane volatile organic compounds; O_3 – (tropospheric) ozone; NH_3 – ammonia.

Waste production and disposal

No global limits defined (only local). The targets were defined based on the *Plano Nacional de Gestão de Resíduos 2011-2020* (Waste management national plan 2011-2020, Ferrão et al. 2011). These boundaries are not actual planetary boundaries but EU targets (similar happens with air pollution emissions). They were set up to reduce (and not eliminate) the impacts of waste on the environment. This means reaching these is no guarantee that the biosphere is not being affected still by waste production targets. These targets are likely to change in the near future for more ambitious ones for the period starting from 2021.

2.3
PORTUGUESE ENVIRONMENTAL FOOTPRINTS

The biophysical indicators were estimated as far back as the data allowed to ensure the period of analysis includes as many generations as possible. Because of data constraints, the biophysical indicators were estimated in territorial terms. This means that imports and exports (a consumption-based approach) and monetary flows (an income-based approach) were not included, only the activities happening in the Portuguese territory[1]. This is a major difference between the current work and the study by O'Neill et al. (2018).

1 Portuguese territory is defined here as the current boundaries, which include mainland Portugal and Azores and Madeira autonomous regions. It excludes regions that are not part of Portugal nowadays, but they were at some point during the period of analysis (1960-2018), such as Angola, Cape Verde, East Timor, Goa, Guiné Bissau, Mozambique, and São Tomé e Principe.

The biophysical indicators were obtained from the literature or estimated by the team, based on data collected. Table 5 presents an overview of the methods used for estimating the indicators.

Table 5
Summary of methods used in estimating the environmental indicators

Biophysical indicator	Methods used
Climate change (GHG emissions)	Energy related emissions (1960-2016): own estimations following the IPCC 2006 guidelines, using data from national and international statistics. Agriculture related emissions (1961-2016): data from FAOSTAT (FAO, 2020). Emissions from manufacturing industry (energy and industrial processes), household and services and wastes (1990-2018): obtained from the National Inventory Report (NIR) (APA, 2019a). Details in the appendix (Section 7.1.2).
Ozone layer depletion (ozone layer thickness)	The indicator is only analysed in global terms, in terms of ozone layer thickness per latitude. Ozone layer thickness per latitude obtained from NASA Ozone Watch (2020). See section 7.1.3 for more details.
Pressure on ecosystems (HANPP)	Measure through HANPP, the indicator was estimated following the approach from Krausmann et al. (2013). Data obtained from FAOSTAT. Details in the appendix (Section 7.1.4).
Water pollution (N and P fertiliser use)	Data from FAOSTAT (FAO, 2020). Details in the appendix (Section 7.1.5)
Freshwater use (blue water withdrawal)	Data from Eora Global Supply Chain Database (Lenzen et al., 2012). Details in the appendix (Section 7.1.6).
Air pollution (pollutant emissions)	Data obtained directly from SNIERPA (APA, 2019a). More details in section 7.1.7.
Air pollution (pollutant concentrations)	Concentration of pollutants per hour obtained from the national air quality monitoring network. Averages for 1-year, 1-day, 8-hour, 1-hour were performed (according to the limit values for each pollutant). More details in section 7.1.7.
Waste production and disposal (Solid waste production, % of wastes that go to landfill)	Solid Waste Production (SWP): sum of municipal solid waste (MSW) with sectoral solid waste (SSW). MSW data from NIR (APA, 2019a) for the period 1960-2018. SSW data from National statistics office (2008-2018). Data on the amount of wastes to landfill and GHG emissions from the waste sector were obtained from APA (2019a). More details in the appendix (Section 7.1.8).

Acronyms used: GHG – greenhouse gas emissions; HANPP – Human appropriation of net primary production; N – Nitrogen; P – Phosphorus; SNIERPA – National System for the Inventory of Emissions and Removals of Air Pollutants; SWP – solid waste production; MSW – municipal solid waste; SSW – sectoral solid waste; APA – Portuguese Environment Agency.

2.4 PORTUGUESE PERFORMANCE: ARE FOOTPRINTS WITHIN THE LIMITS?

The current situation of Portugal in terms of the pressure exerted on the biosphere is summarised in Table 6. In two of the biophysical indicators Portugal is outside the boundary. This is the case of climate change and water pollution. Although these are over the boundary, the trends in climate change and phosphorus flows are already decreasing because of the decarbonisation of electricity and manufacturing industries (for climate change). Pressure on ecosystems is in the safe zone (within the boundary) and with an improving trend (i.e., decreasing trend) due to the reduction of agricultural area used (intensification of agriculture). For the remaining indicators, the situation is mixed.

Table 6
Status of the environmental categories compared to the national biophysical boundaries

Category	Status		
Climate change (1961-2016)	**Over the boundary** Since at least 1989. Trend: decreasing since 2005.		
Ozone layer depletion (1979-2019)	**Over the boundary** For lower latitudes (30S-30N)	**In the risk zone** For the ozone hole (improving) and mid-south latitudes (60S-30S)	**Within the boundary** For mid and higher north latitudes
Pressure on ecosystems (1961-2016)	**Within the boundary** In the last 2 years. Trend has been decreasing (improving) since 1990		
Water pollution (1961-2016)	**Over the boundary** N flows: since 1971. Trend: increasing significantly since 2011 P flows: in the whole period analysed. Trend: decreasing.		
Freshwater use (1961-2016)	**Over the boundary** In dry years, since 2008	**Within the boundary** For an average year and for wet years	

Category	Status		
Air Pollution (1990-2018[a]; 2003-2018[b]; 1995-2018[c])	**Over the boundary** Emissions: NH_3 Conc.: $PM_{2.5}$ (daily), O_3 (8-hour, WHO)	**In the risk zone** Conc.: $PM_{2.5}$ (annual) PM_{10}, SO_2 (daily, WHO)	**Within the boundary** Emissions: $PM_{2.5}$, SO_x, NO_2, NMVOC Conc.: CO, NO_2, SO_2 (daily EU), O_3 (8-hour, EU)
Waste production and disposal (1960-2018[d]; 2008-2018[e])	**Over the boundary** Total waste produced	**In the risk zone** Waste disposal	

In the risk zone refers to: or (1) variables that have more than one boundary and are currently over one of these boundaries and within other boundaries; or (2) variables that have only one boundary and where the variable is over the boundary, but close to the boundary, and with a decreasing trend (i.e., a trend that is getting closer to the boundary).
Notes to the table: a. For emissions; b. For $PM_{2.5}$ concentrations; c. For remaining air pollutants concentrations; d. For municipal solid waste only; e. for sectoral and total solid wastes.

For ozone layer depletion, the world is outside the boundary only for lower latitudes and in the uncertainty/risk zone in the ozone hole area and mid-south latitudes, but with improving trends in terms of the ozone hole latitude. For freshwater use, Portugal is outside the boundary for dry years and below during standard/wet years; however, trends in water consumption are increasing, in part due to the intensification of agriculture and due to increasing service activities. For air pollution, Portugal is over the boundary for NH_3 emissions (national legislation limit value) and for $PM_{2.5}$ 1-day mean concentrations, O_3 8-hour mean concentrations for the WHO guidelines and national ceiling values when applicable. Air pollution is in the risk zone for $PM_{2.5}$ annual concentrations, PM_{10} concentrations and SO_2 1-day mean concentrations for the WHO guidelines (although still within national ceiling values). For waste production and treatment, Portugal is outside the boundary for waste production and in the risk zone for the integration of wastes in the economy (recycling) and wastes disposal (landfilling). Production and treatment are outside the boundary mainly due to municipal solid waste production (as opposed to sectoral/industrial waste), where municipal waste production and municipal recycling rates are low with trends aggravating (i.e., waste produced in increasing and recycling rates are low).

Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15 show the trends of the indicators as well and their boundaries.

In terms of **climate change**, GHG emissions from Portugal peaked between 1998 and 2005, after which they started to decline. Irrespective of the boundary selected, Portugal is outside the boundary (high risk). The date in which Portugal crossed the boundary varies according to how the boundary is defined, from 1967 (for the fixed person-year emissions' budget) to 1980 (for the fixed yearly budget, globally updated) or even 1989 (for the upper government set boundary). Although climate change is outside the boundary, there is a decreasing trend in greenhouse gas emissions since 2005. At the same time, the boundaries are also decreasing at a rate similar to the rate of decrease in GHG emissions, and thus the gap between the emissions and the boundary has only been slightly reduced. As mentioned above, this reduction in the limit is due to the fact that there is a "budget" for GHG until 2100 to be emitted without an increase in the Earth's average annual temperature above 2°C. When this budget is divided over years, we are left with an annual budget. When in a given year humanity exceeds that annual budget, less budget will be available for subsequent years. This is why the ecological limit (= annual GHG budget) may come to decrease (if GHG emissions exceed the annual limit in a given year) or increase (if GHG emissions are below the annual limit).

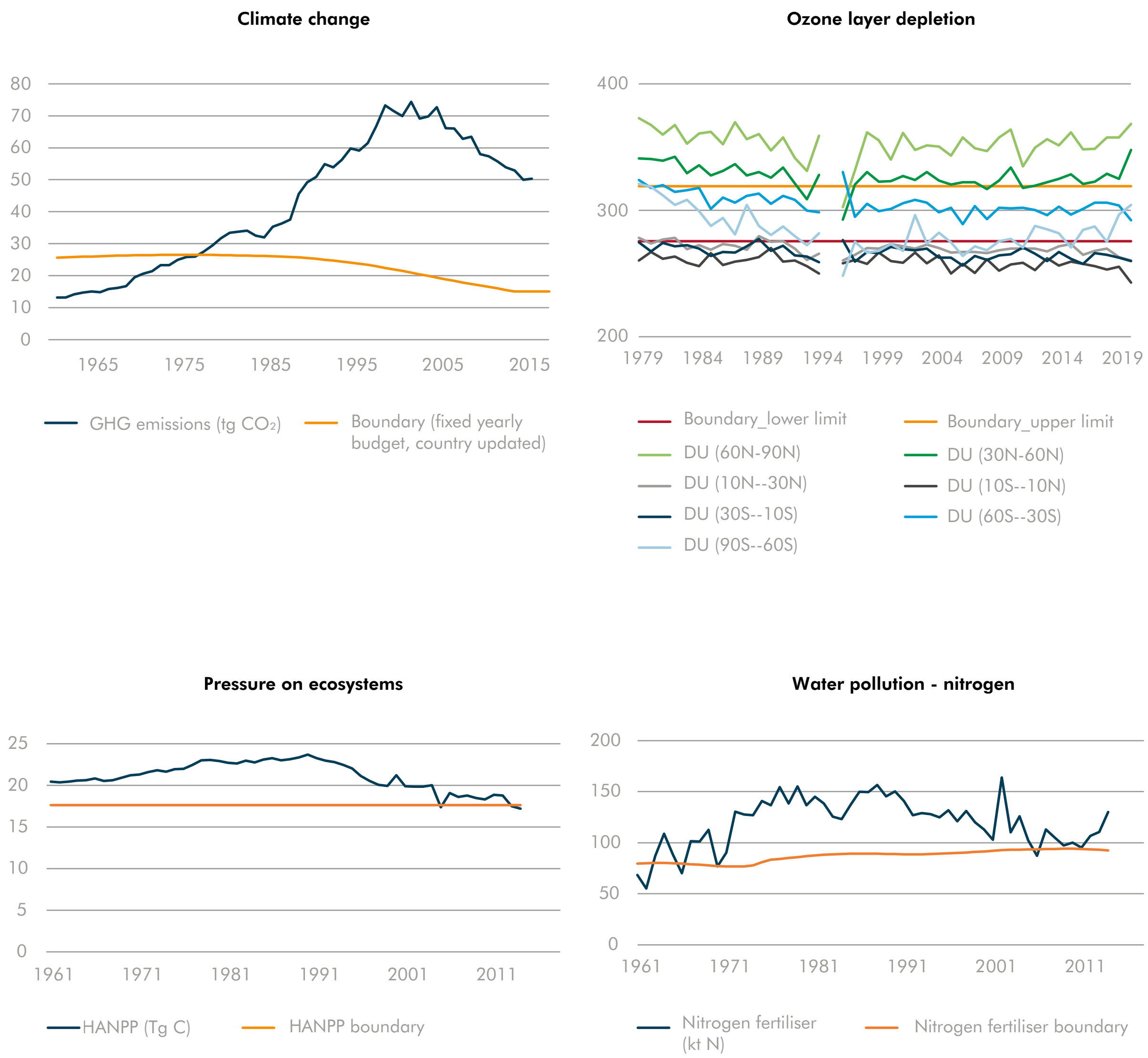
How one goes from the 2100 total budget to an annual budget varies and this study has explored four different approaches (see the technical notes, Section 7.1.2). In 2018, Portugal emitted more GHG than the annual GHG budget in all these ecological limits, which resulted in a progressive decrease in these limits, see Table 7.

Table 7
Variation in the limits for GHG emissions from 1960 to 2018

Type of limit	**Date in which Portugal exceeded the limit** (start of decreasing limit)	**Variation 1960-2018** (negative values represent a decrease)
Fixed annual budget, with international updates	<1960	-72%
Fixed annual budget, with national updates	1989	-41%
Fixed annual budget, with fixed population	1977-78	-45%
Fixed annual budget for each person.year	1981	-43%

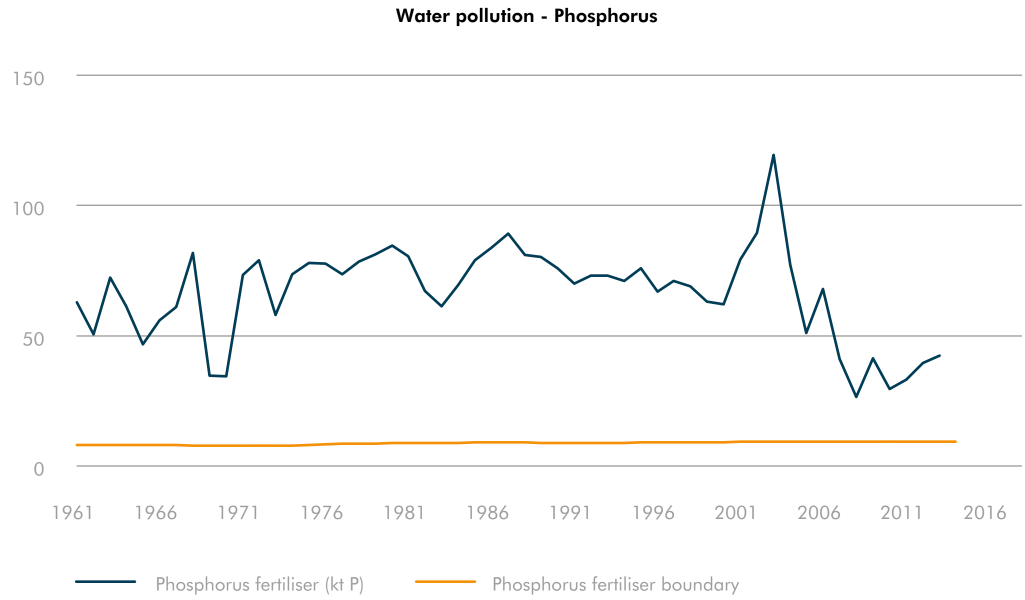
Blue shaded line represents the limit mostly used in the present report.

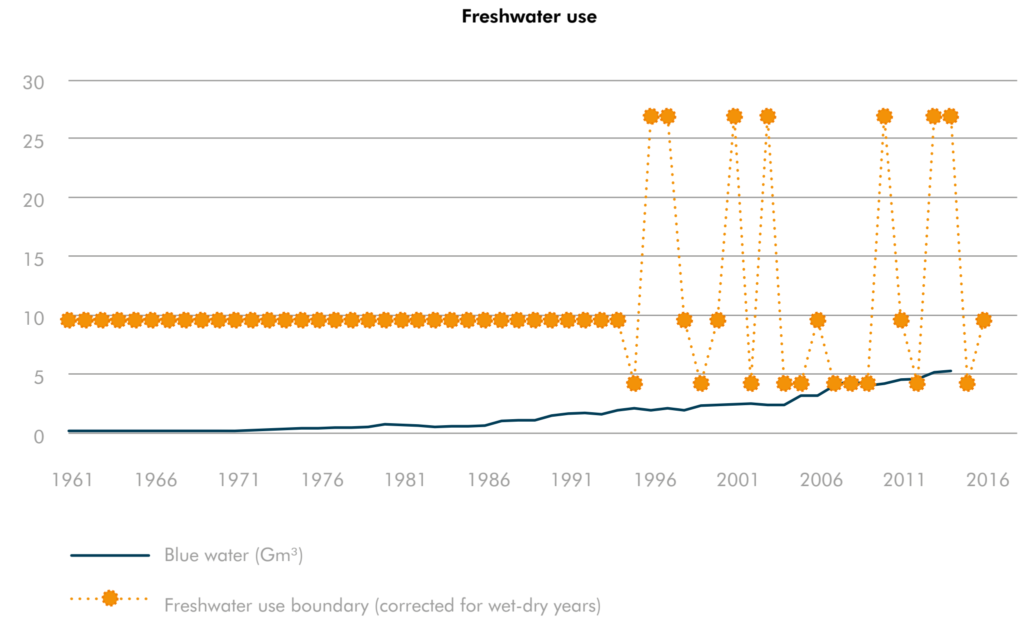
Figure 11
Footprints and boundaries by biophysical indicator



Boundaries presented: climate change – Paris Agreement boundary (in $TgCO_2e$) with fixed yearly budget and values globally updated in 1960; Ozone layer depletion – ozone layer thickness boundary by Steffen et al (2015) (in DU); Pressure on ecosystems (HANPP) - 33% of net primary production in Portugal (Tg C); water pollution - boundaries based on the O'Neill et al. (2018) per capita boundaries multiplied by the Portuguese population in 2010 (in kt N and kt P).

Figure 11
(cont.)





Boundaries presented: Water pollution - boundaries based on the O'Neill et al. (2018) per capita boundaries multiplied by the Portuguese population in 2010 (in kt N and kt P); freshwater - Minimum "environmental flow requirements" corrected for dry and wet years (Gm^3).

Figure 12
Footprints and boundaries for air pollution: annual emissions (kt)

Boundaries for air pollutant annual emissions are defined by ceilings from Portuguese legislation (k tons of pollutant).

Figure 12
(cont.)

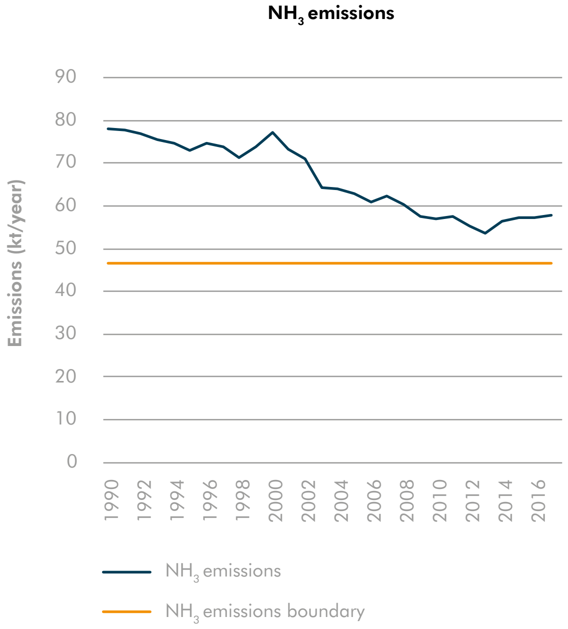


Figure 13
Footprints and boundaries for air pollutants for boundaries in concentrations (mg/m³ for CO, µg/m³ for remaining pollutants)

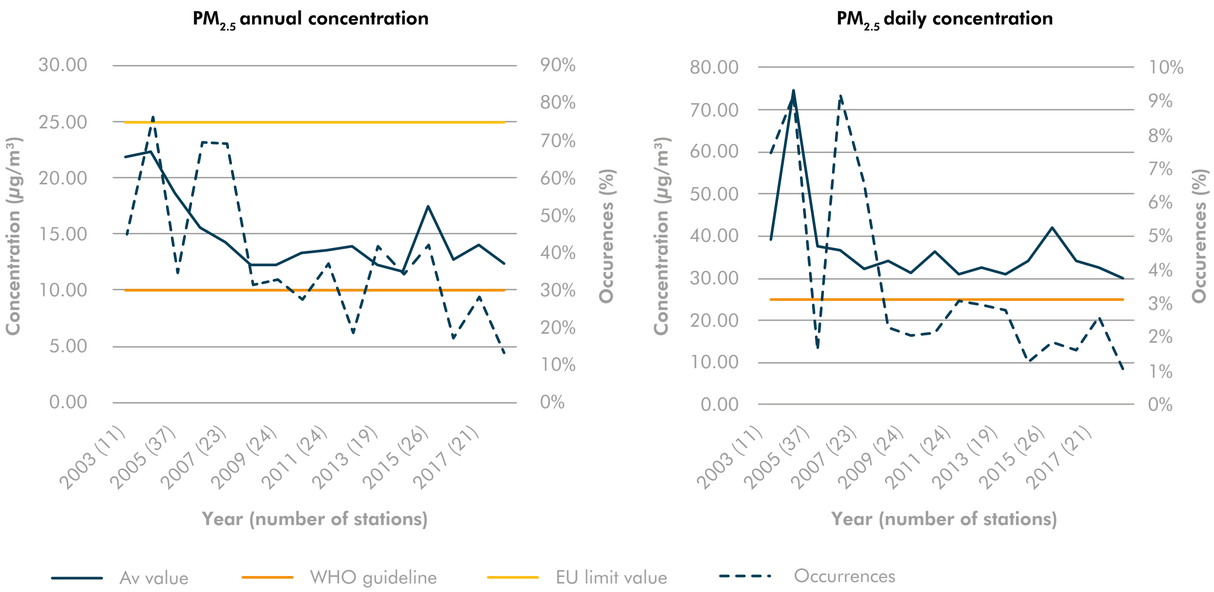
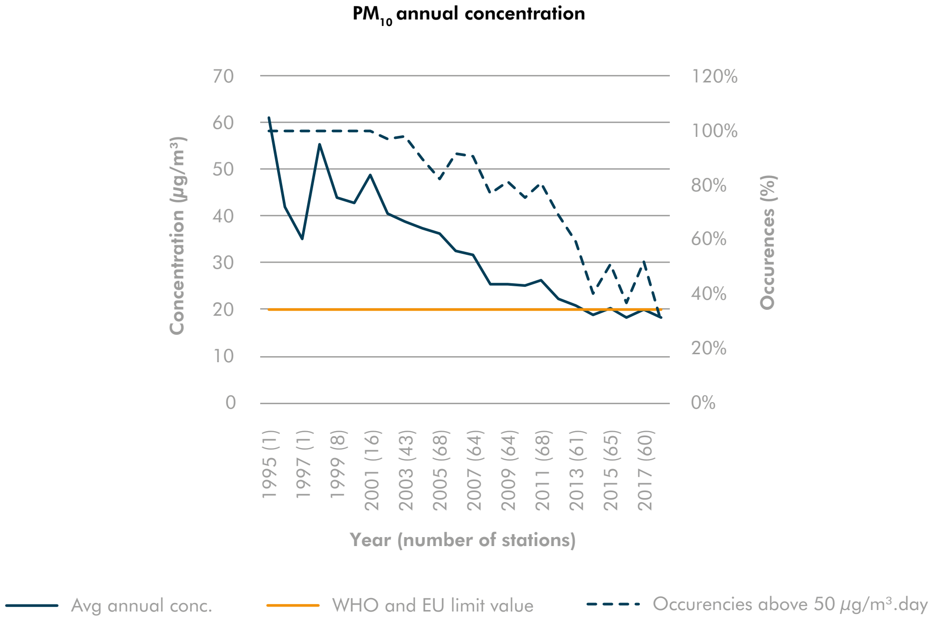
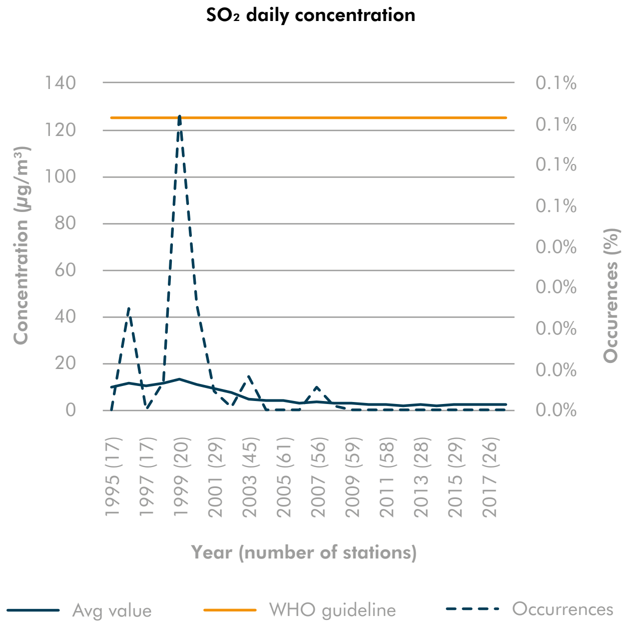


Figure 13
(cont.)





Values between brackets in x-axis represent the total number of stations in that year.
Occurrences: number of times each station exceeded the limit value divided by the total number of stations and total time (1 year or 365 days/year, depending on the type of concentration).
Boundaries for air pollutant concentrations are defined by WHO guidelines and Portuguese legislation (µg/m³, mg/m³,). Measurements of concentrations are made by hour. Means are estimated based on the hourly values to produce 1-year, 1-day or 8-hour means, depending on the limit values.

Figure 13
(cont.)

Figure 13
(cont.)

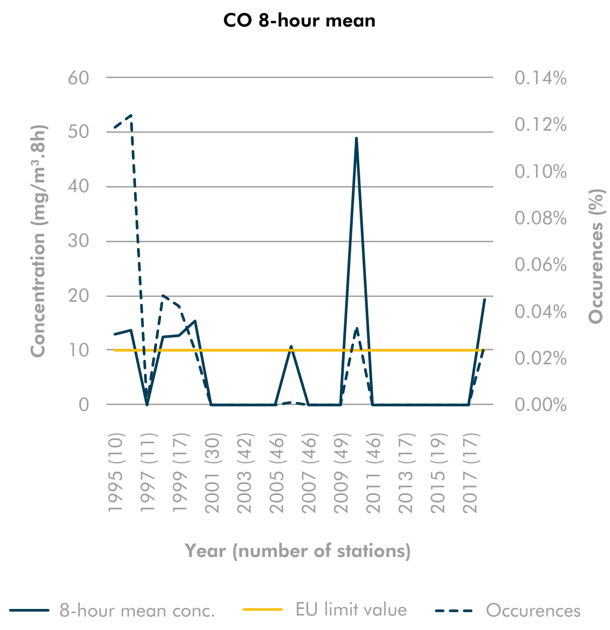


Figure 14

Footprints and boundaries for air pollutants for boundaries in terms of number of occurrences above ceiling values

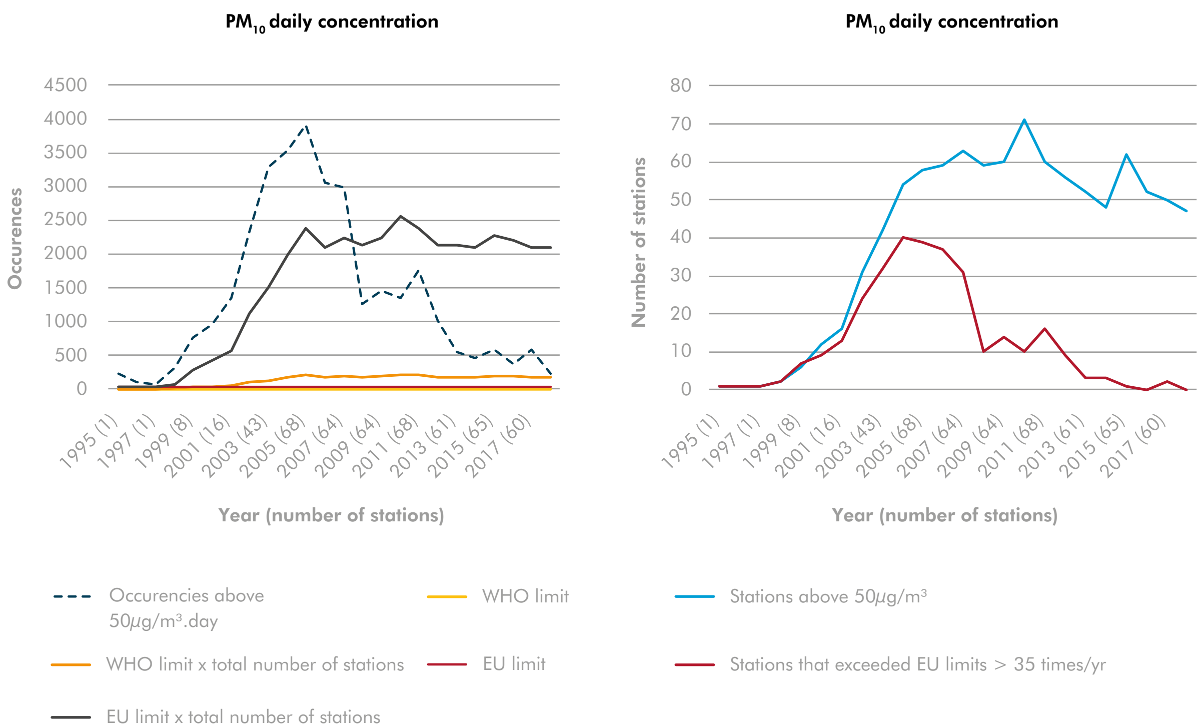
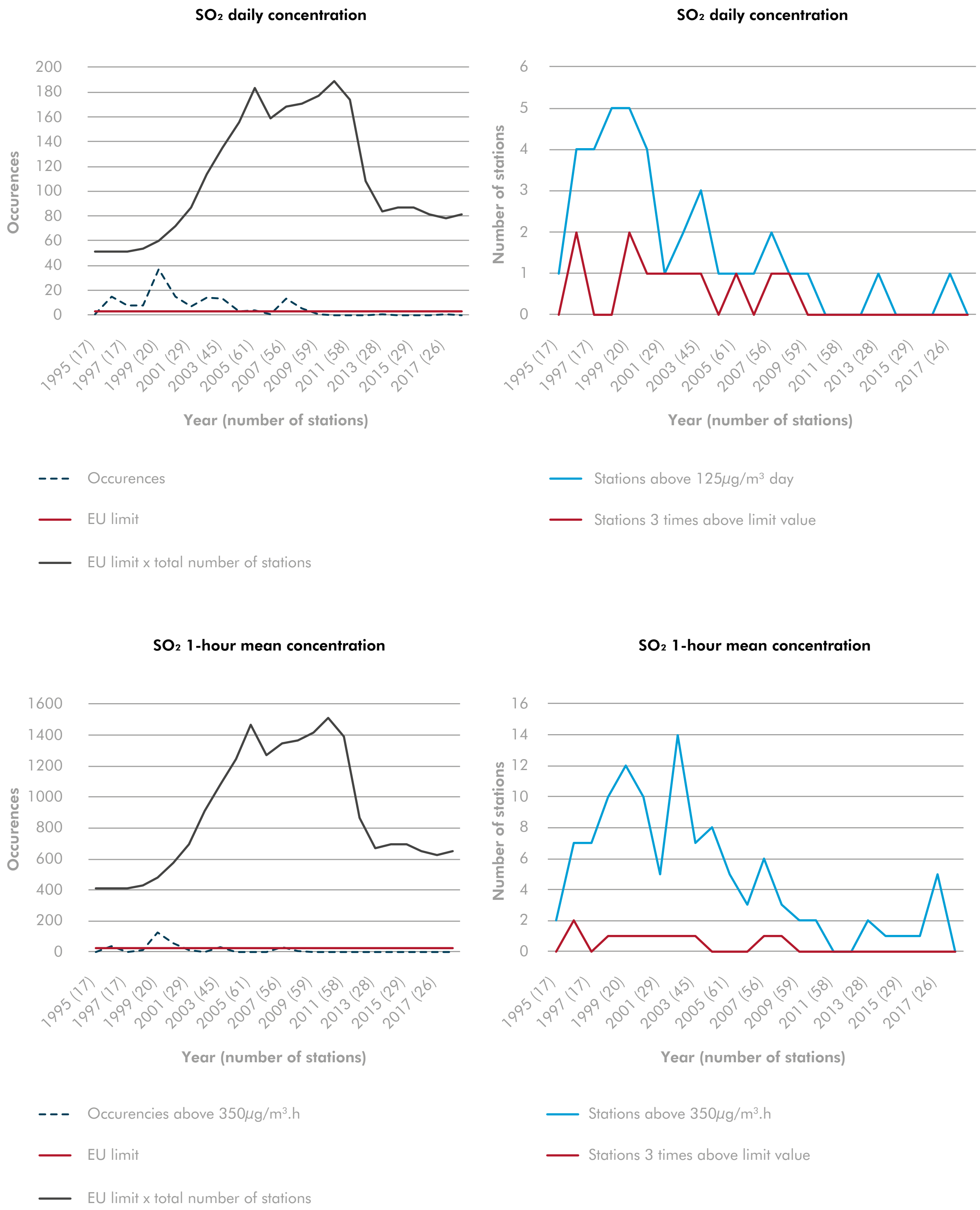


Figure 14
(cont.)



Values between brackets in x-axis represent the total number of stations in that year.
Occurrences: total number of occurrences above ceiling values for all stations divided by total stations and total time in a year (in days/year or hours/year, depending on the type of concentration).
Lower limit: Portuguese (EU) limit; **Upper limit:** Portuguese (EU) limit multiplied by total stations.

Figure 14
(cont.)

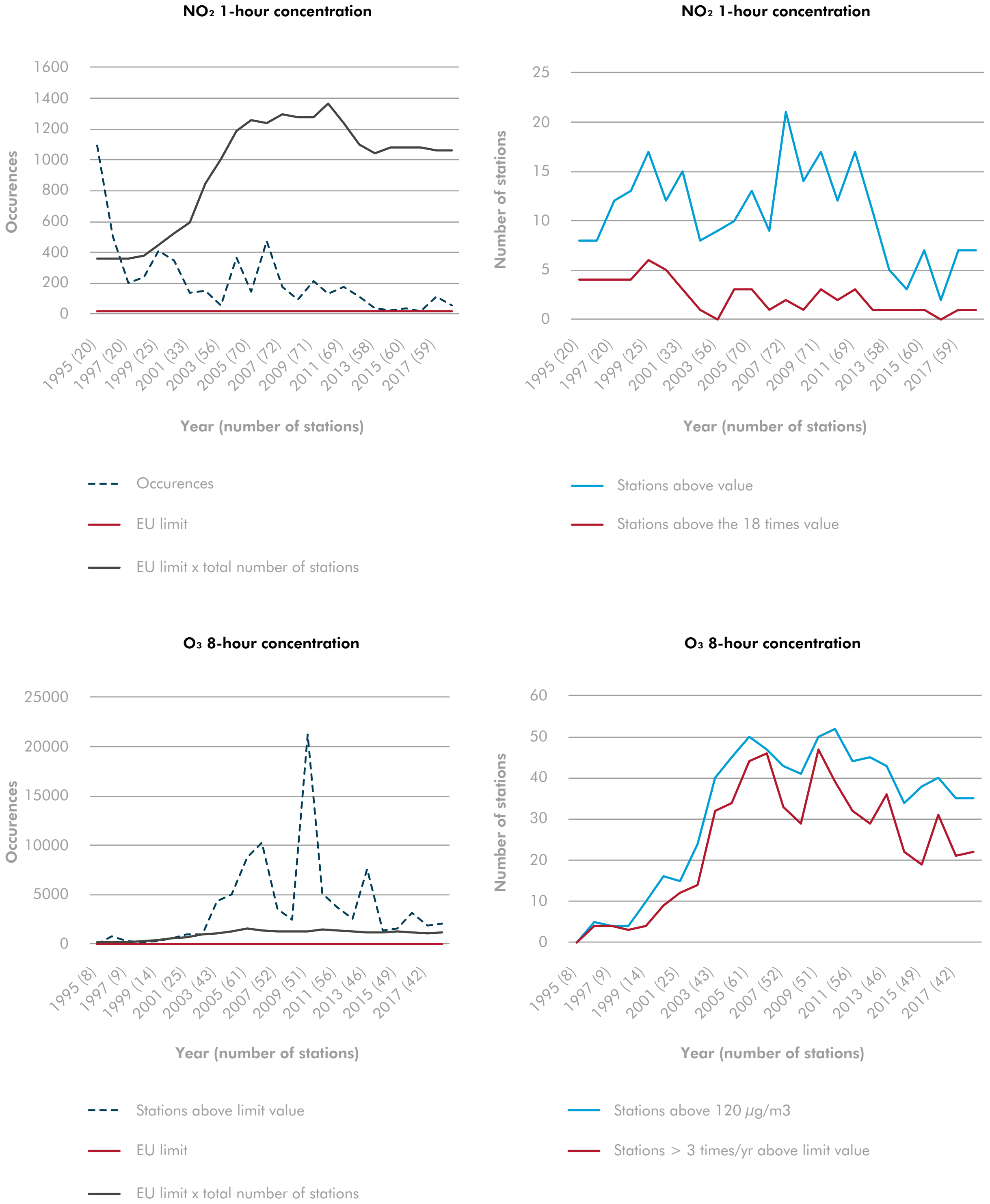
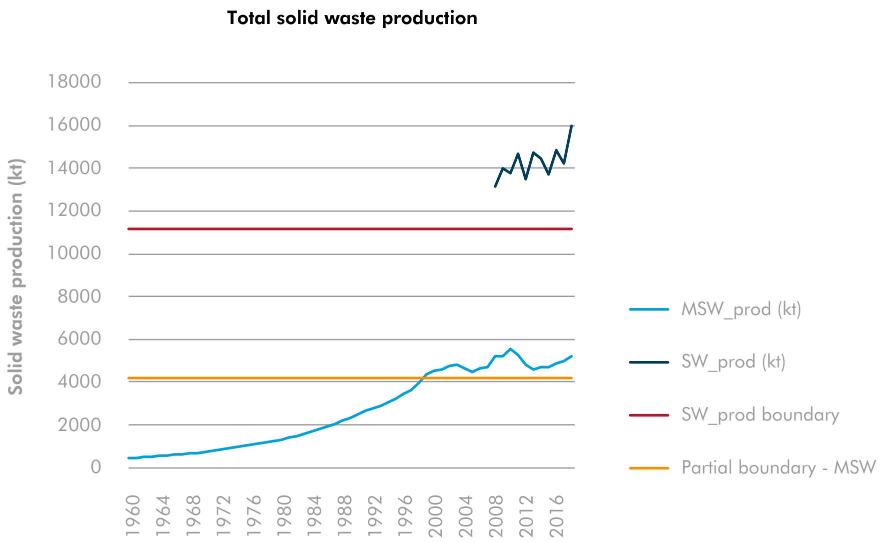
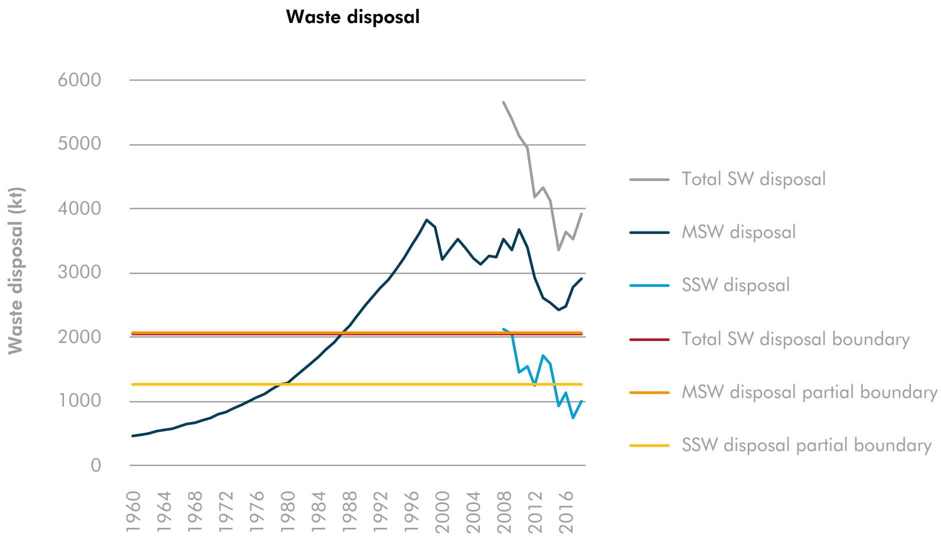


Figure 15
Footprints and boundaries for waste indicators (kt)





For solid waste production, the boundary refers to 20% (in weight) of waste produced in 2009. For waste disposal the boundary refers to a 28% (in weight) reduction on wastes disposed by 2020 based on the 2009 value. Partial boundaries for municipal solid waste (MSW) and sectoral solid wastes (SSW) are also presented.

The **ozone layer thickness** has been improving for the latitudes 60N-90N, 30N-60N and 90S-60S. For the remaining, we can see a decrease when comparing to 1979. Two groups of latitudes are in the safe zone (60N-90N and 30N-60N). Two groups of latitudes are in the uncertainty zone (60S-30S and 90S-60S), one of which refers to the ozone hole area and which has been improving, moving from the danger zone to the uncertainty zone during the period analysed. Three groups of latitudes are in the danger zone (10N-30N, 10N-10S and 30S-10S), these refer to the low latitudes, where the ozone layer is naturally thinner and where a new phenomenon of thinning the layer has been observed (Ball et al., 2018).

The **pressure on ecosystems** in Portugal has increased from 1961 until 1978, where it remained relatively stable until 1990 when it started to drop until 2014. Between 2015 and 2016 the values started to increase. Values were within the boundary between 2013 and 2016. In the particular year of 2010 (year of the analyses conducted in Steffen et al (2015) and O'Neil et al (2018)), our results show that Portugal had crossed the boundary (although close to the boundary), which is consistent with the results provided in O'Neill et al (2018), where, despite being a consumption-based approach, Portugal had also crossed the boundary, although being close to this boundary.

Nitrogen use has been outside the boundary since 1964. Despite the annual variability, we can see an increasing trend until roughly 1988, with the biggest increase happening until 1977. From 1988, there is a decrease in nitrogen-based fertilisers. For **phosphorus use**, Portugal has exceeded the boundary for the entire period analysed. Despite the great annual variability, phosphorus use has declined from 1987 to 2008.

Freshwater use has been roughly increasing in Portugal since 1971 until 2016, with some exceptions. Water use decreased in the periods between 1981-1985 and between 2015-2016. Since 2008, Portugal has been outside the boundary for dry years. This means that in dry years there will be impacts on ecosystems in some of the Portuguese water basins. This boundary reflects annual averages for the whole country, and therefore, it does not include the monthly variations in water availability or local variability. The impacts resulting from monthly variations and local variability (e.g., north vs. south) are not captured by this boundary.

In terms of **air pollutants**, $PM_{2.5}$ annual emissions (Figure 12) are within the boundary since 2012. $PM_{2.5}$ average annual concentrations (Figure 13) are on average within the Portuguese legislation values, but still outside the WHO guidelines. The number of stations above the annual guideline values have been decreasing but are still above 10%. The number of occurrences above WHO guidelines for $PM_{2.5}$ average daily concentrations has decreased from nearly 10% in 2006 to 1-3% for the last 11 years.

PM_{10} average annual concentrations (Figure 13) have been declining and are around the limit value since 2014. The number of stations above the limit value have also been declining and only 18 out of 60 were above the limit value in 2018 (30%). The number of days a station is above the PM_{10} daily value is within the boundary for the EU limits (not exceeding 35 days a year) but well above the WHO guidelines (not exceeding 3 days a year), Figure 14.

SO_2 annual emissions have been reducing and are within the boundary since 2010. Average SO_2 daily concentrations are within the boundary through the period analysed, although there are occurrences still above the limit value for some stations. These occurrences have had a large reduction in their numbers, representing 0.2% of total potential occurrences in 2018 (22 occurrences in 6 stations). The number of days a station is above the SO_2 daily value is within the EU ceilings (not exceeding 3 days a year the 125μg/m^3.day) since 2009 (Figure 14). The number of hours a station is above the SO2 hourly value is within the EU ceilings (not exceeding 24 hours a year the 350μg/m^3.h) since 2009 (Figure 14).

Average CO 8-hour mean concentrations are within the boundary since 2000, except for 2006, 2010 and 2018 (Figure 13). The number of occurrences above the EU limit value is low. In 2018 only one station presented values above the limit values. This happened 36 times (36 8-hour periods) in that year, representing 0.026% of the total occurrences. Average CO 1-hour mean concentrations are within the boundary since 1998 except for a few points in time (2000, 2010 and 2018), (Figure 13). The number of occurrences above the guideline values is low. In 2018 only one station presented values above the guideline values during 6 hours in that year (representing 0.0043% of the total stations-time available in a year).

NO_2 annual emissions have been decreasing since 2002 and are within the boundary since 2012 (Figure 12). Average NO_2 1-year concentrations are within the boundary in the whole period analysed, and the number of stations above the limit value has been dropping, being situated in 8% in 2018 (corresponding to 5 stations out of 59). Average NO_2 1-hour mean concentrations are well within the boundary and the number of station-hours above the limit value has been declining being situated at 0.01% (7 stations with 54 hours above the limit value in total) in 2018 (Figure 13). The number of hours a station is above the NO_2 hourly value has been over the EU limits (not exceeding 18 hours a year 200μg/m^3.h), but with very few situations (Figure 14), representing 0.01% of total situations in 2017 and 2018 (i.e., 1 station reporting 74 hours above the limit or 34 hours above the limit for 2017 and 2018 respectively).

NMVOC annual emissions have been decreasing since 1998 and are within the boundary since 2008 (Figure 12), however, the gap between the trend of the indicator and the gap is decreasing, putting this indicator in a danger zone.

Average O_3 8-hour mean concentrations have been rising but are still within the WHO guidelines. The number of occurrences above the limit value has been increasing as well, corresponding to 3.9% in 2018 (35 stations out of 45 have reported a total of 15 517 8-hour mean periods above the limit value). The O_3 8-hour mean concentrations, although over the EU limits since 2003 (exceeding 25 days over the 120μg/m3.8h limit in a year), Figure 14, represents less than 1% of total potential occurrences since 2014 (i.e., total number of occurrences above ceiling values for all stations divided by total stations and total 8-hour periods available in a year).

Although NH_3 annual emissions have been decreasing in the period analysed (except for the period from 2013 onwards), emissions have remained above the boundary for the whole time-period.

For solid **waste production**, Portugal is outside the boundary (Figure 15). For the partial boundary on MSW, Portugal is outside the boundary since 1999. The tendency is to increase waste production, widening the gap between the boundary and the actual production. Increased waste production means that more materials are being directed to the waste management systems, which brings some environmental impacts (in terms of resources used, energy and emissions). In terms of waste disposal, Portugal is only within the boundary for sectoral wastes (in terms of the partial boundary for sectoral waste disposal). For municipal wastes and total wastes, the amount of waste disposed in landfill is outside the boundary.

From observing the trends, we can see that NMVOC emissions, although within the boundary, that the gap between the trend of the indicator and boundary is decreasing, putting this indicator in a danger zone. On the other hand, for the ozone layer depletion for the latitudes between 90S-60S and NO_2 hourly concentrations, although still in the uncertainty zone of the boundary, these indicators show an improving trend.

In summary, the areas of concern are climate change, ozone layer depletion (for the latitudes between 30N-30S and between 60s-30s), N and P flows, freshwater use, air pollution (for NMVOC and NH_3 emissions, $PM_{2.5}$ annual concentrations, $PM_{2.5}$ and PM_{10} daily concentrations and O_3 concentrations) and waste production, treatment, and disposal (in terms of waste production, integration of solid urban wastes in the economy and solid urban waste disposal). The reasons why these are areas are of concern is because these indicators:

- have crossed the boundary and the gap between the boundary and their trend is not decreasing (the cases of climate change, ozone layer depletion for the latitudes between 30N-30S, N and P flows, freshwater use, NH_3 emissions, O_3 concentrations, total waste production, solid urban waste disposal).
- are in the uncertainty zone of the boundaries and the gap between their trends and the boundary is not decreasing (the cases of ozone layer depletion for the latitudes between 60S-30S, HANP, $PM_{2.5}$ annual concentrations).
- are within the boundary, but the gap between the trend of the indicator and the gap is decreasing (the case of NMVOC emissions).
- have crossed the boundary, and the gap between the trend of the indicator and the boundary is decreasing (the cases of $PM_{2.5}$ and PM_{10} daily concentrations, integration of solid urban wastes in the economy).

Within these and comparing the situation of the footprints and their limits on the latest year, as well as their trend in the last years (Table 8), one could state that the most pressing environmental areas for Portugal are climate change, water pollution by phosphorus and the freshwater use. This is because: (1) climate change and water pollution are the two indicators that present the highest distance between their footprint and their limit for the latest year (deficit), or (2) water pollution by phosphorus and freshwater use both present the highest growth rate, which means that the situations on these indicators will get worse quicker.

Table 8
Distance to the boundary and trend in the last years for selected footprints

Environmental category	Ecological deficit (% above the boundary) (a)	Trend in last years (normalised)
Climate change	2.34	-0.03
Stratospheric ozone depletion	0.14	-0.01
Pressure on ecosystems	0.00	0.01
Water pollution by nitrogen	0.12	-0.09
Water pollution by phosphorus	4.22	0.13
Freshwater use	0.20	0.09
Ammonia annual emissions	0.24	0.02
$PM_{2.5}$ 1-day concentrations	0.20	-0.09
O_3 8-hour concentrations	-0.40	-
Urban solid waste production	0.25	0.02

(a) Deficit = (footprint on the latest year-boundary for that year)/(footprint on the latest year).

Areas of less concern are the ozone layer for the latitudes between 90S-60S (the ozone hole latitude), 60N-30N and 90N-60N, pressure on ecosystems, $PM_{2.5}$ SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 and NO_2 hourly concentrations, solid sectoral waste disposal. This is because these indicators:

- are in the safe zone and their current trend will keep them in the safe zone (for ozone layer depletion for the latitudes between 90N-30N, $PM_{2.5}$, SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 hourly concentrations, solid sectoral waste disposal),
- although still in the uncertainty zone of the boundary, show an improving trend (for ozone layer depletion for the latitudes between 90S-60S, NO_2 hourly concentrations).

The limitations of this approach are: (1) being a territorial approach, it only accounts for the pressures exerted within national boundaries, not accounting for the impacts of the consumption of imported goods and services; (2) local impacts are diluted as impacts are analysed in national terms. This is particularly relevant for water (where regional water scarcity (e.g., in the south) is diluted with regions with less scarcity) and air pollution, in particular, air pollution related with traffic, where limits might be transgressed locally, but not when national averages are analysed; (3) some air pollutants, like heavy metals in PM, were not accounted due to lack of data. Given these limitations, the results presented here provide a good indication of the status of the Portuguese territory. For the cases of air pollution concentrations and water use, when these are within the boundaries nationally, there might still be cases where locally this might not be observed.

3.

EXPLANATORY HYPOTHESES FOR BIOPHYSICAL RESOURCE USE IN PORTUGAL

Our aim in this Chapter is to present explanatory hypothesis for the observed trends in the biophysical indicators analysed in Chapter 2 of this report. We have analysed the relationship of the biophysical indicators with many variables ranging from energy use to agriculture, passing through transport, production and consumption, identifying the relationships between the variables and identifying studies to back up these potential relationships.

In this Chapter we first present the approach we have followed (section 3.1). We then present the results by explanatory hypotheses (section 3.2), ranging from the energy policy, in particular, policies affecting the electricity mix, to waste policies. The Chapter ends with a section on key-messages (section 3.3). At the end of this report we present a Technical Note describing in more detail GDP historical dynamics (section 7.2.2) and its relation to the different sectors (section 7.2.3), and a description of the main sectoral policies analysed in this Chapter (sections 7.2.4 to 7.2.9).

3.1 APPROACH

The aim of this section of the study was to identify aspects in Portuguese history that could lead to the observed patterns in the biophysical indicators. For this, we have reviewed the literature on the biophysical indicators to understand their potential causes and links with historical factors in Portugal (a brief overview is presented in Technical Note 2, section 7.2.1). This allowed us to identify variables linked with the indicators (e.g., GDP, energy demand, agricultural area) and the links of these variables with historical events in Portugal.

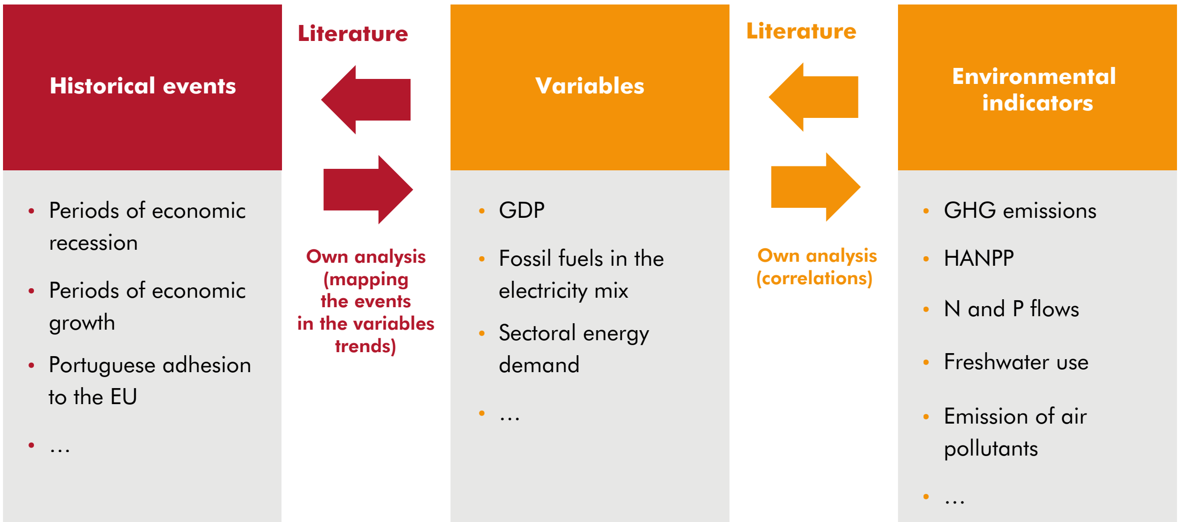
We analysed the relationship between these variables and the biophysical indicators. We made this mostly through the identification of common patterns in the dynamics of the variables and the indicators (visually), correlations between these, and, for the case of air pollutant concentrations, looking into more detailed data on the typology of the air quality monitoring stations reporting the higher concentrations for each pollutant[2].

Finally, we analysed the effects of the historical events in the variables and as we already identified the relationships between the variables and the biophysical indicators, it was possible to link the historical events with the biophysical indicators, formulating explanatory hypotheses for the indicators' dynamics. This was made by mapping the historical events through time with the variables and the indicators to identify the effects of the events in the variables and indicators.

Figure 16 presents an overview of the approach followed in this Chapter.

2 This latter approach was introduced because we have worked with country-level average values, but pollutant concentrations are localised. This meant that, using the same approach that was used for the remaining indicators, some of the effects/ links between the variables and the air pollutant concentrations got diluted (local peaks got diluted in national averages). This more localised analysis allowed us to reverse this dilution.

Figure 16
Overview of the approach followed for linking historical events to the biophysical indicators



3.2 EFFECT OF POLICIES ON THE INDICATORS

Table 9 presents a summary of the sectors that affect the biophysical indicators analysed, based on the literature reviewed (details in section 7.2.1). The next sections explore these relationships in detail.

Table 9
Main relationships between biophysical indicators and economic sectors

Sector	Biophysical indicator	Source
GDP	Waste production	APA (2019a)
Energy industries	Climate change, air pollution	APA (2019a), EEA (2019), WHO (2018)
Road transport	Climate change, air pollution	APA (2019a), EEA (2019), WHO (2018)
Industry (production)	Climate change, Ozone layer depletion, air pollution	APA (2019a), EEA (2019), WHO (2018)
Household and services (consumption)	Ozone layer depletion, Freshwater use, air pollution	PNGBH, EEA (2019), WHO (2018)
Agriculture	Climate change, ozone layer depletion, pressure on ecosystems, water pollution, freshwater use, air pollution	APA (2019a), PNGBH, Krausmann et al. (2013), EEA (2019), WHO (2018)
Waste policy	Waste disposal	APA (2019a)

3.2.1 Energy Policy and the biophysical indicators

Power generation, due to the use of fossil fuels such as coal, oil, and natural gas, influences the biophysical indicators climate change and air pollution (PM_{10}, SO_2, NO_2, NMVOC).

Our explanatory hypotheses are that (1) GDP affected electricity demand and the costs of using coal but (2) decarbonisation policies, in particular the ones reducing coal and oil from power generation, had a significant effect in terms of the environmental impacts analysed (climate change and air pollution). GDP dynamics (growth, stagnation, recession) affects indirectly the biophysical indicators by affecting the economic activities and providing family income which lead into increased energy demand. The last recession, between 2010 and 2013, led to reduced industrial activity, leading to an increase in unused CO2 licenses which led to a reduction of the price of the licenses to emit CO_2 in the European Emission Trading Scheme (EETS). This effect was visible because at the same time, coal international prices decreased due to an international increase in supply.

Governmental policies changing the electricity mix, in particular, the ones reducing coal and oil use (e.g., introduction of natural gas, investment in renewable sources of electricity) have affected electricity and the biophysical indicators analysed.

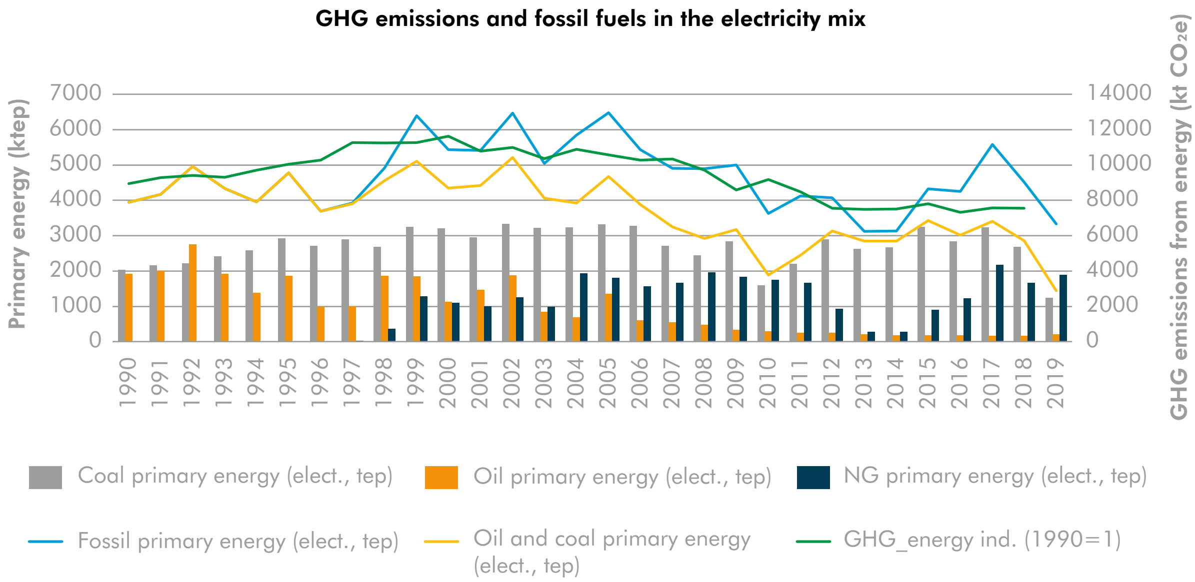
In the next sections we describe the relationship between the biophysical indicators and these explanatory hypotheses. In the technical notes we provide a more detailed description of GDP dynamics (section 7.2.2), its relationship with electricity (section 7.2.3), and an overview of the energy policy in Portugal (section 7.2.4).

Climate change

Electricity sector contributed with 26.5% of Portuguese GHG emissions in 2018 (APA, 2019a). GHG emissions from the electricity sector come from the use of fossil fuels for electricity production. Within the fossil fuels, coal and oil contribute the most (Figure 17), as these have higher GHG emissions per unit of energy than natural gas. The decreasing trend verified in GHG emissions between 2000 and 2012 is linked with the elimination of oil from the electricity mix and with the decrease in the use of coal due to an increase in renewable sources of electricity and increase in natural gas use in the mix. From 2010 onwards, the reduction in emissions (and in the use of fossil fuels for power generation) is also due to a decrease in energy demand due to the economic recession.

Although the economic recession lasted until 2013, GHG emissions from power generation stabilised from 2012 onwards. This was because coal prices went down (due to increased coal supply worldwide) and the decrease in GHG market prices within the EU (EU-ETS market crash) during this period, which made the use of coal cheaper than using natural gas. As a result, natural gas use decreased, and coal use increased between 2011 and 2017. This balanced the effect of the reduced demand for electricity leaving emissions relatively stable during 2012 and 2017.

Figure 17
GHG emissions from energy industries and primary energy used for power generation, by fuel type



Data sources: GHG emissions – APA (2019a), primary energy uses – national energy balances from DGEG.

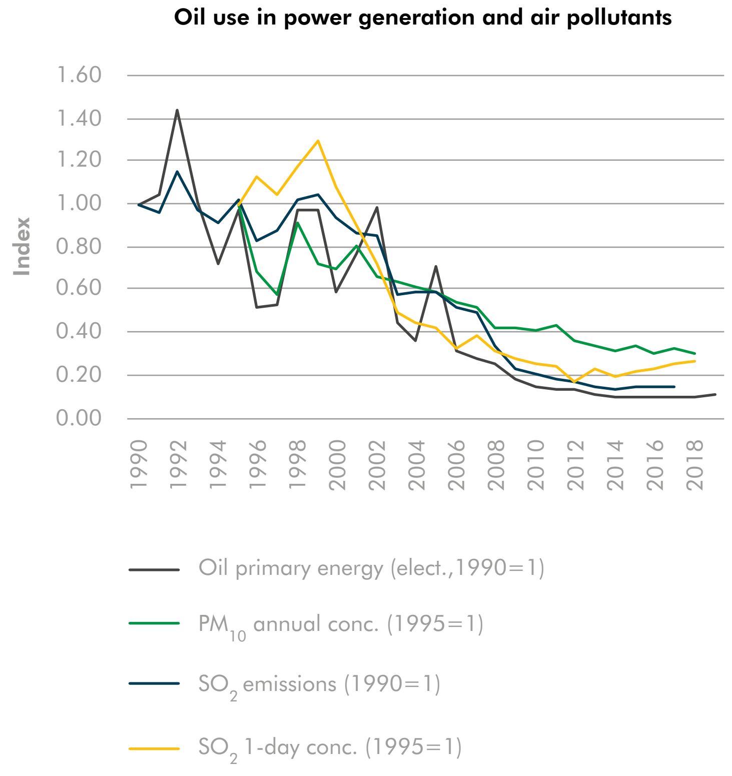
Air pollution

PM_{10} concentrations and SO_2 emissions and concentrations

All, WHO (2018), EU (EEA 2019) and APA (2019a) identify SO_2 emissions and concentrations to be linked with fuel combustion and power generation. WHO (2018) links PM_{10} concentrations to combustion processes, amongst others. From the data analysed, we can see a clear relationship between PM_{10} concentrations and SO_2 emissions and concentrations with oil used for power generation (Figure 18). The contribution from coal is residual[3]. This means that sulphur oxide emissions and PM_{10} are linked with the policy decision to eliminate oil from power generation.

Figure 18

Oil use for power generation and PM_{10} concentrations and SO_x emissions and concentrations



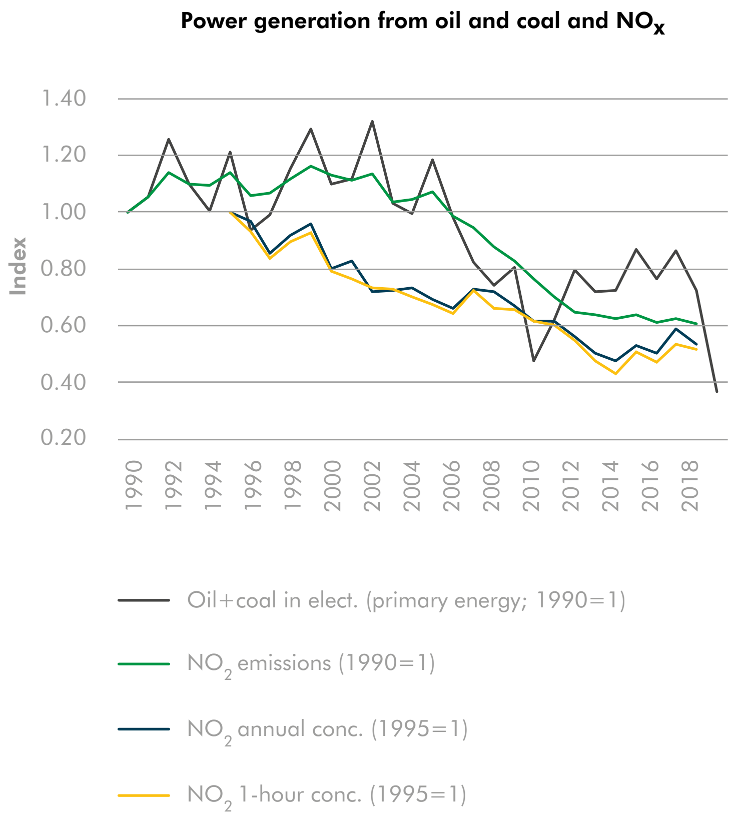
Data sources: Primary energy from oil from the national energy balances from DGEG; SO_x emissions from APA (2019a); SO_x 1-day concentrations and PM_{10} annual concentrations obtained from own calculations based on the national air quality monitoring network data.

3 The annual fluctuations observed in Figure 17 are linked with hydraulicity index (wet and dry years, affecting the availability and use of hydropower, respectively, affecting the amount of coal being used). These fluctuations related more to coal, which is increased or decreased depending on the hydropower available. Diesel varies little with these yearly fluctuations, being diesel the variable that most affects PM_{10} and SO_2, these variations are also not so prominent in PM_{10} and SO_2 concentrations.

NO_2 emissions and concentrations

According to WHO (2018), EU (EEA 2019) and APA (2019a), NO_x emissions and concentrations are linked with combustion processes. From the analysis of the data, we can see that these are particularly linked with the use of coal and oil in power generation (Figure 19). Therefore, NO_x emissions and concentrations are linked with the policy decisions of decreasing the use of coal and oil in the electricity mix, as well as market forces dictating the prices of coal (including the EU Emissions Trading Scheme).

Figure 19
Coal and oil used for power generation and NO_x emissions and concentrations



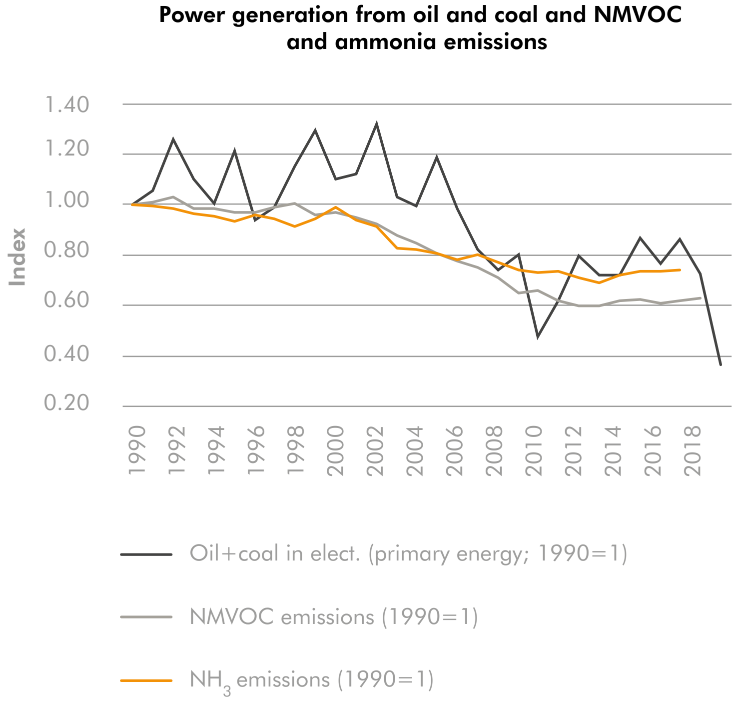
Data sources: Primary energy from coal and oil from the national energy balances from DGEG; NO_x emissions from APA (2019a); NO_x concentrations from own calculations based on the national air quality monitoring network data.

Ammonia and NMVOC emissions

According to APA (2019a), NMVOC and NH_3 emissions are linked with power generation. From the data analysed, we can see that this relationship is mainly due to coal and oil used for power generation (Figure 20) and not because of natural gas. This means the policy decisions of reducing oil and coal from the electricity mix have greatly contributed to the reduction of these pollutants.

Figure 20

Coal and oil used for power generation and NH_3 and NMVOC emissions



Data sources: Primary energy from coal and oil obtained from the national energy balances from DGEG; NH_3 and NMVOC emissions obtained from APA (2019a).

3.2.2 Mobility and vehicle policies

Road transport affects some of the indicators analysed, such as climate change (due to the use of fossil fuels) and air pollutants such as NO_x, NMVOC, CO, O_3 and NH_3.

Our explanatory hypotheses are that (1) GDP affects transport but (2) mobility and vehicle policies have had a significant effect in terms of the environmental impacts analysed. GDP dynamics (growth, stagnation, recession, recovery) affects indirectly the biophysical indicators by affecting the economic activities and providing family income which lead into increased transport. Governmental policies such as taxing pollution from vehicles (or the fuel tax), incentives for the acquisition of cleaner vehicles, incorporation of biodiesels in fuels, introduction of catalytic converters in petrol vehicles, and investments in infrastructure (public transport and roads) have affected transport and the biophysical indicators analysed.

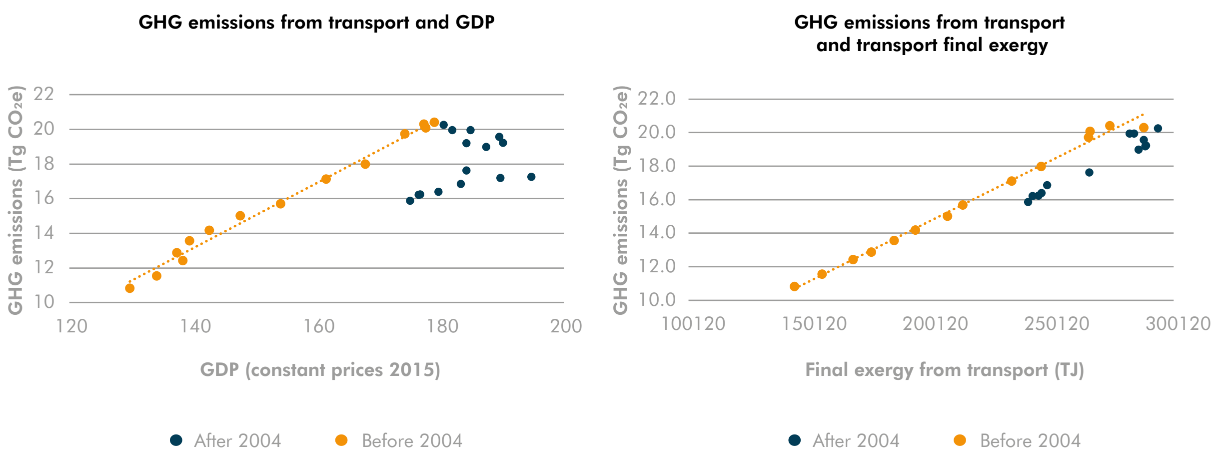
In the next sections we describe the relationship between the biophysical indicators and these explanatory hypotheses. In the technical notes we provide a more detailed description of GDP dynamics (section 7.2.2), its relationship with transport and mobility (section 7.2.3), and an overview of transport and mobility measures adopted in Portugal (section 7.2.5).

Climate change

GHG emissions from transport are linked with GDP and final exergy consumption until 2004 (Figure 21), increasing with increases in GDP and final exergy. From 2005, several factors came into play changing this relationship and GHG emissions from transport are stabilising despite the variability in GDP. The factors that have been contributing to the decoupling of GHG emissions from transport from GDP are:

- Taxation of polluting vehicles (introduction of a CO_2 component in annual circulation tax and in vehicle purchase tax),
- Incentives for vehicle substitution ("Renove o Carro" program),
- Incorporation of a biodiesel fraction in diesel and gasoline,
- Introduction of exemptions to fuel tax for biofuels, public transport, and hybrid and electric vehicles,
- Continuous governmental investments in public transport.

Figure 21
Transport GHG emissions and GDP and transport final exergy demand



Air pollution

NO_2 emissions and concentrations

The relation between GDP and NO_2 emissions is less direct than the relationship between GHG emissions from transport and GDP. This is because: (1) emissions of NO_2 also depend on electricity generation and industrial activity; and (2) of the introduction of petrol cars with catalytic converters to reduce NO_2, NH_3, NMVOC and CO and stricter regulations of diesel vehicles emissions activity. Air quality monitoring stations with the highest concentrations in terms of NO_2 are stations linked with traffic (Table 10).

Table 10

Type of air quality monitoring stations reporting highest concentrations of NO_x

Year (# of monitoring stations)	**Type of stations reporting the highest:** 1-year mean concentrations	1-hour mean concentrations
1995 (20)	Traffic	Background
1996 (20)	n.a.	n.a.
1997 (20)	n.a.	Traffic
1998 (21)	Traffic	n.a.
1999 (25)	n.a.	Background
2000 (29)	n.a.	Background
2001 (33)	n.a.	Industrial
2002 (47)	Traffic	Background
2003 (56)	Traffic	n.a.
2004 (66)	n.a.	n.a.
2005 (70)	Traffic	Background
2006 (69)	Traffic	Traffic
2007 (72)	Traffic	n.a.
2008 (71)	Traffic	Traffic
2009 (71)	Traffic	Background
2010 (76)	Traffic	Background
2011 (69)	Traffic	Traffic
2012 (61)	Traffic	Background
2013 (58)	Traffic	Background
2014 (60)	Traffic	Traffic
2015 (60)	Traffic	Traffic

Year (# of monitoring stations)	Type of stations reporting the highest:	
	1-year mean concentrations	1-hour mean concentrations
2016 (60)	Traffic	Traffic
2017 (59)	Background	Traffic
2018 (59)	Traffic	Traffic

Definitions: *n.a.* – not available; *Traffic* – stations located in areas where traffic is expected to be the main source of air pollution (specific busy traffic routes); *Industrial* – stations located in areas where industrial activity is expected to be the main source of air pollution (close to specific factory buildings); *Background* – stations located in areas with several types of sources of pollution.

NMVOC emissions

NMVOC emissions are now decoupled from fossil fuel use in road transport due to the catalytic converters and other measures for cleaner vehicles.

NH_3 emissions, and PM_{10}, CO and O_3 concentrations

The relationship between NH_3 emissions, and PM_{10}, CO and O_3 concentrations and fuel use in road transport does not seem clear. The reason for this is: (1) the introduction of catalytic converters and other measures for cleaner vehicles help decoupling NH3 emissions and CO concentrations from fossil fuel use in vehicles; (2) other sources of these pollutants might disguise their relationship with transport, and (3) concentrations (in opposition to emissions) are a consequence of the emissions, but also depend on local weather and bioclimatic local conditions, which can disperse pollutants even when emissions are high.

But we know there is a relationship between these variables because fossil fuel use in road transport is used to estimate the emissions from GHG, NO_2 and NH_3 (APA, 2019a), and air quality data shows that the pollutants PM_{10}, CO, NO_2 and O_3 have a relevant traffic component.

Regarding the last point, in terms of PM_{10} annual concentrations, the stations that reported the peaks in concentration are all linked with traffic pollution (Table 11). As traffic is a localised effect and, in this study, we are working with national wide values, these peaks get diluted overall as well as traffic in these areas gets diluted with traffic energy use in the whole country. Road transportation is therefore one of the drivers for PM_{10} emissions.

Table 11

Stations with the highest concentrations of PM_{10}

Year	Total stations	Avg value (μg/m³)	Max value (μg/m³)	Station name	Station type	Station zone
2003	11	21.9	33.0	Vermoim	Traffic	Urban
2004	17	22.3	48.2	Fundão	Background	Rural
2005	37	18.7	33.9	Ervedeira	Background	Rural
2006	20	15.6	24.7	Estarreja/Teixugueira	Background	Suburban
2007	23	14.2	23.9	Estarreja/Teixugueira	Background	Suburban
2008	22	12.2	16.1	Estarreja/Teixugueira	Background	Suburban
2009	24	12.2	14.8	Estarreja/Teixugueira	Background	Suburban
2010	25	13.3	15.4	Estarreja/Teixugueira	Background	Suburban
2011	24	13.6	16.6	Estarreja/Teixugueira	Background	Suburban
2012	21	13.9	17.1	Estarreja/Teixugueira	Background	Suburban
2013	19	12.3	15.5	Terena	Background	Rural
2014	23	11.7	16.4	Monte Velho	Background	Rural
2015	26	17.5	66.3	Fidalguinhos	Background	Urban
2016	23	12.7	14.4	Entrecampos	Traffic	Urban
2017	21	14.0	20.7	Entrecampos	Traffic	Urban
2018	22	12.3	13.5	Entrecampos	Traffic	Urban

Definitions: *Traffic* – stations located in areas where traffic is expected to be the main source of air pollution (specific busy traffic routes); *Industrial* – stations located in areas where industrial activity is expected to be the main source of air pollution (close to specific factory buildings); *Background* – stations located in areas with several types of sources of pollution.

CO concentrations are within the limits apart from a few peaks. The highest concentrations where mostly observed in traffic related monitoring stations (Table 12), which are localised impacts. We conclude that the main contributor to carbon monoxide is traffic.

Table 12
Stations reporting main CO concentrations in Portugal

Year	Peaks observed	Type of station with the highest concentration	Name of station with the highest concentration	Municipality with the station with the highest concentration
1995		Traffic	Benfica	Lisbon
1996	1-hour peak 8-hour peak	Traffic [a]	R. dos Bragas	Oporto [a]
1997	1-hour peak	Traffic	R. dos Bragas / Av. Liberdade	Oporto [a] / Lisbon
1998	1-hour peak 8-hour peak	-	Hospital Velho	-
1999	8-hour peak	-	Hospital Velho	-
2000	1-hour peak 8-hour peak	Traffic [a]	Rua dos Bragas / Hospital Velho	Oporto [a] / - -
2001	-	Traffic	Benfica / Entrecampos	Lisbon
2002	-	Traffic [a]	Av. Casal Ribeiro	Lisbon [a]
2003	-	Traffic	Benfica	Lisbon
2004	-	-	Município	-
2005	-	Traffic	S. João / Baguim	Funchal / -
2006	8-hour peak	Background	Vila Nova da Telha	Maia
2007	-	Industrial	Perafita / Baguim	Matosinhos / -
2008	-	-	Matosinhos / Baguim	Matosinhos / -
2009	-	Background / Traffic	Alfragide-Amadora / Benfica	Amadora / Lisbon
2010	1-hour peak 8-hour peak	-	Município	-
2011	-	Background / Traffic	Mindelo-Vila do Conde / David Neto	Vila do Conde / Portimão
2012	-	Traffic	Francisco Sá-Carneiro-Campanha / David Neto	Oporto / Portimão

Year	Peaks observed	Type of station with the highest concentration	Name of station with the highest concentration	Municipality with the station with the highest concentration
2013	-	Background / Traffic	Alfragide-Amadora / David Neto	Amadora / Portimão
2014	-	Background / Traffic	Alfragide-Amadora / David Neto	Amadora / Portimão
2015	-	Traffic	David Neto	Portimão
2016	-	Traffic	São João	Funchal
2017	-	Traffic	João Gomes Laranjo-S. Hora	Matosinhos
2018	1-hour peak 8-hour peak	Background	Instituto Geofísico de Coimbra	Coimbra

a. information not available, value defined by the team.
Definitions: *Traffic* – stations located in areas where traffic is expected to be the main source of air pollution (specific busy traffic routes); *Industrial* – stations located in areas where industrial activity is expected to be the main source of air pollution (close to specific factory buildings); *Background* – stations located in areas with several types of sources of pollution.

3.2.3 Production (manufacturing industries) and Consumption (households and services)

Manufacturing industries, households, and service activities (including commercial, tourism and institutional activities) impact many of the biophysical indicators analysed, such as climate change (due to energy production and manufacturing industrial processes), ozone layer depletion (due to the use of ozone depleting substances), freshwater use, and air pollutants such as $PM_{2.5}$, SO_2, NO_2, NH_3, NMVOC and O_3 (due to energy production and other activities). Our explanatory hypotheses are that (1) GDP, (2) national sectoral policies and (3) international agreements were the main factors affecting the variables above.

GDP dynamics (growth, stagnation, recession) affect indirectly the biophysical indicators by either affecting production (i.e., manufacturing industry activity and services) or consumption (i.e., purchase power). Some national sectoral policies have contributed to a decoupling of some biophysical indicators from GDP. These are, for example, the introduction of natural gas in Portugal, energy efficiency policies for manufacturing industries and buildings (incentives for energy efficiency improvements, legislation on energy in buildings and incentives for micro-electricity generation).

International agreements, namely the Montreal Protocol and its amendments, succeeded in eliminating the production and consumption of ozone depleting substances.

In the next sections we describe the relationship between the biophysical indicators and these explanatory hypotheses. In the technical notes we provide a more detailed description of GDP dynamics (section 7.2.2), its relationship with manufacturing industries and households and service activities (section 7.2.3), the energy efficiency measures adopted in Portugal (section 7.2.6), and the international agreements regulating ozone depleting substances' production and consumption (section 7.2.7).

Climate change

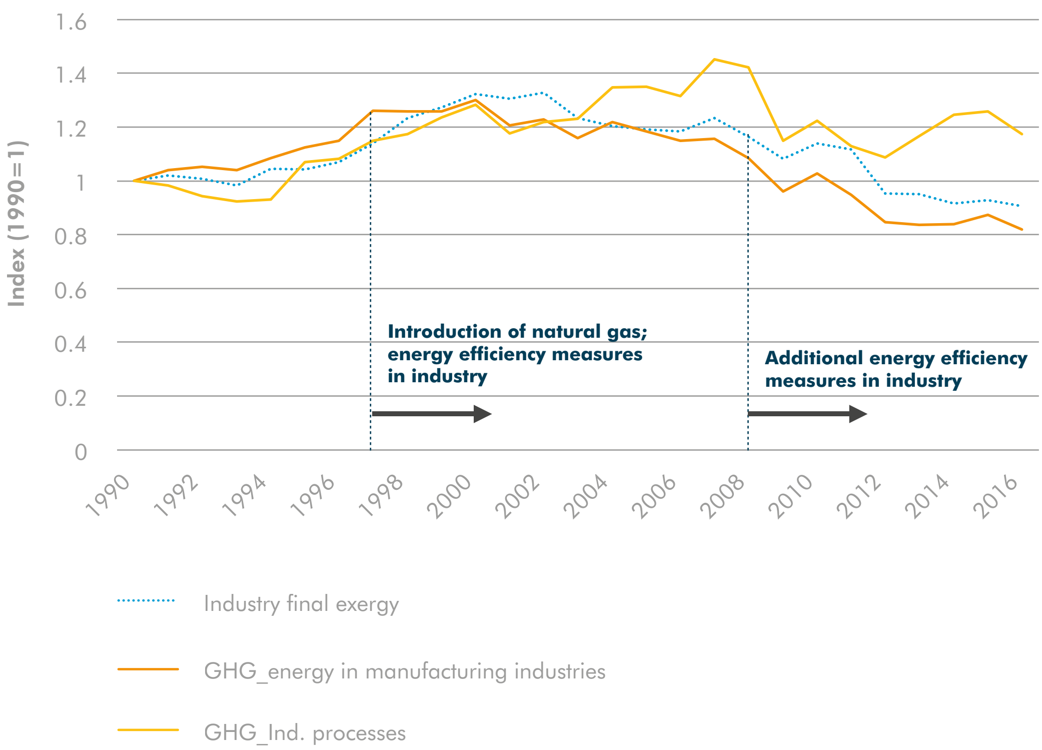
GDP can only explain part of the dynamics observed in GHG emissions from manufacturing industry and residential and services. The increase in GHG emissions verified between 1995 and 2000 and the decrease in GHG emissions between 2008-09 and between 2010-13 can be explained by GDP growth and recession, respectively (Figure 22). However, we can see (1) a decrease in exergy consumption in manufacturing industry from 2002 accompanied by a decrease in GHG emissions from energy use in manufacturing industries and (2) a decoupling of GHG emissions from residential and services from exergy consumption from 2005 onwards.

Figure 22
GDP influence in GHG emissions from manufacturing industries, households and services

The first can be explained by the energy measures implemented in industry (described in section 7.2.6), Figure 23. These started being implemented from 1997 and include the introduction of natural gas in Portugal, feed-in tariffs for CHP production and the implementation of the Intensive Energy Consumption Management System.

Figure 23

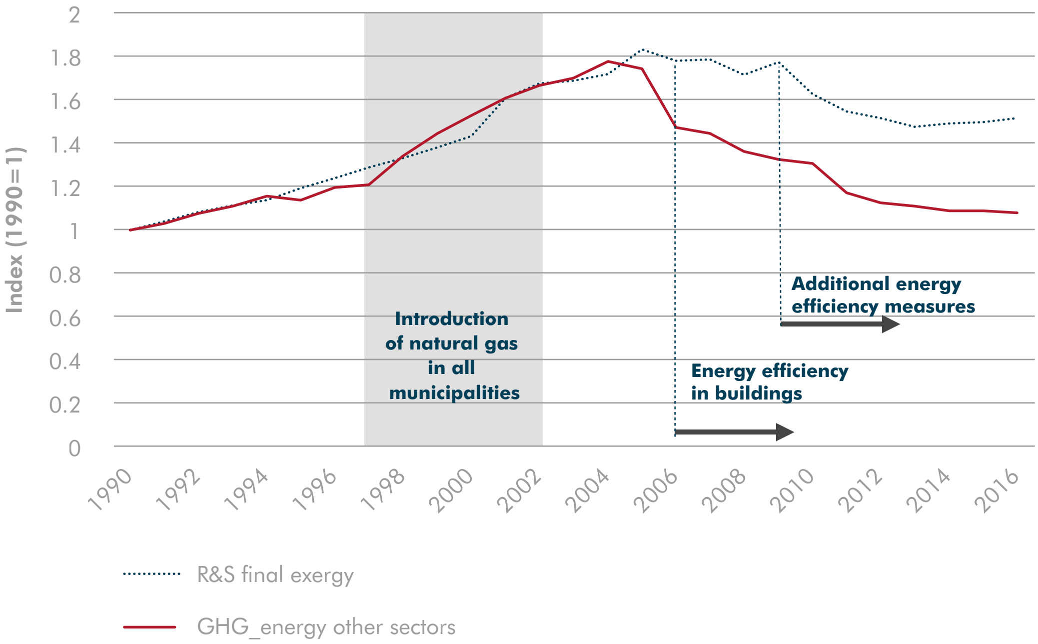
GHG emissions and exergy use by manufacturing industries



Sources: APA (2019a) for GHG emissions, own calculations based on national energy balances for final exergy from industry.

The second is due to: (1) the introduction of natural gas in Portugal. This process started in 1997 and was completed in all municipalities by 2002, and whose uptake by households (substituting butane gas bottles) would only take effect in subsequent years having not yet full uptake nowadays; (2) the regulation in buildings from 2006, which included energy certification in buildings and made compulsory the installation of solar thermal for water systems in new buildings and some service buildings, Figure 24.

Figure 24
GHG emissions from residential and services[4] and final exergy consumption



Sources: APA (2019a) for GHG emissions, own calculations based on national energy balances for final exergy from residential and services.

From 2008 onwards, several energy measures and incentives have been adopted by Portuguese government (details in section 7.2.6), which have effects in terms of energy use (light bulb substitution, and incentives for efficient equipment and insulation) and in terms of decoupling energy use from GHG emissions (incentives for micro-electricity generation, installation of solar thermal, regulation on buildings). These effects might explain the decrease in energy consumption between 2009-10 (prior to the economic recession) and be camouflaged by the recession effects.

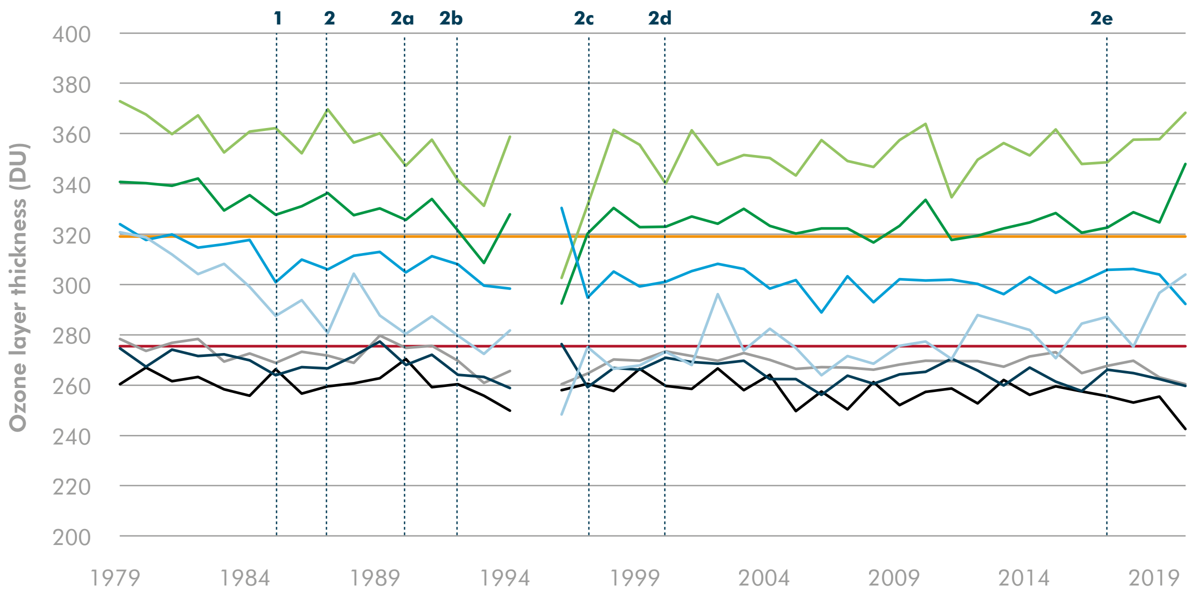
The new legislation for buildings (DL 58/2013) will have a major impact on the energy provision in new (residential, commercial, and service) buildings both in terms of energy use and in terms of decarbonisation of the energy used as buildings will need to incorporate a significant amount of energy supply from within the building itself or from the surrounding areas.

Ozone layer depletion

Figure 25 maps the international agreements regulating the production and consumption of ODS, and the ozone layer thickness. Most of these agreements happened before 2000 and well before we started to see a recovery of the ozone hole area (2011). From Figure 26 we can see that most of the targets agreed happened before the ozone hole started to recover.

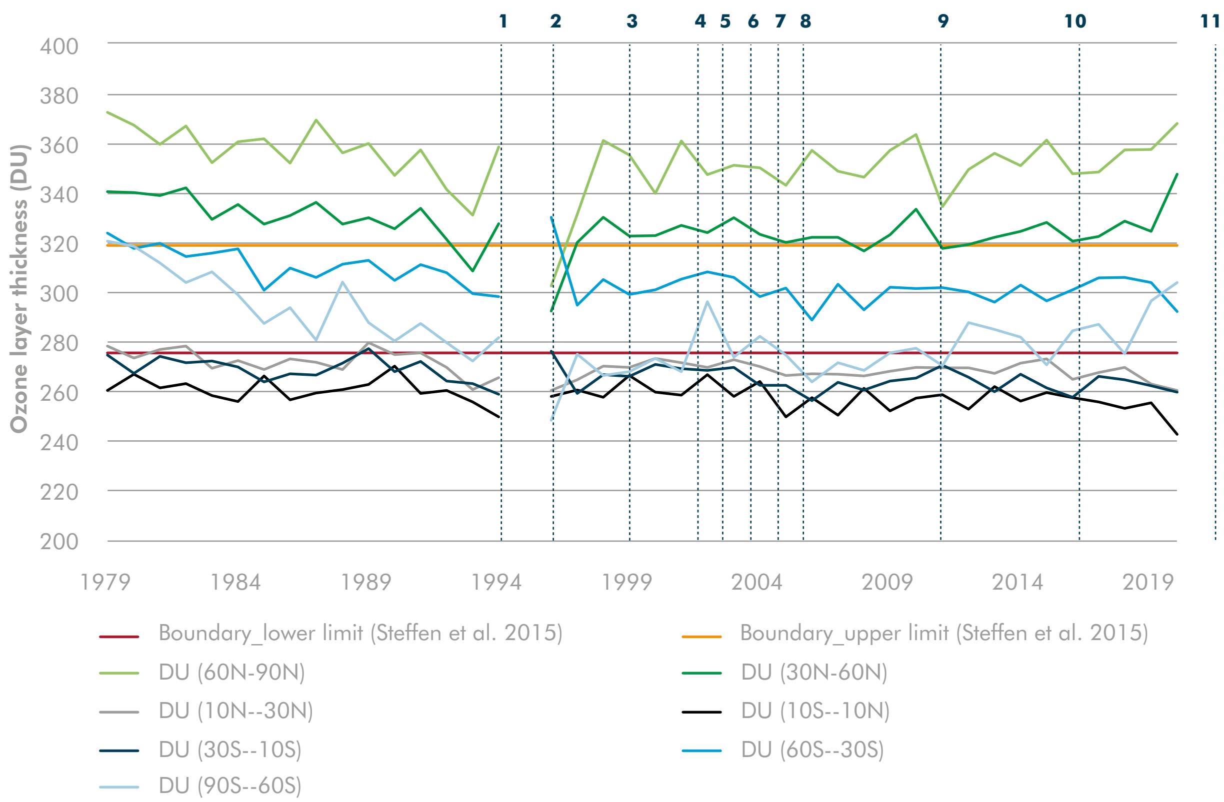
4 These values also include GHG emissions from energy use in agriculture and fisheries, which are expected to be low, having little effect of the values presented.

Figure 25
International agreements on ODS restrictions through time and the ozone layer thickness



1 – The Vienna Convention; 2 – The Montreal Protocol; 2a – The London Amendment; 2b – The Copenhagen Amendment; 2c – The Montreal Amendment; 2d – The Beijing Amendment; 2e – Kigali Amendment.

Figure 26
ODS restriction targets through time and the ozone layer thickness



1 – Halons targets; 2 – CFCs, carbon tetrachloride, methyl chloroform and HBFCs targets; HCFCs freeze levels;
3 – Methyl bromide 25% reduction; 4 – Methyl bromide 50% reduction; 5 – Bromochloromethane target;
6 - Methyl bromide 75% reduction; 7 – HCFCs 35% reduction; 8 - Methyl bromide phaseout;
9 – HCFCs 65% reduction; 10 – HCFCs 90% reduction; 11 – HCFCs 99.5% reduction.

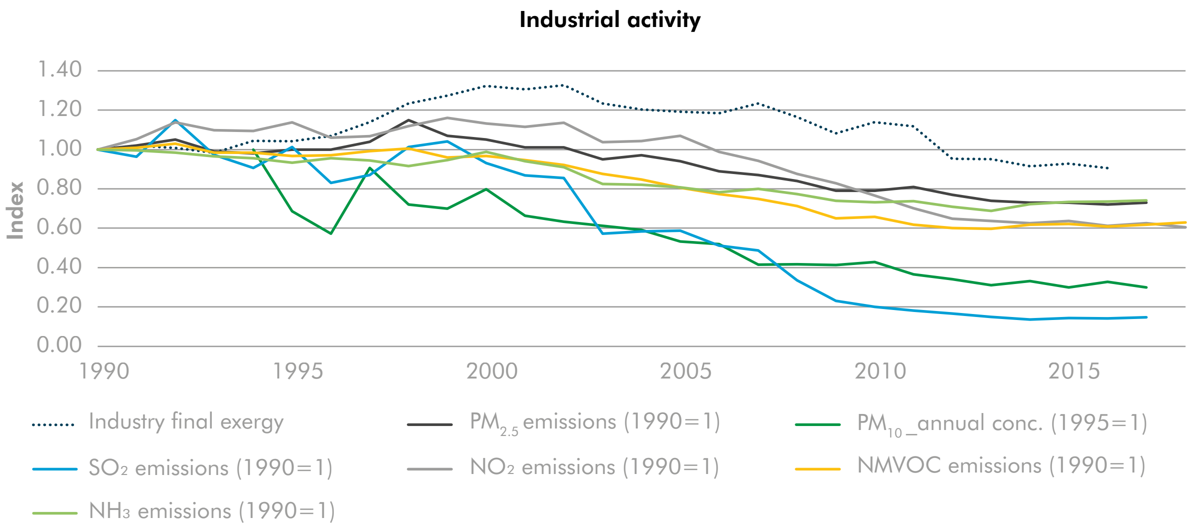
Freshwater use

According to the National Plan for Water Basins Management, urban activities (including residential, commerce and tourism) are the second largest freshwater consumer in Portugal (more details in section 7.2.1). Although being a second largest contributor to freshwater use, this effect has a small weight when compared to the effect of agriculture in freshwater use, which represents 70% of water uses. The relation between freshwater use and agriculture is explored in section 3.2.4.

Air pollution

Emissions from the air pollutants ($PM_{2.5}$, SO_2, NO_2, and NH_3) are linked with final exergy consumption by manufacturing industry (Figure 27).

Figure 27
Final exergy consumption from manufacturing industries and emissions of air pollutants



Source of data: final exergy – own calculations based on national energy balances from DGEG; air pollutant emissions from APA (2919a).

For concentrations of SO_2, trends seem a little phased-out with manufacturing industrial activity, which can be explained by: (1) they are concentrations, therefore, not direct consequence from the activity, (2) they relate to local monitoring stations, so localised impacts which can be diluted in this national analysis. When we investigate which air quality stations reported higher concentrations for SO_2 (Table 13), we can see that many of these are of the industrial type (located in Sines, Barreiro, Matosinhos and Santiago do Cacém).

Table 13

Air quality monitoring stations with highest values for SO_2 concentrations

Year (total nr. of stations)	Type of worst station for 1-day mean concentrations	Type of worst station for 1-hour mean concentrations
1995 (17)	Traffic	n.a.
1996 (17)	Traffic	n.a.
1997 (17)	-	Industrial
1998 (18)	Industrial	Industrial
1999 (20)	-	Industrial
2000 (24)	Industrial	Background
2001 (29)	Industrial	Industrial
2002 (38)	Industrial	Industrial
2003 (45)	Industrial	Industrial
2004 (52)	Industrial	n.a.
2005 (61)	Industrial	Background
2006 (53)	Industrial	Industrial
2007 (56)	Industrial	Industrial
2008 (57)	Industrial	Industrial
2009 (59)	Background	n.a.
2010 (63)	Background	Industrial
2011 (58)	Background	Traffic
2012 (36)	Industrial	Background
2013 (28)	Background	Industrial
2014 (29)	Industrial	Industrial
2015 (29)	Background	Industrial
2016 (27)	Background	Traffic
2017 (26)	Industrial	Industrial
2018 (27)	Industrial	Industrial

Definitions: *n.a.* – not available; *Traffic* – stations located in areas where traffic is expected to be the main source of air pollution (specific busy traffic routes); *Industrial* – stations located in areas where industrial activity is expected to be the main source of air pollution (close to specific factory buildings); *Background* – stations located in areas with several types of sources of pollution.

The case of O_3 concentrations, which seem completely off the trend in manufacturing industrial activities, is due to O_3 being a secondary pollutant. Its concentrations depend on the complex relationship between emissions and concentrations of primary pollutants as well as radiation. When looking into the type of air quality monitoring stations that identified the higher concentrations in this pollutant, we can see that some of these stations are of the industrial type (in Sines, Matosinhos and Santiago do Cacém).

3.2.4 Agricultural Policies

Agriculture has an effect on many of the biophysical indicators analysed, such as climate change (mostly due to nitrogen-based fertiliser use and ruminants production), pressure on ecosystems (through competing areas), water pollution (due to fertiliser use), freshwater use (due to irrigation), and air pollutants such as PM_{10}, NMVOC and NH_3 (due to soil tillage, wind erosion, silage, manure management, grazing and nitrogen fertiliser use).

These variables are affected by the agricultural policy in Portugal. Our explanatory hypotheses are that (1) the agricultural policies implemented through the dictatorship regime (until 1974) and (2) the EU policies on agriculture (from 1986) were the main factors affecting the biophysical indicators analysed.

During the 60s and 70s, the dictatorship regime implemented an agricultural reform to react to the increasing abandonment of agriculture and poverty in rural communities. The reform aimed to shift agricultural production towards more profitable products such as forestry, other more profitable crops than cereals and animal production. Forestry campaigns, particularly in community areas (in the "baldios") reduced the grazing areas. The reform also focused on mechanising and irrigating agriculture. This reform led to an increased use of fertilisers, machinery, and animal production with the exception of sheep (which made use of grazing areas that were being substituted by forestry). Those reforms (in the 60s and 70s) led to a slight increase in GHG emissions from agriculture, an increase in the pressure on ecosystems and increases in fertiliser use (N and P).

Between 1975 and 1982 there was a large increase in GHG emissions. This increase coincides with the political regime shift that happened in 1974 (from a dictatorial regime to a democratic regime), leading to think that this change is related with an adaptation period to the new regime. The activities responsible for this increase are animal production in general, and swine production in particular.

EU policies on agriculture, namely, the Portuguese transition period to the EU Common Agricultural Policy (CAP, between 1986-2000) and the internationalisation of the EU agricultural market (in 1993) led to first a decrease in agricultural production followed by an intensification of agriculture. Animal production decreased except for non-dairy cattle, which increased. The result is a decreased trend in GHG emissions from agriculture, pressure on ecosystems, fertiliser use, NH_3 and NMVOC emissions and PM_{10} concentrations.

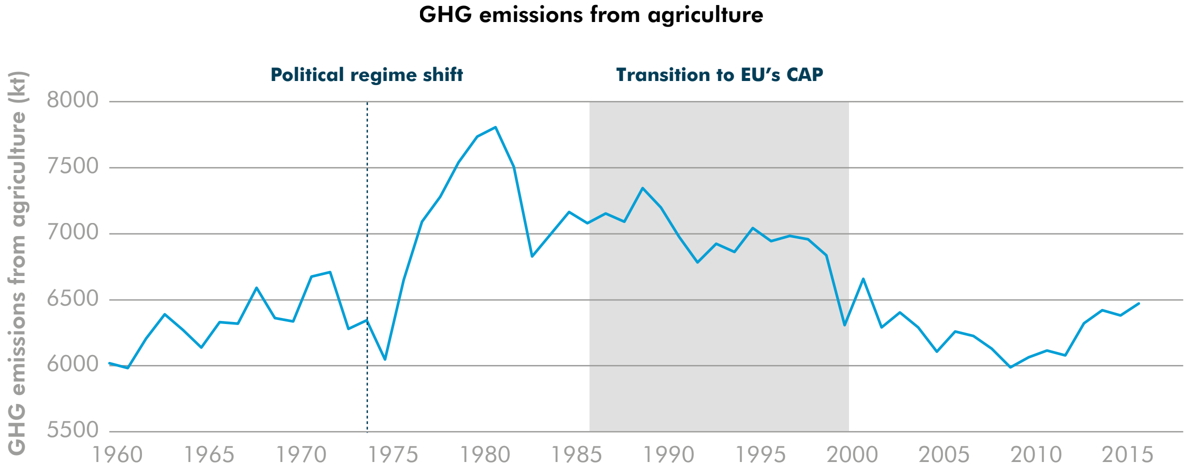
The effects of these two groups of policies are described below. In Technical notes 2 (section 7.2.8) we present a more detailed description of the policies implemented during the dictatorial regime and the policies from the EU.

Climate change

Climate change is affected by the use of nitrogen-based fertilisers and the production of ruminants (APA, 2019a). The shift in the political regime introduced an increase in GHG emissions, which rapidly reduced (Figure 28). During the transition period to the EU there was a reduction trend in GHG emissions, only starting to increase from 2010 onwards. This increase in GHG emissions between the end of the dictatorial regime and joining the EU is observed in all animal production numbers (see Figure 38 in section 7.2.8 in the technical notes).

Figure 28

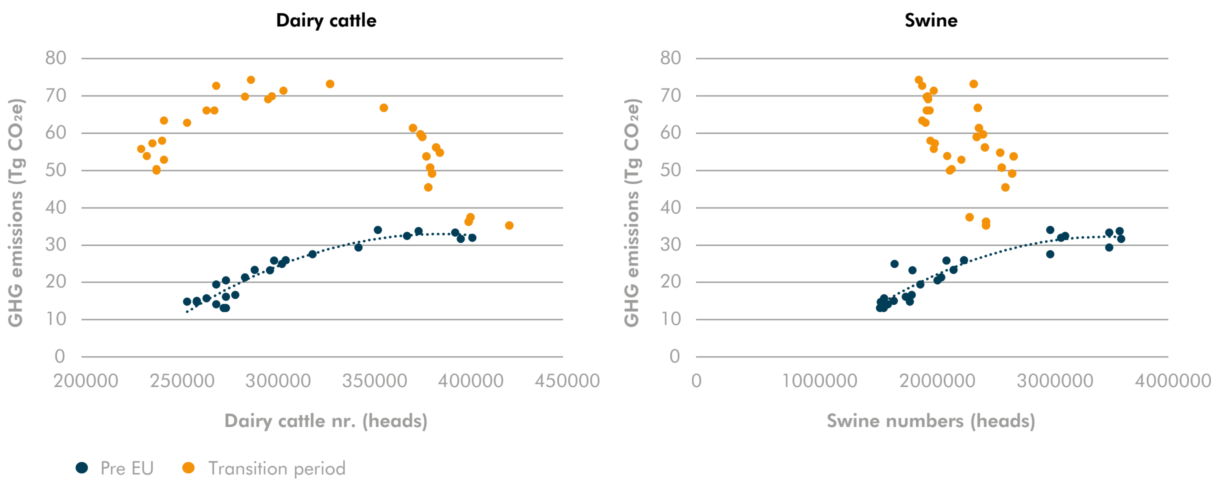
Agriculture GHG emissions and main agriculture policy shifts

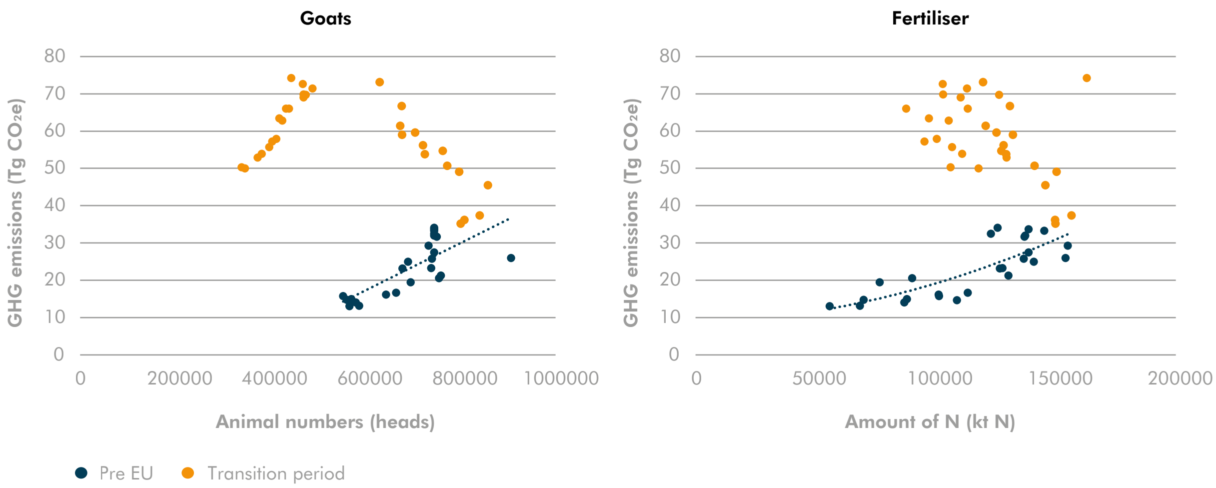


Prior to Portugal joining the EU, we can see a relationship between GHG emissions from agriculture and dairy cattle, goat, and swine numbers, as well as with nitrogen fertiliser use, where the increase in these variables leads to an increase in GHG emissions from agriculture (Figure 29). All these variables had a slight increase until 1974 and then had a jump in their numbers before 1986.

Figure 29

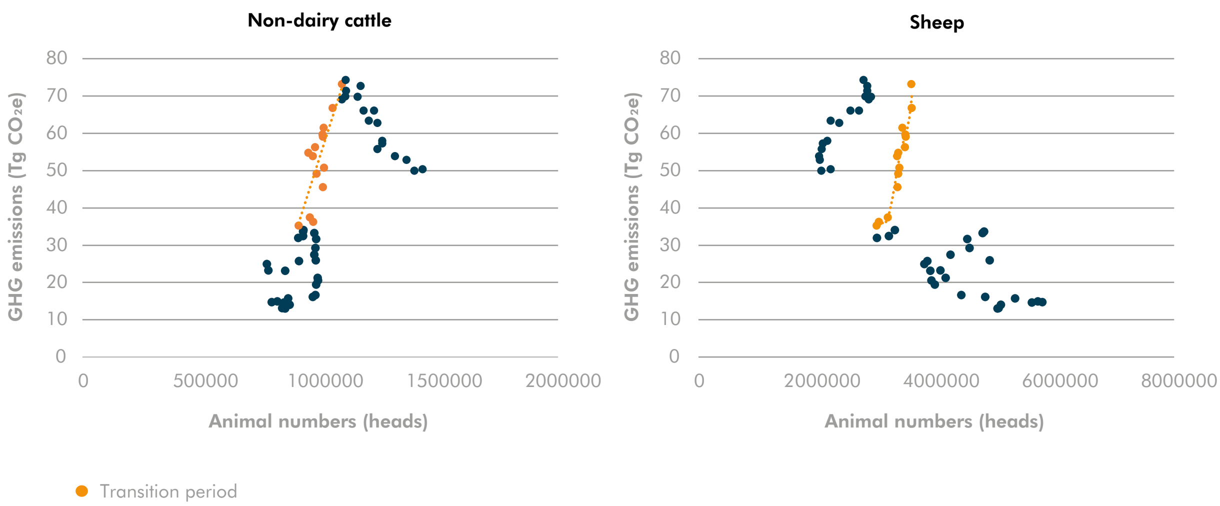
Relationship between animal numbers and GHG emissions prior to Portugal joining the EU





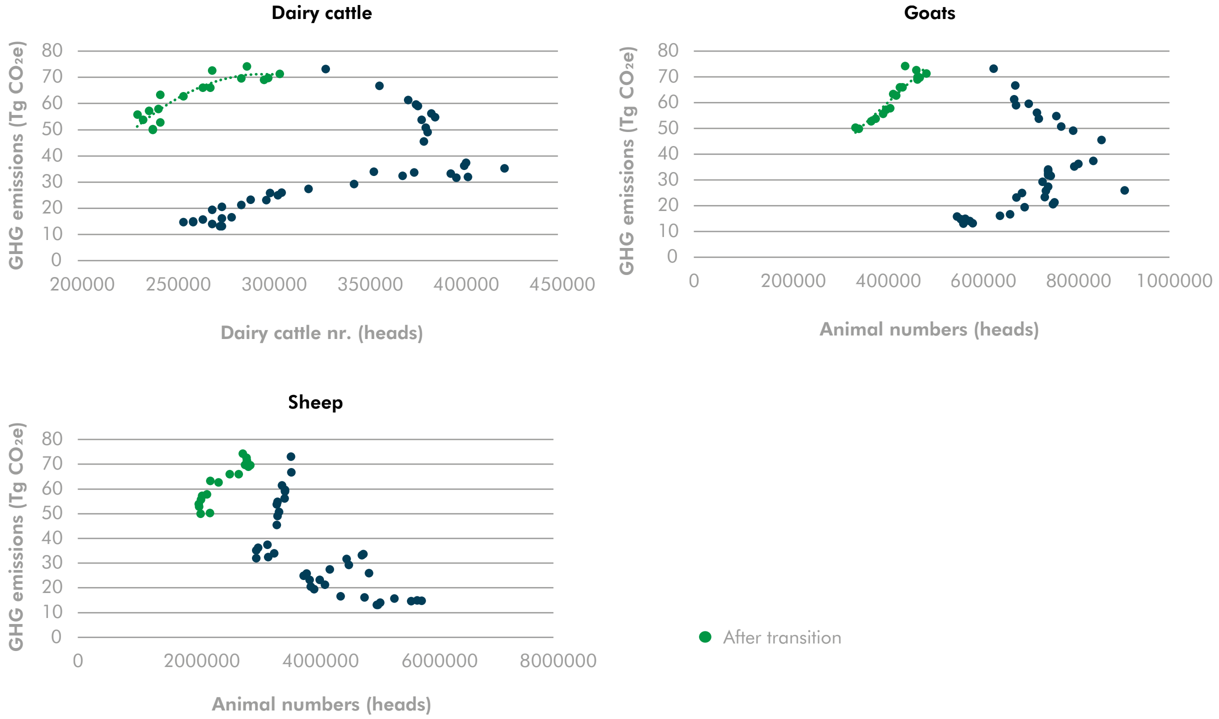
During the transition period, non-dairy cattle started to increase, substituting other forms of animal production. These led to a decrease in direct GHG emissions from agriculture (Figure 30).

Figure 30
Relationship between animal numbers and GHG emissions from agriculture during the period of transition to the EU



After the transition period, we can see a relationship between GHG emissions from agriculture and dairy cattle, goat, and sheep numbers (Figure 31). As these decrease, GHG emissions decrease.

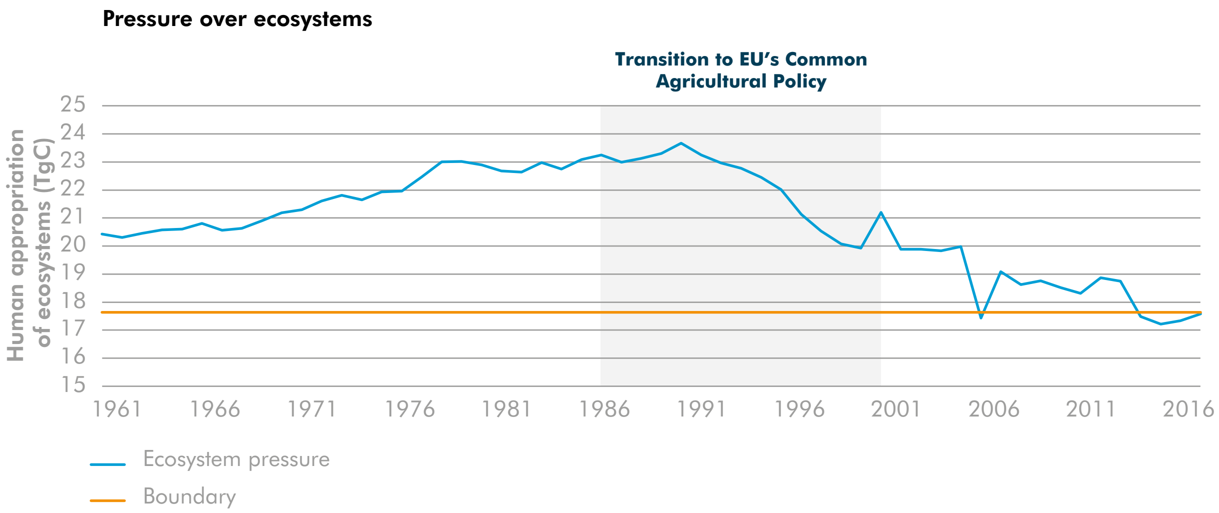
Figure 31
Relationship between GHG emissions from agriculture and animal numbers after the transition period



Pressure over ecosystems

EU policies on agriculture led to a decrease in the pressure on ecosystems (Figure 32).

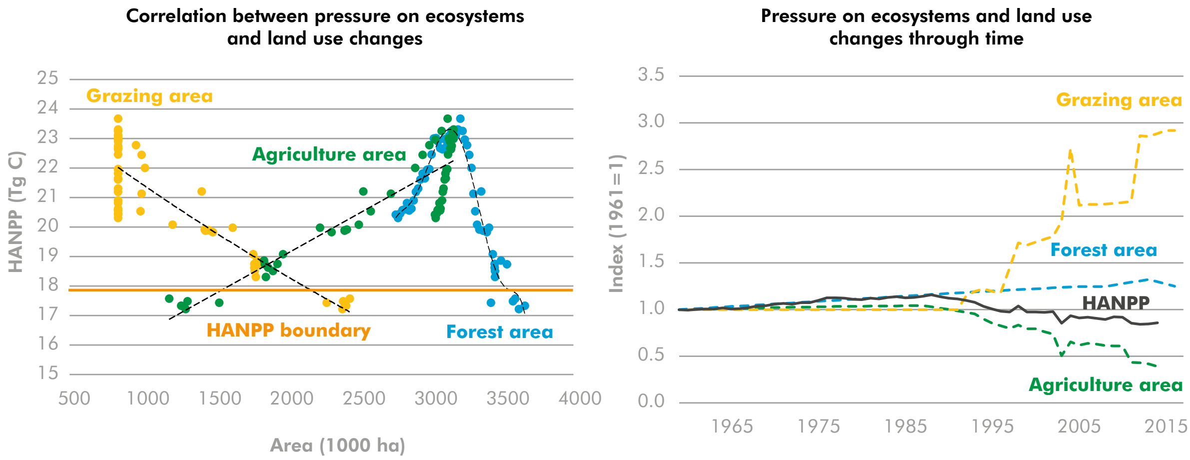
Figure 32
Pressure over ecosystems and the shift in agricultural policies in Portugal



Pressure on ecosystems is mostly affected by land use changes, in particular the ones occurring to forest, agricultural areas and grazing areas (Figure 33). Forest areas and grazing areas (which include shrubland) contribute to a decrease in the pressure on ecosystems (the more of these areas, the less human appropriation of primary production). An inverse relationship is found for agricultural areas. As grazing and forest areas have been increasing (grazing areas during the transition period of Portugal to the EU's CAP), and agricultural areas decreasing, this reflects a decreasing pressure on ecosystems in particular during the transition to the EU's CAP.

Figure 33

Relationship between pressure on ecosystems (HANPP) and land use changes. Left: correlation. Right: through time.

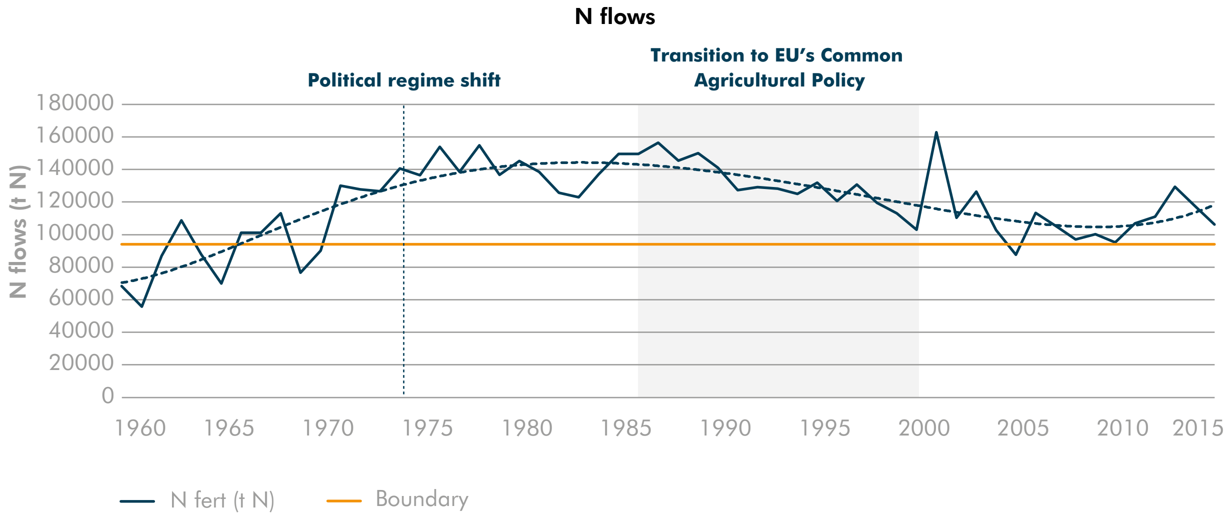


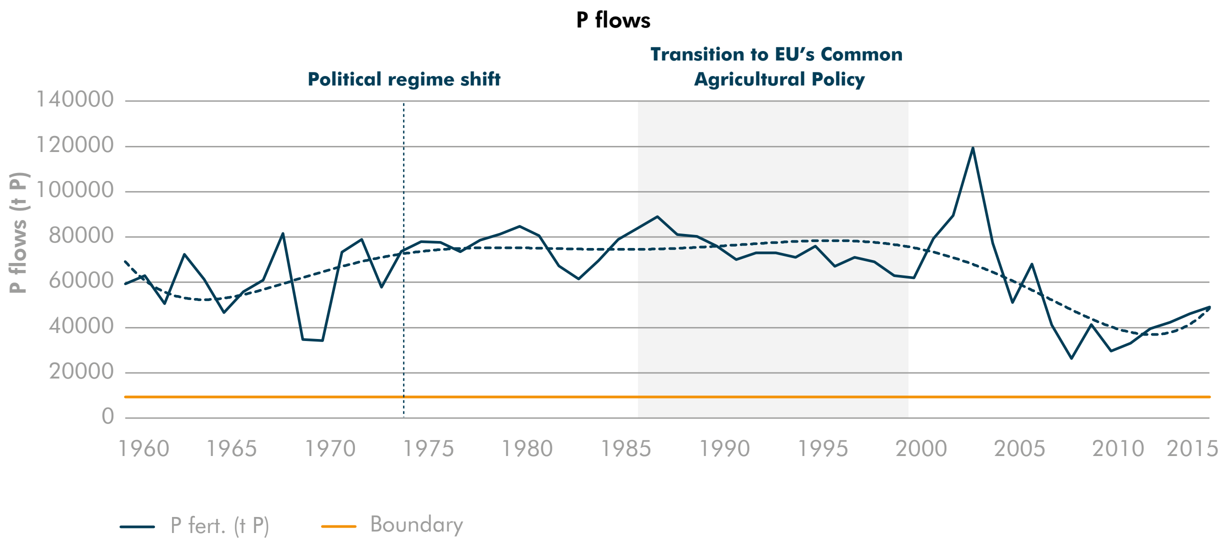
Grazing areas include shrublands. Trend lines in black.
Data sources: own estimations for HANPP, COS for forest area, FAOSTAT for remaining variables.

Water pollution and ozone layer depletion

N and P emissions have increased during the dictatorial political regime with a tendency to stabilisation after the regime shift (Figure 34). During the transition to the EU agricultural policy, N flows in Portugal decreased, as a result from reducing subsidies and decreasing agricultural production. N and P flows have only started to increase in more recent years (from 2010 onwards). N use in agriculture is responsible for N_2O which is both, a GHG gas and an ODS.

Figure 34
N and P flows and the shift in agricultural policies in Portugal



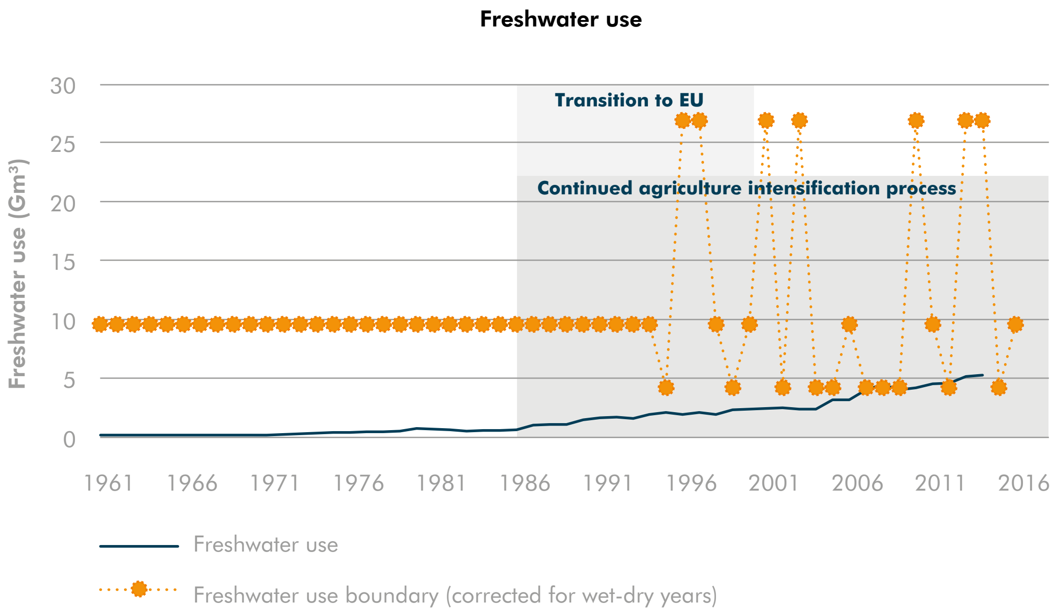


Trendlines added to aid interpreting fertiliser flows.

Freshwater use

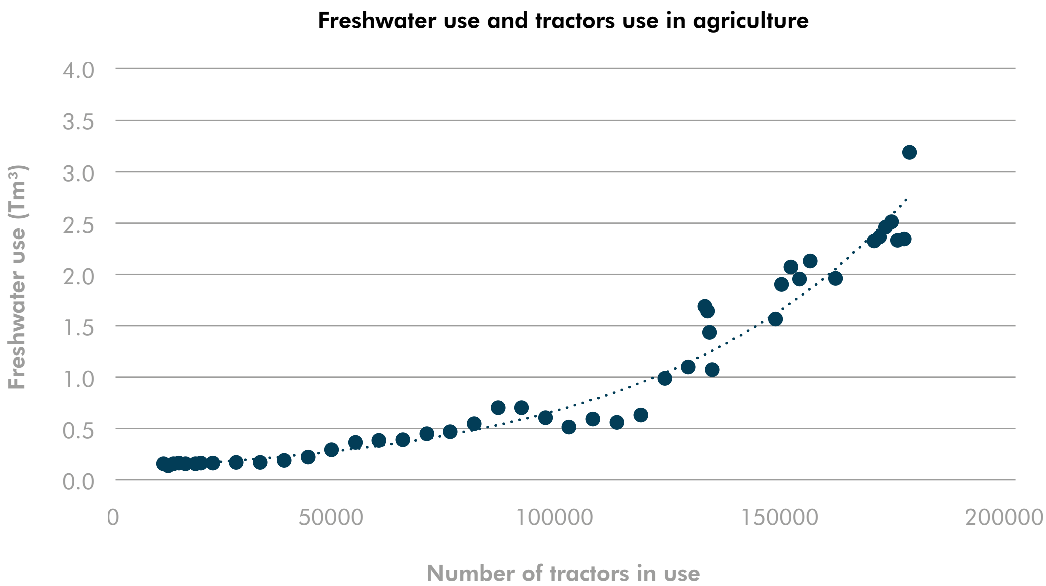
Water consumption has greatly increased from the period of transition to the EU and has been increasing since then, in contrary to the agricultural area. This is because water consumption is linked with the intensification of agriculture, rather than the area itself (i.e., it is proportional to the irrigated area, rather than the agricultural area as a whole). This is visible in Figure 36, where the increase in freshwater use goes together with the increase in tractors used in agriculture. The increase in the number of tractors is a sign of an intensification of agriculture.

Figure 35
Freshwater use and the main agricultural policy shifts in Portugal



Between 1961 and 1994 there was no data available for hydraulicity index, therefore, those years were assumed as normal years (hydraulicity index=1). The result is a constant boundary between 1961 and 1994.

Figure 36
Freshwater use and the use of tractors in agriculture (intensification of agriculture)



Source of data: FAOSTAT.

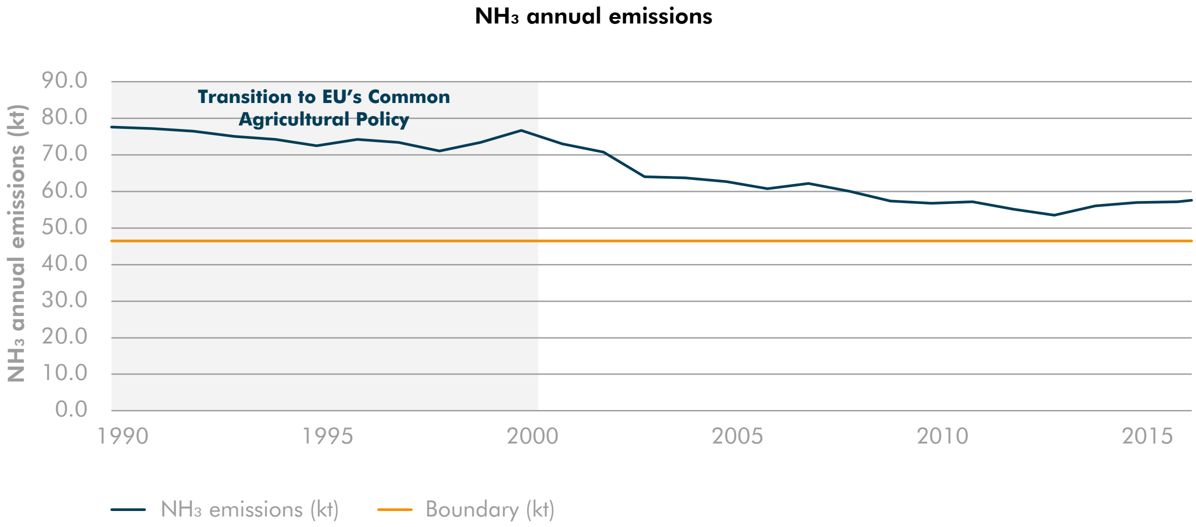
Air pollution

NH_3 emissions

Figure 37 presents the ammonia emissions trends and maps the main agricultural policy shifts in Portugal. Ammonia emissions present an apparent unaffectedness to the policy change introduced by the EU, maintaining its decreasing trend similarly to agricultural areas. Given the inexistence of data prior to 1990, we cannot observe the effect that the political regime shift of 1974 might have had in ammonia emissions, however, we can deduce that emissions were increasing prior to 1990 and started to decrease from 1990 onwards, in resemblance to the trends observed for agricultural areas and nitrogen fertiliser use.

Figure 37

Ammonia emissions and the transition of Portugal into the EU



Fertiliser use contributes with ammonia emissions and GHG emissions. In both pollutants, this relationship is not a direct one, as we can see from Figure 38. Nitrogen from fertilisers needs to be dissolved in water (from air or from soil) giving origin to ammonia. With GHG emissions, nitrogen from fertiliser first volatises into nitrous oxides and then it converts into nitrous oxide, which is a GHG. The more (or less) nitrogen fertiliser used, the more (or less) ammonia emissions there will be, although with some variability. This is visible in both Figure 38 and Figure 39. What we can also see is that the higher the agricultural area (and lower the lower the grazing area), the more ammonia emissions we have, this is due to a potential link between area used for agriculture and fertiliser use. With GHG emissions, the fact that it is an undirect effect and the fact that other emissions from animal production have also a significant contribution to GHG emissions (as discussed before), the effect is somehow diluted.

Figure 38
Nitrogen fertiliser and GHG emissions from agriculture and ammonia annual emissions

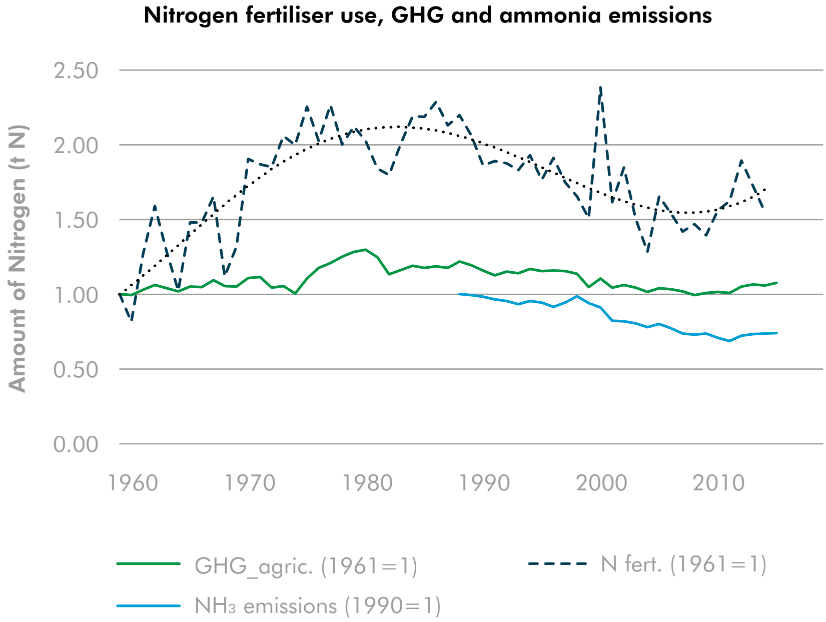
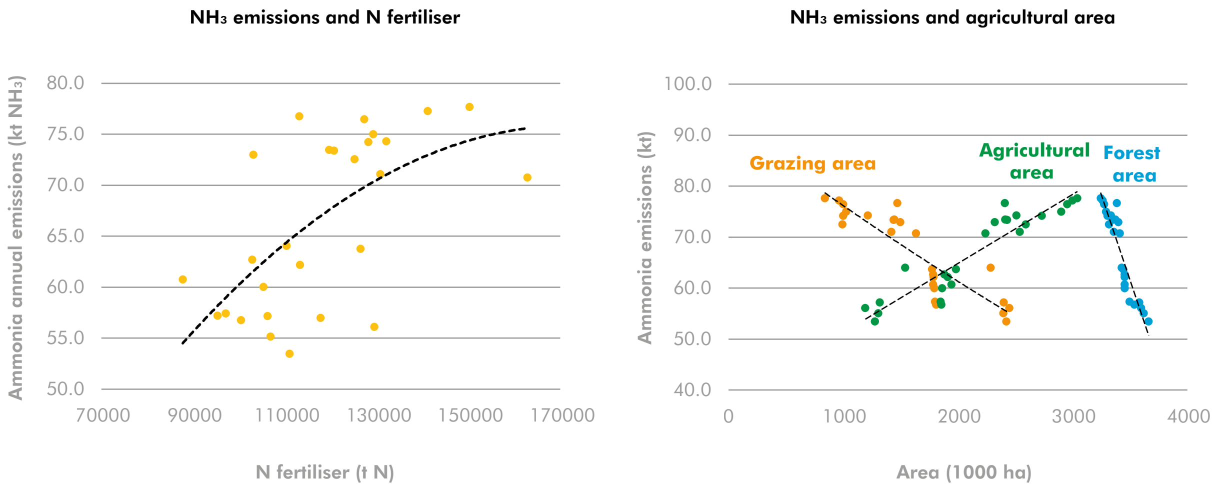


Figure 39
Relationship between ammonia emissions and nitrogen fertiliser and land use

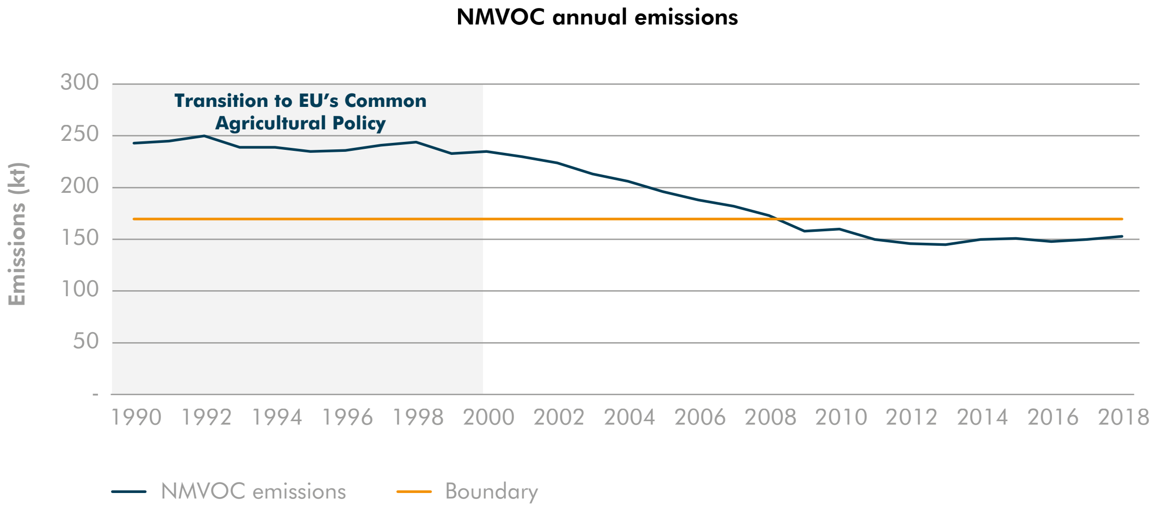


NMVOC emissions

NMVOC emissions have declined from 2000 onwards, which corresponds to the period of the end of the transition period of Portugal into the EU's CAP (Figure 40). This is linked with the fact that agricultural areas in Portugal have been declining during the same period.

Figure 40

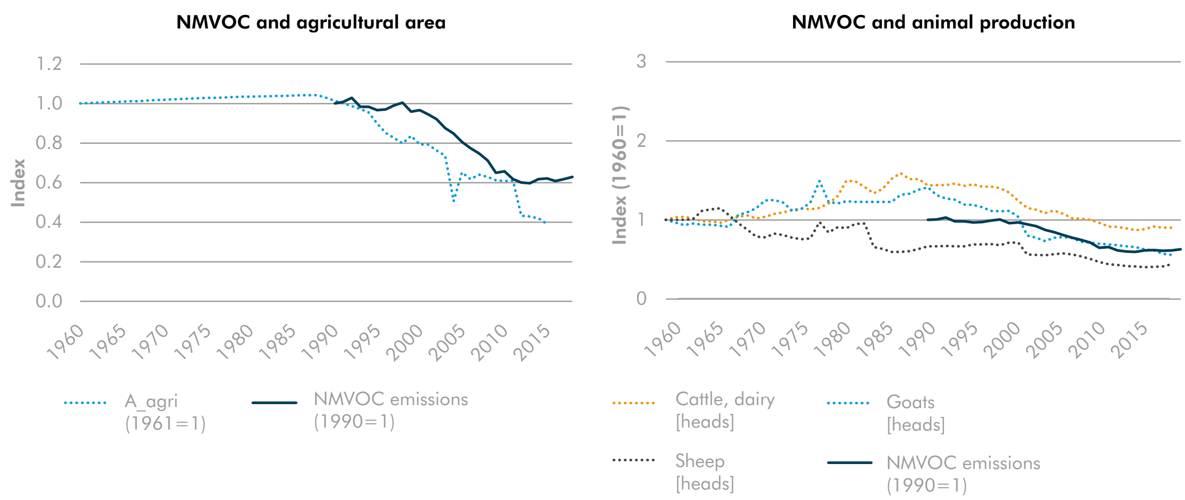
NMVOC and the transition to EU agricultural policies



In general, NMVOC emissions have a pattern like the size of the agricultural area in Portugal (Figure 41). The size of the agricultural area in Portugal is a proxy for the size of agricultural activities such as tillage and silage, and a proxy for wind erosion from uncovered soils. This area started to decrease with the Portuguese transition to the EU's CAP and therefore, NMVOC emissions have also decreased. NMVOC emissions are also linked with manure management practices and grazing and therefore, the reduction in the numbers of animals typically produced in extensive farming (grazing) result in a reduction in the emissions of NMVOC.

Figure 41

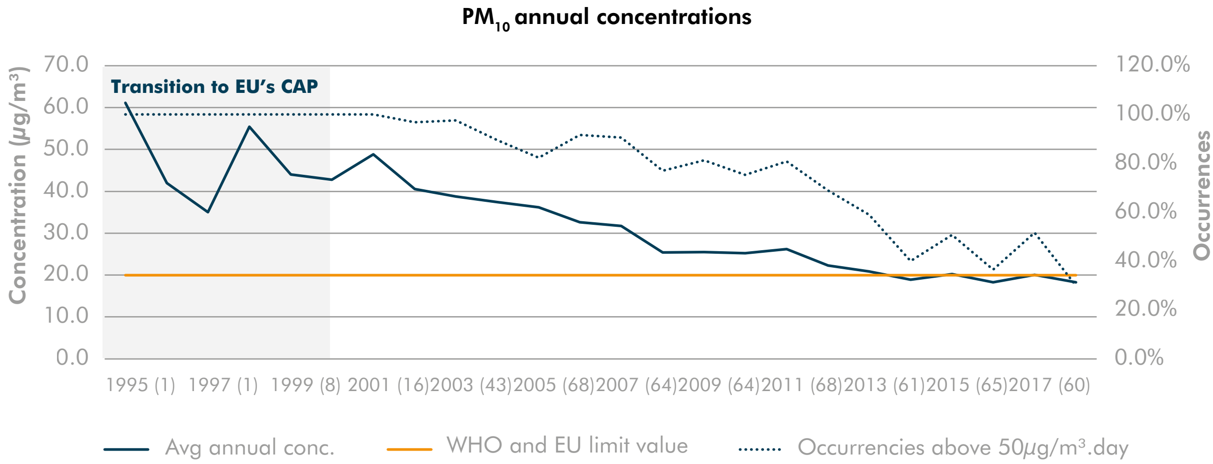
NMVOC emissions and agricultural area (left) and animal numbers (right)



PM_{10} concentrations

PM_{10} annual concentrations have declined from 2000 onwards, which corresponds to the period of the end of the transition period of Portugal into the EU's CAP (Figure 42). This is linked with the fact that agricultural area in Portugal has been declining during the same period.

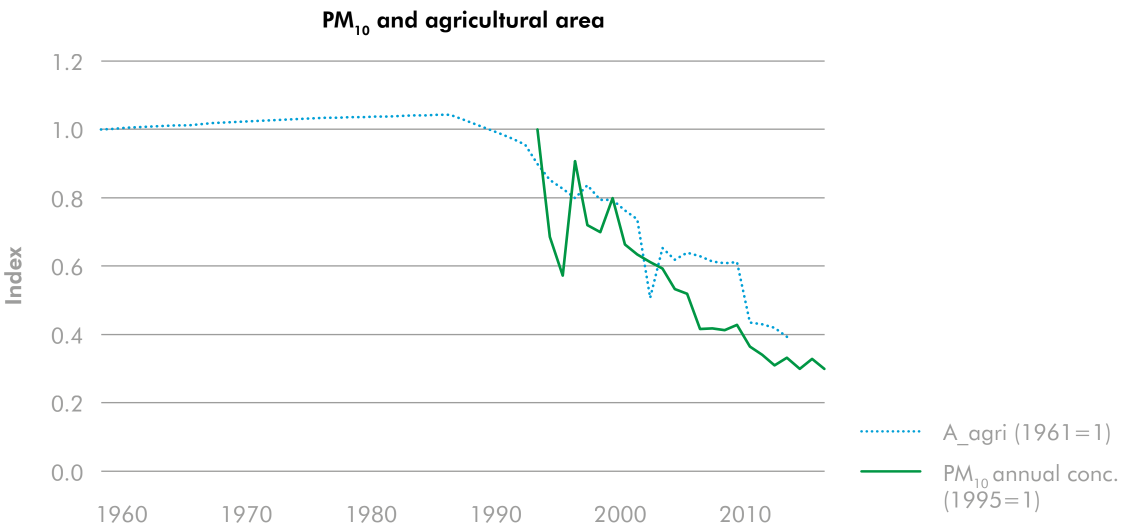
Figure 42
PM_{10} annual concentrations and the transition period to the EU's CAP



CAP – Common Agricultural Policy.
Occurrences refer to the number of stations above the limit value divided by total number of stations (number between brackets in the x axis).

PM_{10} emissions tend to increase with soil tillage, silage, and wind erosion, which are strongly linked with agricultural areas. Agricultural area has been declining since the transition period to the EU and PM_{10} concentrations follow a similar trend (Figure 43).

Figure 43
PM_{10} concentrations and agricultural area in Portugal

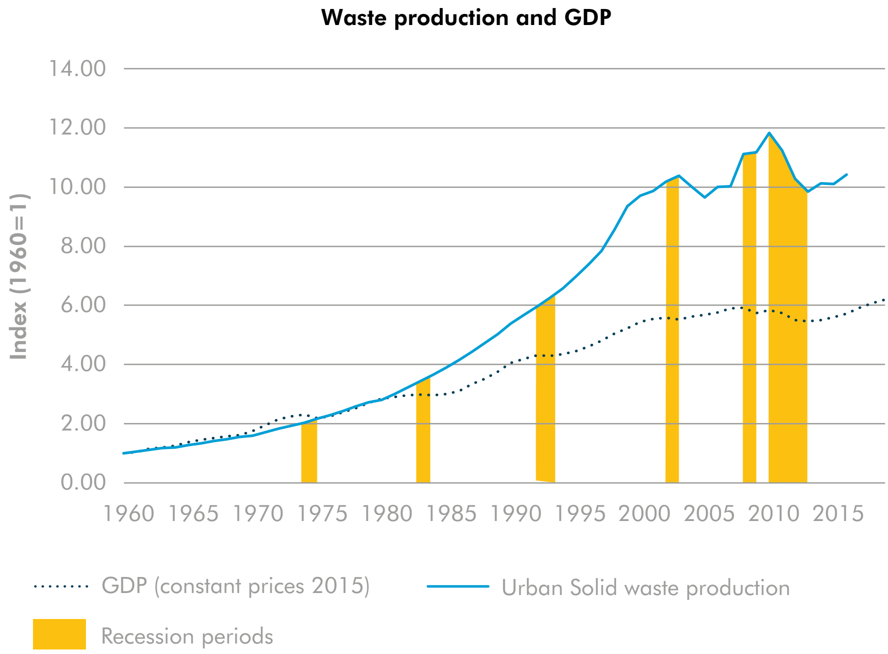


3.2.5 Waste Policies

Waste policies, together with GDP, influence waste production and disposal. Our explanatory hypotheses are that (1) GDP growth is the main contributor to the increase in waste production and wastes disposed and (2) waste policies promoting waste treatment have contributed to softening the trends in waste disposal. A review on the waste policy in Portugal is presented in the Technical Notes (section 7.2.8).

In general, we can see that waste production is linked with GDP. Growth in GDP led to increases in the amount of wastes and their disposal. Decreases in GDP (due to economic recessions) led to reductions in waste production and waste disposal (Figure 44).

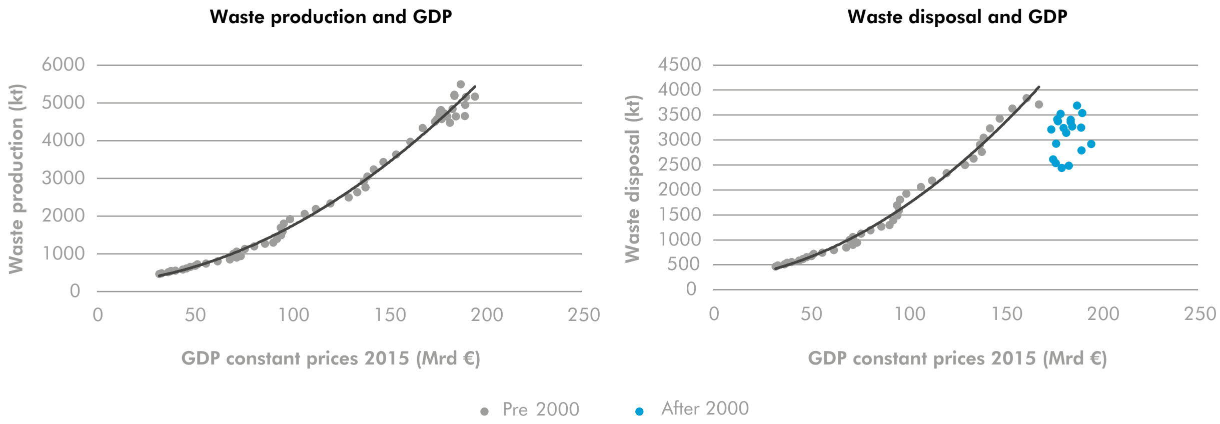
Figure 44
Waste production and GDP through time



The relationship between GDP and waste disposal is not as direct as for wastes production. Up until 2000, the relationship is almost linear (Figure 45), where waste produced is sent for disposal (landfill) without much prior treatment. From 2000 onwards, the investments in material, biological and energy valorisation broke this relationship with GDP, as there was a lesser amount of wastes per GDP being sent to disposal. Hence, the introduction of policies on waste treatment and disposal had a significant effect in terms of softening the effects of GDP in waste disposal. As there are no policies on waste production for the period under analysis, similar cannot be concluded for waste production.

Figure 45

Relationship between municipal waste production (left) and disposal (right) with GDP



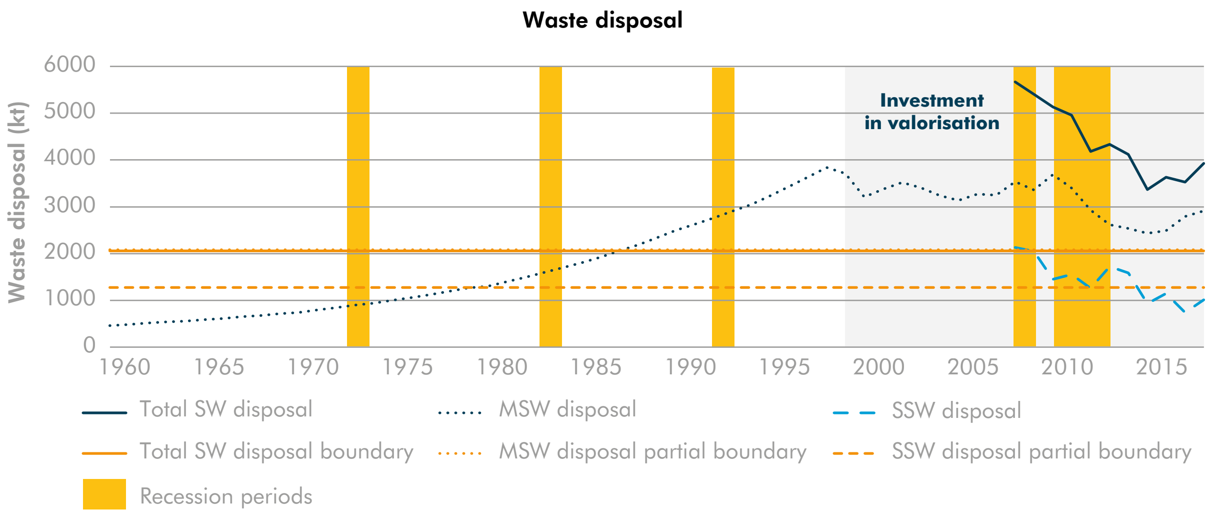
Trendlines added to aid interpretation.

The policies that have been being implemented in Portugal, and that affect waste disposal, were:

- Improvement in waste collecting systems. Waste collection systems have increased from 40% in the 60s to 100% in 2000 (APA, 2019a), more waste was being reported until 2000, so part of the increase in waste production until 2000 can also be related to the increase in waste reporting.
- The introduction of waste incineration (two plants introduced in 1999 in mainland Portugal, 1 in Madeira in 2001 and one in the Terceira/Azores in 2015), improvement in recycling rates (that started to increase from 2000 onwards) and the introduction of biological treatment and recovery processes (2007-2016) all contributed to a reduction in wastes disposal (Figure 46).

Figure 46

Main waste policy events and the amounts of waste treated and disposed



SW – solid waste; MSW – Municipal solid waste; SSW – Sectoral solid waste.

3.3 KEY MESSAGES

The main factors identified leading to the observed trends in the indicators analysed were:

- GDP dynamics,
- Partial decoupling of the biophysical indicators from GDP has been obtained through policies promoting the decarbonisation of electricity; energy efficiency (for industry and buildings); cleaner vehicles and fuels; regulating the production and consumption of ozone depleting substances; policies on waste valorisation.
- The agricultural policies associated to entering the EU (from 1986).

3.3.1 GDP dynamics

GDP dynamics (growth and recession) affect indirectly the biophysical indicators as it is a result from private consumption and family income, which lead to increased energy demand, road transport, production activities (industrial activity), consumption (of products but also of water) and waste production and disposal. GDP, as it is linked with production and consumption activities, is the main cause of transgressing the boundaries in the biophysical indicators analysed. This is valid for most of the indicators analysed (except for the agriculturally linked indicators such as the pressure on ecosystems, water pollution and freshwater use), and assumes particular relevance for the waste production and disposal indicators.

Waste production and disposal are above the boundary. These indicators have been following GDP trends. The case for waste production, it had decreased with the last economic recession (2010-2013), but it has gone back increasing with the recovery of the economy, in particular as this recovery is linked with an increase in tourism, which is a sector with high waste production (APA, 2019a). Waste disposal, on the other hand, has decoupled from GDP in the year 2000 (just at the end of the last economic growth period). This decoupling is linked with the promotion of waste recycling and with the introduction of waste incineration plants in Portugal. Waste provides two examples, one with the absence and the other with the presence of policies and its effect in terms of decoupling wastes from GDP.

GDP influences almost all variables analysed in certain interval periods. We have found a strong relationship between GDP and (1) GHG emissions from energy industries until 2005, when decarbonisation policies started influencing electricity production; (2) industry energy demand until 2002; (3) households and services until 2005; (4) road transport emissions until 2004; (5) waste production in all years analysed (1960-2018); and (6) waste disposal until 2000 (date when recycling rates started becoming significant and incineration was introduced).

The last recession, between 2010 and 2013, led to reduced industrial activity, leading to an increase in unused CO_2 licenses which led to a reduction of the price of the licenses to emit CO_2 in the European Emission Trading Scheme (EETS). This effect was visible because at the same time, coal international prices decreased due to an international increase in supply. The recession also led to a reduction in road travel. The recession also led to a reduction in the emission and concentration of air pollutants (e.g., SO_x NO_x, $PM_{2.5}$ and NH_3).

3.3.2 Policies leading to a decoupling between GDP and the biophysical indicators

Many policies have been implemented since the 90s that have had a contribution to the biophysical indicators analysed. We are referring to policies promoting the decarbonisation of electricity, road transport and waste disposal; energy efficiency measures (for industry and buildings); policies promoting cleaner vehicles and fuels; policies regulating the production and consumption of ozone depleting substances (ODS); policies on waste valorisation.

We have found that:

- Decarbonisation policies had a strong effect on air pollution from 1997 and on GHG emissions (from energy industries) from 2005 with the introduction of natural gas and investment in renewable sources of electricity,
- Energy efficiency measures had a strong effect in terms of GHG emissions from manufacturing industries from 2002 onwards, when these policies started to have a significant effect; and on building energy efficiency from 2005,
- Policies for cleaner fuels and transport have had a strong effect on air pollutants from road transport from 2004 onwards,
- Waste policies, in particular the ones promoting recycling and incineration, have had a significant effect from 2000 onwards on waste disposal.

One example of such policies, which had a great deal of relevance, was the introduction of natural gas in Portugal, in 1997, which had a transversal impact across environmental indicators affecting climate change and a series of air pollutant concentrations. Natural gas replaced oil in electricity generation, butane gas in household and services, and influenced the manufacturing industry. This affected positively GHG emissions (overall, and in particular GHG emissions from electricity production, energy use in manufacturing industries and energy use in residences and services) and air pollutant emissions (namely PM_{10}, SO_2, NO_2, NMVOC, and NH_3).

3.3.3 Agricultural policies

Prior to Portugal joining the EU, there was a growing intensification of agriculture with increased use of fertilisers and machinery and lead to a generalised increase in animal production. This was mainly a result of agricultural policies implemented during the 60s to improve agricultural income, resulting in the intensification of agriculture (Branco 2015). The result was a slow increasing trend in in GHG emissions from agriculture, pressure on ecosystems and fertiliser use (N and P flows).

Portugal joined the EU in 1986. The Portuguese transition period to the EU Common Agricultural Policy (CAP, between 1986-2000) and the internationalisation of the EU agricultural market (in 1993) led to first a decrease in agricultural production followed by an intensification of agriculture (namely seen in the increased N input per unit area) in the more productive and irrigated areas and extensification or abandonment elsewhere. Agricultural areas and animal production decreased. The exception is for more intensive forms of animal production such as non-dairy cattle which increased (and, later, swine production also increased). The result is a decreased trend in pressure on ecosystems, fertiliser use in total, NH_3 and NMVOC emissions (due to manure management, grazing and fertilisation) and PM_{10} concentrations (due to grazing and ploughing).

3.3.4 Summary

Table 14 summarises the main events that contributed to the biophysical indicators analysed.

Table 14
Summary of main factors affecting the biophysical indicators

Sector[1]	Main events	Effect of the sector in the biophysical indicators
Electricity sector The amount of oil and coal used in power generation	• Demand for electricity, • costs of coal use (coal and CO_2), • the introduction of natural gas, • the decision to eliminate oil from electricity mix, and • the investments in renewable sources of electricity.	**Climate change** GHG emissions increase with the use of oil and coal. **Air pollution** PM_{10}, SO_x, NO_x, NH_3 and NMVOC increase with the use of oil and coal.
Manufacturing industry Fossil fuel demand; some industrial processes emit GHG (CO_2, SF_6), NO_x, NH_3 and SO_2.	• Demand of energy, • Introduction of natural gas, • Energy efficiency measures for manufacturing industries, • Air quality emission standards, • International agreements on stopping the production of equipment with ODS	**Climate change** GHG emissions increase with energy demand (but decrease with the use of natural gas and renewables sources of energy) and with GDP. GHG emissions also decrease with energy efficiency measures. **Air pollution** As $PM_{2.5}$, SO_2, NO_x, NH_3 and O_3 increase with increased industrial activity. Air quality policy contributed to their continuous monitoring and reduction.
Household and services Fossil fuel demand; water demand; use of equipment with ODS.	• Demand of energy, • Introduction of natural gas, • Energy efficiency measures for buildings, including renewable energy production, • International agreements reducing equipment with ODS and regulations on maintenance and disposal of such equipment.	**Climate change** GHG emissions increase with the use of fossil fuels. Natural gas introduction and energy efficiency measures promoted a reduction in GHG emissions. **Ozone layer depletion** ODS are reduced by the reduction in consumption, certified maintenance, and disposal of equipment containing ODS.

Sector[1]	Main events	Effect of the sector in the biophysical indicators
Road transport Fossil fuel consumption and efficiency of vehicle technology	• Family income (linked with the economy), • Investment in infrastructures by government – road infrastructure and EV charging points, • Incorporation of biodiesel in fuels (from 2006) • Introduction of catalytic converters in gasoline vehicles, • Incentives for car abatement and substitution, • Taxes on CO_2 emitted by vehicles, • Incentives for the acquisition of electric and hybrid vehicles.	**Climate change** GHG increase with fossil fuels increase. **Air pollution** PM_{10}, CO, NO_x, NH_3 and O_3 are linked with fuel consumption and vehicle technology (e.g., catalytic converters in vehicles).
Agriculture sector Animal production (intensive and extensive), and crop production (fertiliser use, soil tillage and silage)	• Transition to EU's Common Agriculture Policy (CAP - 1986-2000), • Internationalisation of the European agriculture market (1993), • After the transition to CAP (with the end of the reduction of EU subsidies on production)	**Climate change** GHG emissions increase with animal production and nitrogen fertiliser use. **Ozone layer depletion** N_2O emissions (an ODS) from the use of nitrogen fertilisers. **Pressure on ecosystems** Pressure on ecosystems increases with agricultural area. Intensification or abandonment of agriculture reduces the pressure on ecosystems. **Water pollution** N and P emissions increase with increased fertiliser use. **Freshwater uses** Freshwater uses increase with intensification and mechanisation of agriculture. **Air pollution** PM_{10}, NMVOC and NH_3 increase with grazing animals (extensive farming) and agricultural area land. Agricultural intensification lead to decreases of air pollutants.
Waste sector Amount of waste produced and disposed	• Consumption activities (linked with GDP), • Introduction of wastes' material recycling • Introduction of incineration plants • Introduction of composting facilities	**Waste production and disposal** Increased valorisation of wastes (recycling, incineration, and composting) leads to reduced amounts of disposed wastes.

1. Ozone layer depletion is included in the manufacturing industries and household and services.

4. INTERGENERATIONAL ANALYSIS

The aim of the work in this Chapter was to estimate the impact of biophysical resource use by different generations, providing insights into what each generation received from the previous generation and left to the next. This was made by allocating the impacts and the boundaries to different generations.

4.1
APPROACH FOLLOWED

To explore how much each generation has used in terms of biophysical resources and how much it is leaving to the next generations, annual impacts were allocated to the population using an age-based consumer profile per year. For this, birth-cohorts and generations were used. In the next sections, birth-cohorts and generations are defined, and the method used for the analysis.

4.1.1 Birth cohorts and generations used in the analysis

25 birth cohorts were defined, based on 5-year intervals, covering all cohorts living between 1960 and 2020. The cohorts are defined in:

- Table 15, which presents the cohorts born before 1945,
- Table 16, which presents the cohorts born between 1945 and 1949, often referred to as post-World War II baby boomers (baby boomers or bb, hereafter),
- Table 17, which presents the cohorts born between 1960 and 1979, often associated with the Generation X (Gen X, hereafter),
- Table 18, which presents the cohorts born between 1980 and 1999, also named as Generation Y (Gen Y) or Millennials, and
- Table 19, which represent the cohorts born after 2000, referred to as Generation Z (or Gen Z).

To make it easier for the interpretation of results, the nomenclature for birth-cohorts was the following: "C" from cohort, and "number" reflecting the age of the youngest member of the cohort in 2020. Given the period of analysis (1960-2020), this means that not all cohorts are complete; in fact, only the cohorts C56 to C41 are complete.

Generations, as used here, are aggregations of birth-cohorts. Five generations were considered: Pre-WWII divided in the groups C121-C101 and C96-C81, Baby Boomers (C76-C61), Generation X (includes birth cohorts C56-C41), Generation Y (includes birth cohorts C36-C21) and Generation Z (includes birth cohorts C16-C01). The birth-cohorts included in each are presented through Table 15 to Table 19.

Table 15
Cohorts born before WWII

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C121	-	1895-1899	1910-1914	**1960-1964**
C116	-	1900-1904	1915-1919	**1965-1969**
C111	-	1905-1909	1920-1924	**1970-1974**

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C106	-	1910-1914	1925-1929	**1975-1979**
C101	-	1915-1919	1930-1934	**1980-1984**
C96	>96	1920-1924	1935-1939	**1985-1986**
C91	>91	1925-1929	1940-1944	**1990-1994**
C86	>86	1930-1934	1945-1949	**1995-1999**
C81	81-85	1935-1939	1950-1954	**2000-2004**

Bold: years in the period of analysis.

Table 16
Cohorts usually referred to as Baby Boomers

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C76	76-80	1940-1944	1955-1959	**2005-2009**
C71	71-75	1945-1949	**1960-1964**	**2010-2014**
C66	66-70	1950-1954	**1965-1969**	**2015-2019**
C61	61-65	1955-1959	**1970-1974**	2020-2024

Bold: years in the period of analysis.

Table 17
Cohorts usually referred to as Generation X

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C56	56-60	**1960-1964**	**1975-1979**	2025-2029
C51	51-55	**1965-1969**	**1980-1984**	-
C46	46-50	**1970-1974**	**1985-1989**	-
C41	41-45	**1975-1979**	**1990-1994**	-

Bold: years in the period of analysis.

Table 18
Cohorts usually referred to as Generation Y

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C3	36-40	**1980-1984**	**1995-1999**	-
C31	31-35	**1985-1989**	**2000-2004**	-
C26	26-30	**1990-1994**	**2005-2009**	-
C21	21-24	**1995-1999**	**2010-2014**	-

Bold: years in the period of analysis.

Table 19
Cohorts usually referred to as Generation Z

Cohort	Age in 2020	Year of birth	Year when 15 years old	Year when 65 years old
C16	16-20	**2000-2004**	**2015-2019**	-
C11	11-14	**2005-2009**	**2020 -**	-
C06	6-10	**2010-2014**	-	-
C01	1-5	**2015-2019**	-	-

Bold: years in the period of analysis.

To determine the number of citizens by age in each birth-cohort, population numbers from 1971 to 2019 from PORDATA were used. Population numbers per year was aggregated into 5-year intervals, apart from the first interval (1971-1974), where only four years were included in the interval. Based on age and year of the age we were able to determine how many members of each birth-cohort existed in each year. The result was a profile of the number of members of each cohort per age.

4.1.2 Procedure for allocation of impacts to birth-cohorts and generations

The allocation of impacts was made using the age distribution of the household heads through time. This approach differentiates age groups based on their probability of being a household head, and therefore, being responsible for the spending of the household. With this approach, the age groups that have higher numbers of household heads in a particular year will be allocated with a higher share of the environmental impacts. We have used the age distribution of the head of the household available from the national statistics office (INE 1971, 1986, 2008 and 2017). Head of the household is defined as the member of the household with the highest earnings. We have used the age-distribution of the head of the household because (1) we assume that having higher income in the household, the head of the household will have most responsibility in the consumption decisions in the household and (2) we assume that the household is a good unit to analyse consumption.

We have additionally made two corrections to the head of the household age-distributions: (i) ages within compulsory schooling age were allocated zero impact; and (ii) from 60 years of age to 80 years of age, the share of impacts decreased to zero, reaching zero at 80 years of age. This later assumption assumes that from 80 years of age there is no head of household.

The data sources used were:

- Age-distribution of the head of the household in Portugal: INE (1971, 1986, 2008, 2017).
- Years of compulsory education in Portugal: Ministério da Educação (Ministry for Education).

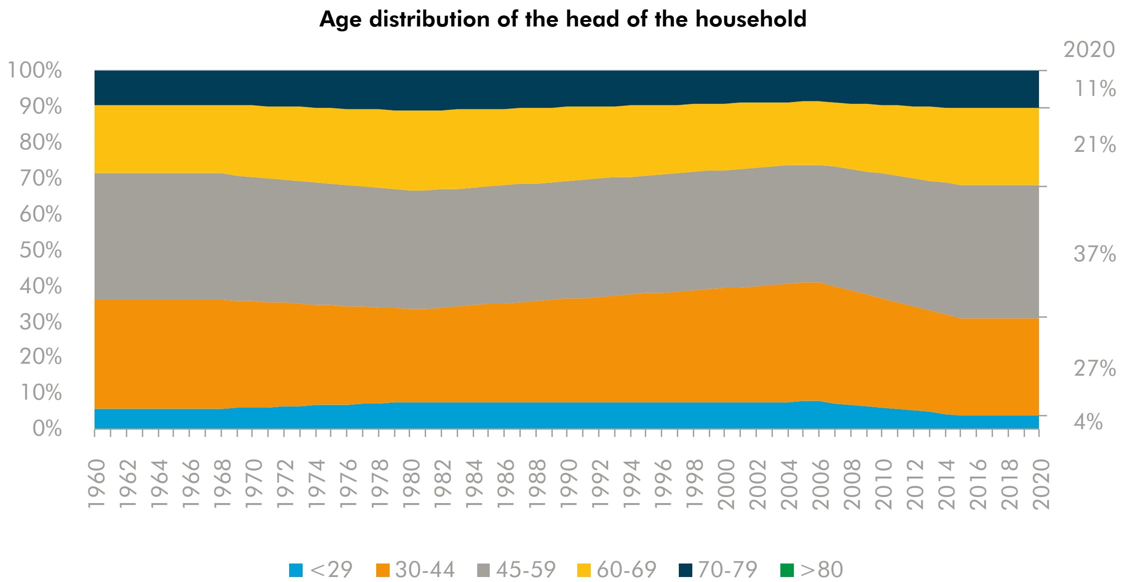
Age-distribution of the head of household was only available for four years. The first step was to complete the time series using a linear transition in the intervals between available data.

In a second step, we decomposed the youngest age group from INE ("<=29") into two groups: from 0 to *x* and from *x+1* to 29, where *x* is the age when finishing compulsory education, which varied through time. For the impacts associated with the interval from 0 to *x* we have allocated zero impact, for the interval between *x+1* and 29, we have allocated the share in household spending for the group <=29.

Finally, we decomposed the oldest group (">=60") into three age groups: 60-69, 70-79, and over 80. For the "over 80" group we attributed zero impact. For the group 70-79 we attributed 1/3 of the household spending for the age group ">60"; and for the age group 60-69 we have attributed 2/3 of the impact of the household spending for the age group ">60".

The resulting shares from this approach are presented in Figure 47.

Figure 47
Age distribution of the head of the household



Legend refers to age groups. Data source: own calculations based on INE

Each yearly estimated biophysical indicator was multiplied by the shares of household spending per age group of the head of the household, per year, with the corrections above. The result is the impact per age group per year.

After aggregating the years into 5-year intervals, each impact per age group per year was divided by the population in each age group in each year obtaining an impact per person, per age group per year. By doing this, we are assuming that the impact of a cohort is equal to the impact of the heads of households who belong to that cohort as we do not know who in that cohort is head of a household and who is not. By assuming an average impact to all members of the cohort, we are accounting for the probability of a member of the cohort being a head of a household or not.

Two other allocation procedures were explored. These were:

- Allocating annual impacts by the population living in that year (Approach 1),
- Allocating annual impacts by the population working in that year (Approach 2).

From the three approaches, the one that revealed to be more complete (in terms of including a larger number of variables) was the one we have followed throughout this study. The remaining approaches are detailed in the Technical Notes (section 7.3.1).

4.1.3 Analysis of results

Generations were compared against each other within each environmental impact. This allowed knowing the impact of each generation and how well or not each generation performed relatively to the other generations. The biophysical indicators considered here included climate change (for total emissions), pressure on ecosystems, N and P flows, freshwater use, air pollution (only annual emissions from $PM_{2.5}$, SO_2, NO_2, NMVOC, NH_3 and concentrations from O_3 (8h-mean) and $PM_{2.5}$ (1-day mean) were considered, as the remaining ones are either linked to these ones or are on the safe zone) and waste production and disposal.

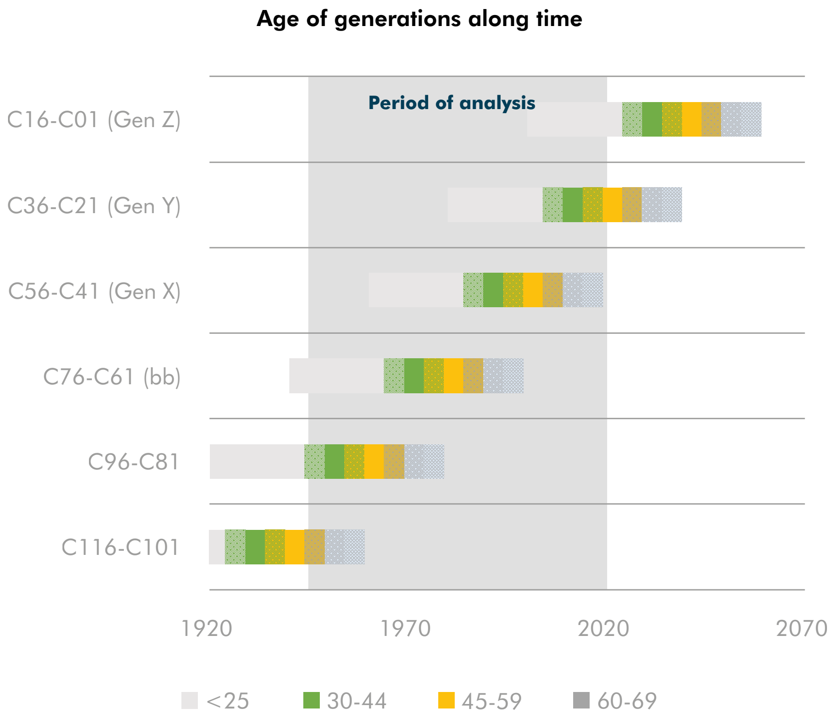
Generations' impacts were also compared to a "generation boundary". This gives an indication of how much biophysical resources and services each generation is leaving to the next generations. The "generational boundary" was estimated based on the boundaries for each indicator, allocating it to each generation and age group using the same approach described for the biophysical indicators themselves (i.e., using the consumer age profile).

4.2 DETAILED INTERGENERATIONAL IMPACTS

What we have seen from the results is that the impact a certain generation has depends on two factors: (1) the consumption profiles assumed for calculations (consumption per age group) and (2) the trends observed in the environmental impacts themselves (impact per year).

The consumption profiles assume higher impacts to generations between 30 and 70 years of age (Figure 47 and Figure 48). Older generations have had many years in these age groups, in particular baby boomers (C76-C61) and pre-baby boomers (in particular, the group C96-C81). Therefore, we would expect these generations to have higher impacts just because the period where their consumption per capita was highest is being considered in this analysis. But the dynamics of the indicators (when they were high and when they were low) also has a significant contribution to the results. The combination of these two factors results in the variety of the patterns observed in Figure 49, Figure 50 and Figure 51. Because of this, we cannot generalise that older generations (pre-baby boomers and baby boomers) have higher environmental impacts per capita than younger generations (generations Y and Z).

Figure 48
Ages of higher consumption levels per generation, through time

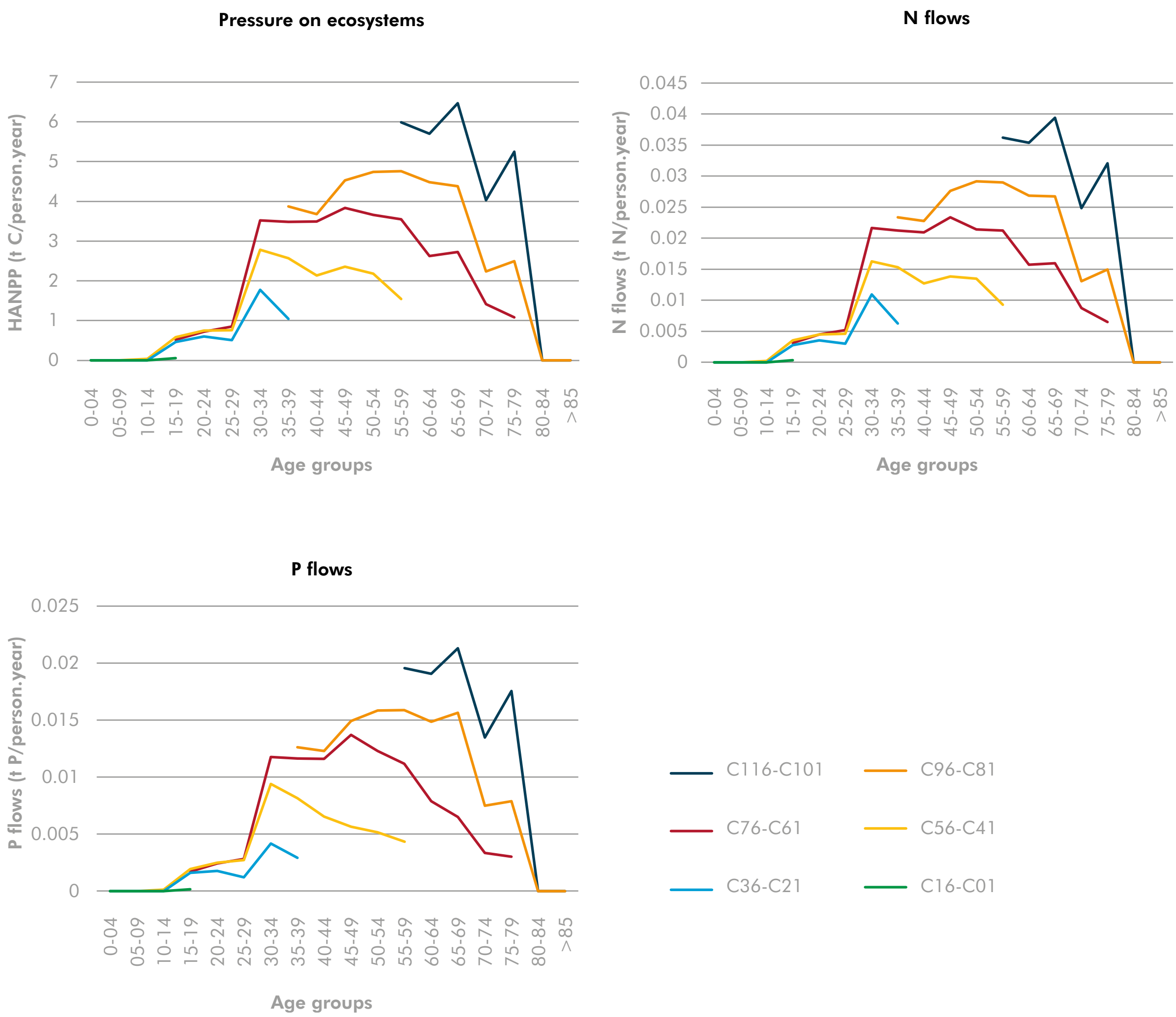


Transitions between ages are shaded as in these periods refer to generations with members in both age groups.

This is only observable for the pressure on ecosystems and N and P flows. For these indicators, the older the generation, the higher their impacts. In all these indicators the variability is small, and these have increased until 86-2000 and been decreasing since then. This combined with the consumption age-profiles of the generations leads to the patterns that older generations have higher impacts (Figure 49).

Figure 49

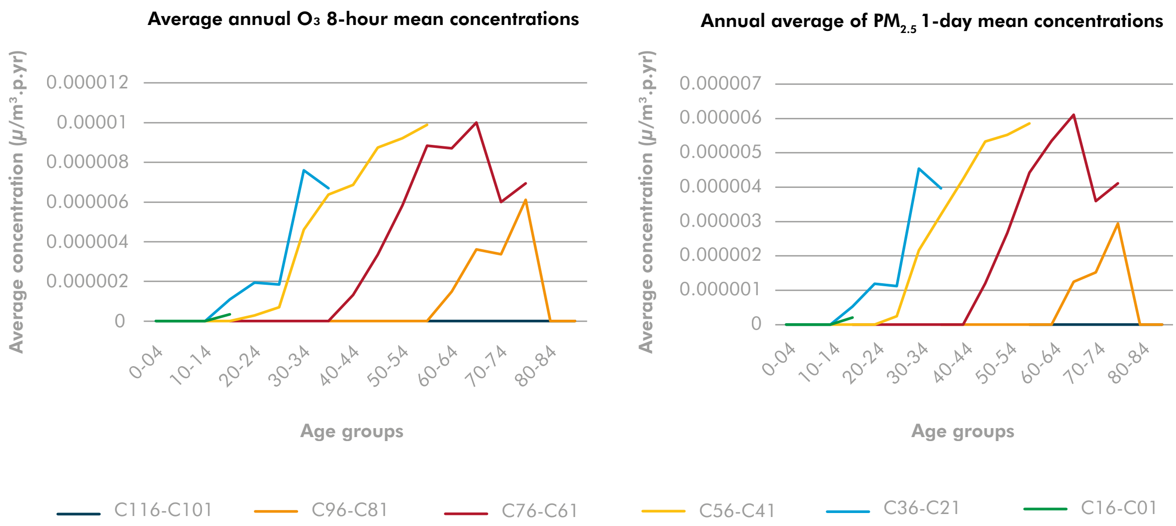
Impacts per generation and per age group for pressure on ecosystems, N and P flows



For the remaining environmental impacts, depending on which age group we are looking at, the generation with higher impacts varies. What we can see is that for different age groups, different generations present the highest impacts.

For O_3 8-hour mean concentrations and $PM_{2.5}$ 1-day mean concentrations we find three generations (Baby Boomers (C76-C61) and generations X (C56-C41) and Y (C36-C21)) that have revealed the highest impacts for certain age groups. Generation X in particular have its impacts still increasing and which might be higher than Baby Boomers for the age groups from 60 years of age (Figure 50). Note that the oldest generation (C116-C101) and to some extend the generation C96-C81 have lesser or no impacts because data on air pollutant concentrations was only available from 1995 for O_3 and 2003 for $PM_{2.5}$, not capturing the ages when the generations were at consuming age.

Figure 50
Impacts per generation and per age group for air pollutant concentrations



Note that the oldest generation (C116-C101) and to some extend the generation C96-C81 have lesser or no impacts because data on air pollutant concentrations was only available from 1995 for O_3 and 2003 for $PM_{2.5}$, not capturing the ages when the generations were at consuming age.

For climate change, freshwater use, SO_2, $PM_{2.5}$, NO_2, NMVOC and NH_3 annual emissions, and waste production and disposal, four generations: pre-Baby Boomers (C96-81), Baby Boomers (C76-C61) and generations X (C56-C41) and Y (C36-C21), had a peak in their impacts in certain age groups (Figure 51). For the particular case of air pollutant emissions and concentrations, as data was only available from 1990 onwards, older generations have lesser or no impacts. This is just because of data and not because these generations have had no impacts.

Figure 51

Environmental impacts per capita, by age group

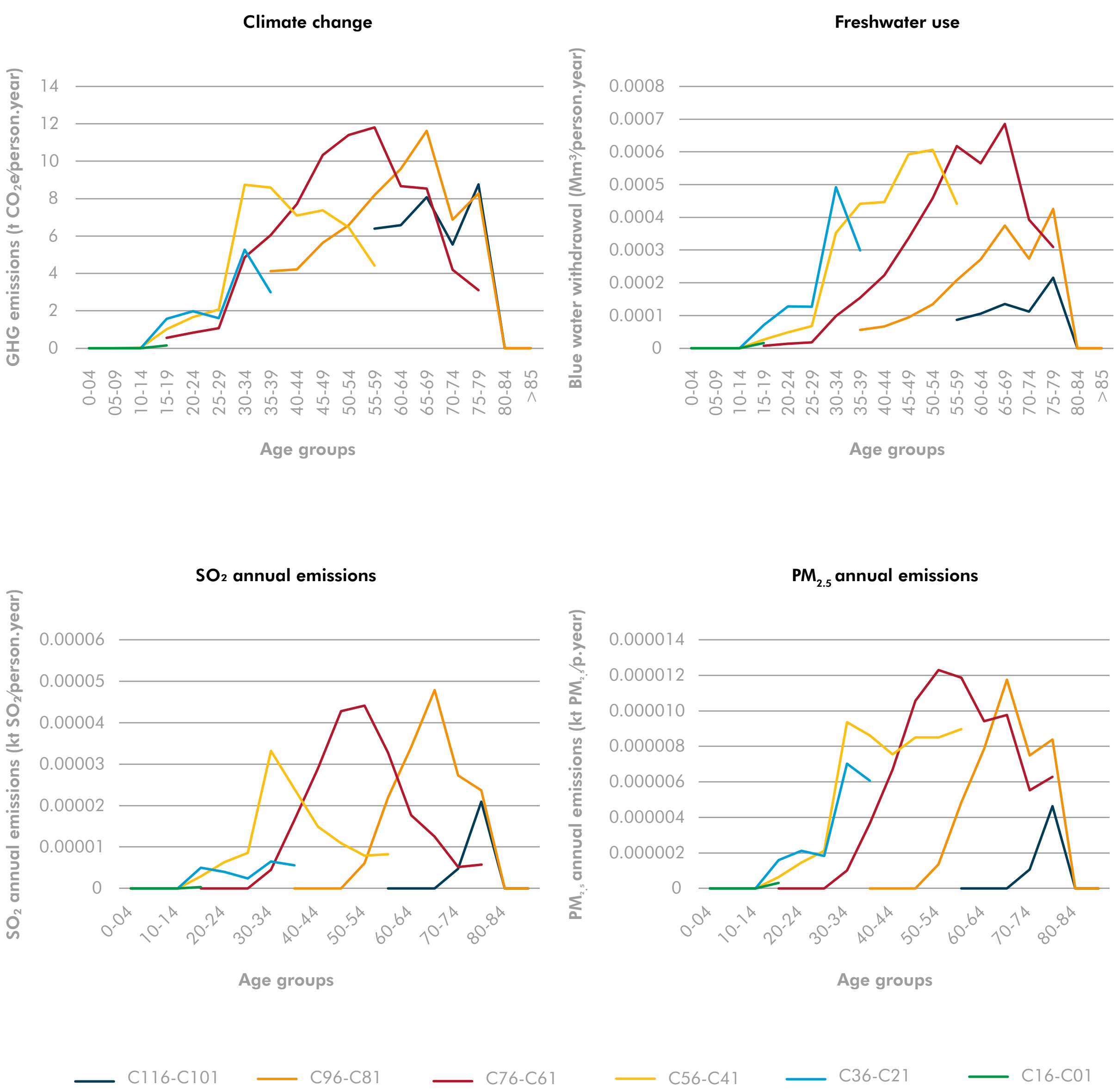


Figure 51
(cont.)

Although the impacts of some generations are lower than the ones from other generations for the same group of age, this does not mean that their impacts are low. In fact, most of the generations have their impacts high when compared to the boundary. This means that although some generations have considerably lower impacts, they still contribute to environmental impacts. This is relevant for all indicators, but particularly for climate change, where the boundary refers to a fixed budget/stock available until 2100 and where the more is used now (i.e., using more than the annual allowance), the less is available in the coming years (i.e., the annual allowance for next years will be reduced).

Figure 52 and Figure 53 present an example of this for four indicators: three indicators linked with GDP and decoupling policies implemented from 2000 onwards (climate change, waste production and waste disposal), and another indicator (pressure on ecosystems), related agricultural policies, namely, the Portuguese transition to the EU, and which follows a typical pattern of older generations having higher impacts of younger generations. For climate change, all generations present impacts above the boundary, including the youngest ones. Generation X (C56-C41), Babby Boomers (C76-C61) and Pre-Baby Boomers (C116-81) have the highest differences between the boundary and their actual impacts.

For the particular case of climate change, and as mentioned above (Section 2.4), in 2018 Portugal emitted more GHG than the annual GHG budget (limit), which resulted in a progressive reduction of this limit (becoming less available to be emitted until 2100). This means that present and future generations, in order to respect the ecological limit, will have a lower GHG emission budget than the generations living in 1960, a figure that is around 41-45% less. Take for example, between 1975-1979 (the first 5 years after the Portuguese political regime shift), the ecological limit for climate change was still 26.5 Tg CO_2e (=Mton), with GHG emissions still below the annual budget (using the limit "Fixed annual budget, with national updates"). Between 2015-2019, this limit was already at 15.1 TgCO_2e, with a reduction of 43% between these periods.

Overall, a citizen (or an age group) in 2018 had a lower emission budget than a citizen of the same age in previous years, according to Table 20.

Table 20
Changes in the ecological limit between different years and 2018

	Changes in the limit in 2018
Compared to 1961	-41%
Compared to 1970	-43%
Compared to 1980	-43%
Compared to 1990	-41%
Compared to 2000	-31%
Compared to 2010	-11%

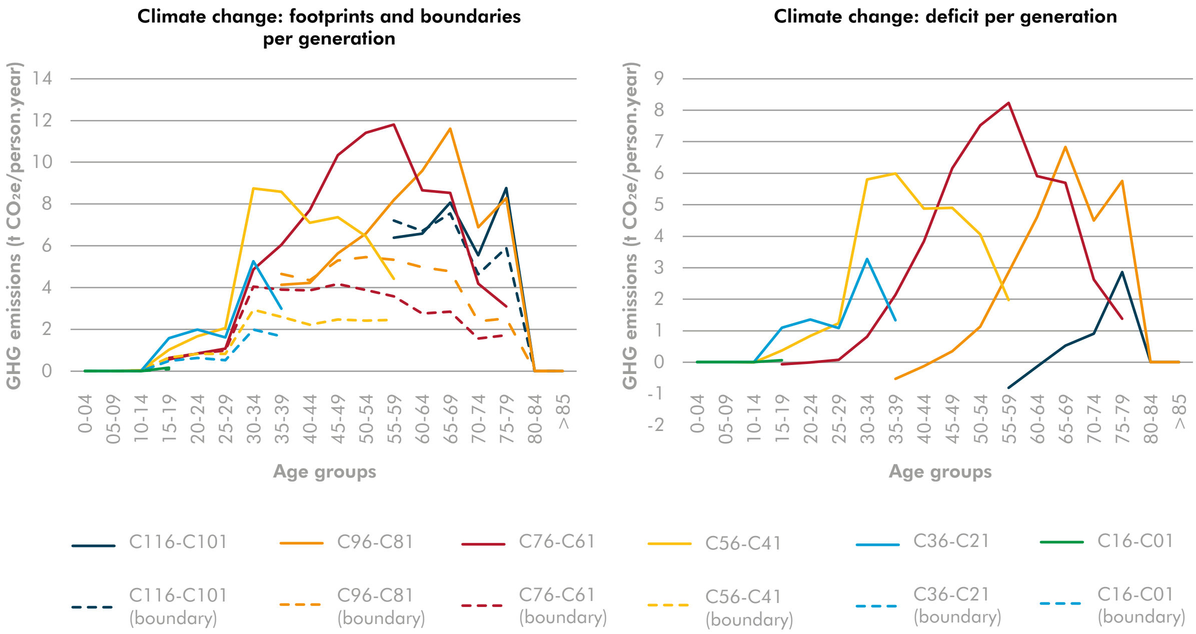
Based on the ecological limit "Fixed annual budget, with national updates".

For the pressure on ecosystems, the decrease of the limit when it is exceeded no longer happens. For the same age group (in different generations), the differences observed are only due to the fact that there are more or less people with that age to live in that period and the probability that they are heads of family.

For the pressure on ecosystems, the oldest generations present the highest differences between their impacts and the boundary, but all the generations, with exception of the youngest one (Generation Z - C16-C01), present values above the boundary. For waste production and disposal, the older generations (Pre-Baby Boomers - C116-81) and the youngest ones (generation Z - C16-C01) are the only generations whose impacts were below the boundary. The remaining generations have impacts above the boundaries.

Figure 52

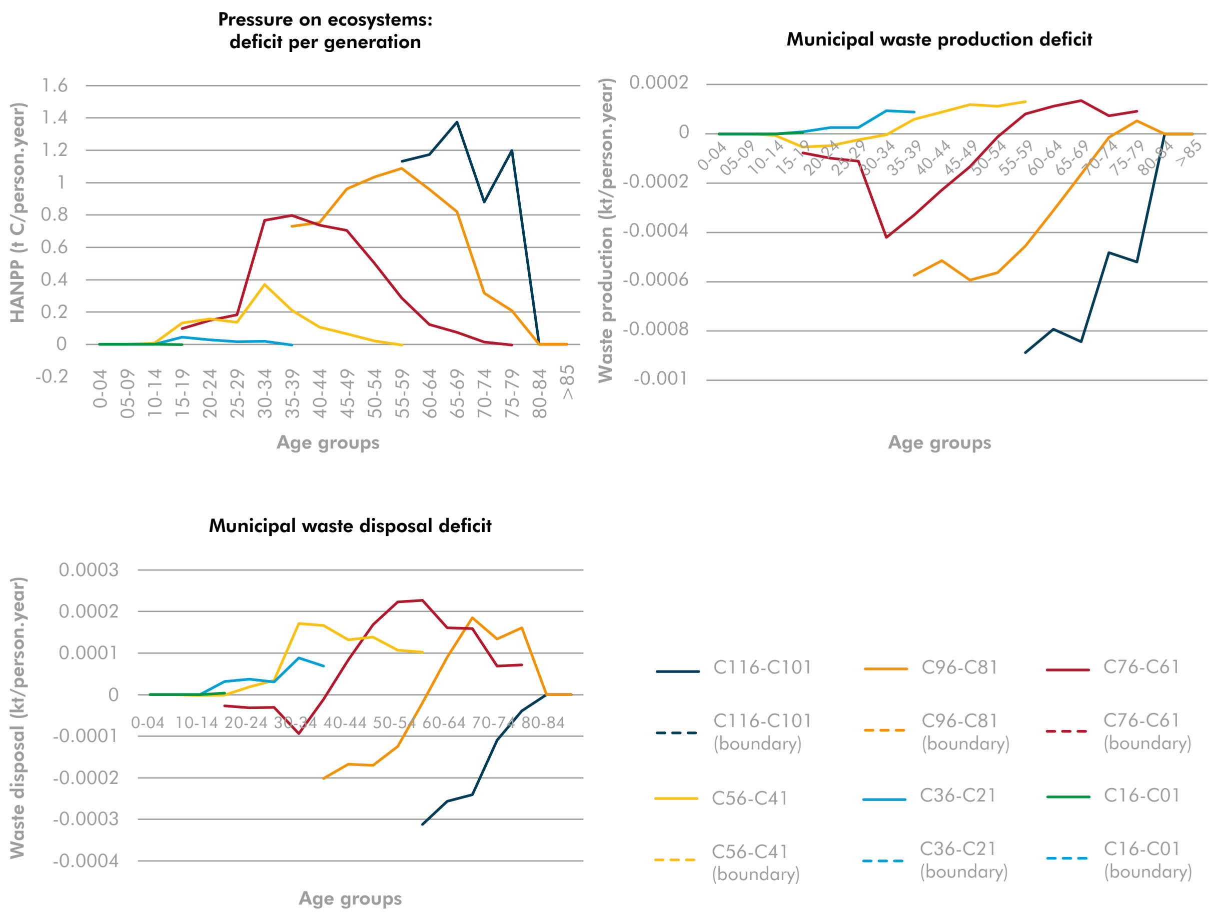
Real impacts vs generation boundary for climate change



On the left: impacts estimated, by generation (full lines), and generation boundary: boundary for each generation, using the same allocation procedures (consume profiles) as for determining the impacts for generation (dashed lines).

On the right: difference between estimated impacts and the boundary for each generation. Positive values refer to impacts above the boundary. Negative values refer to impacts below the boundary.

Figure 53
Real impacts vs generation boundaries for pressure on ecosystems, waste production and disposal



Lines represent the difference between actual impact and the boundary for each generation. Positive values refer to impacts above the boundary. Negative values refer to impacts below the boundary.

Although older generations had significant impacts on many biophysical indicators, they have also contributed to the implementation of policies that led to a reduction in these indicators, leaving their own generation and younger generations with lesser impacts. As we have seen from Chapter 3 of this report, the reason why the biophysical indicators have been declining is due to GDP dynamics but also, due to policies for efficiency and cleaner processes that have been decided, agreed, and implemented before the effects of the impacts were felt. This means that generations living in those periods, independently of their impact per individual, have had a contribution for reducing the impacts of their own generation and the generations coming after them. This includes generations C96-C81, C76-61 (Baby Boomers), C56-C41 (generation X) and to a lesser extent, C36-C21 (generation Y). So, although some of these generations had major impacts per individual in terms of all environmental categories analysed here, they have also contributed to reduce the environmental impacts of the younger generations. Additionally, new generations are growing in an environment of public awareness of the global and local environmental impacts of human activities and have cleaner technologies available that older generations did not have. It can be expected that the environmental impacts of younger generations will be kept on decreasing.

4.3
KEY MESSAGES

From the results of this project, the impacts of generations depend on two factors: (1) the consumption profiles assumed based on the age-distribution of the household heads (consumption per age group) and (2) the trends observed in the biophysical indicators (impact in each year). The combination of these two factors results in the variety of the patterns observed in terms of the impacts of each generation in each biophysical indicator. This made the results very different for each environmental indicator:

- Older generations have higher biophysical impacts per capita than younger generations for the biophysical indicators pressure on ecosystems and N and P flows.
- For the remaining environmental indicators, all generations have an age interval where their impacts were the highest for that age interval across generations.
- This age interval has been happening earlier and earlier from the older to the younger generations (i.e., the age interval the younger generations had highest impacts compared to the remaining generations is lower/younger than for older generations, which happened later in life).

For O_3 8-hour mean concentrations and $PM_{2.5}$ 1-day mean concentrations we find three generations that have revealed the highest impacts for certain age groups. These were: Baby Boomers (C76-C61) and generations X (C56-C41) and Y (C36-C21). Note that for air pollutant emissions and concentrations (which include O_3 concentrations), as data was only available from 1990 onwards, older generations have lesser or no impacts. This is just because of data and not because these generations have had no impacts.

For other biophysical indicators (climate change, freshwater use, SO_2, $PM_{2.5}$, NO_2, NMVOC and NH_3 annual emissions, and waste production and disposal), we find even four generations revealing peaks in the environmental impacts depending on the age group (pre-Baby Boomers (C96-81), Baby Boomers and generations X and Y).

Older generations had significant impacts on many biophysical indicators. Older generation have, at the same time, contributed to the implementation of policies that led to a reduction in these indicators, leaving their own generation and younger generations with lesser impacts.

When comparing the footprints with the boundaries from each generation, an interesting fact comes out from the analysis: most of the generations analysed had their impacts above the boundary for most of the environmental categories. This means that although some generations have considerably lower impacts when compared to the remaining generations, they still contribute to environmental impacts.

For the particular case of climate change, because once the limit is exceeded, this decreases (becoming less available to be issued until 2100), it was concluded that a citizen (or an age group) in 2016 had an emission budget lower than a citizen of the same age in previous years: -31% compared to a citizen of the same age in 2000, -43% to a citizen of the same age in 1980, -41% to a citizen in 1961 at the same age.

5.

CONCLUSIONS

From the application of the planetary boundaries' framework to Portugal, we concluded that there are several areas of concern as Portugal is completely within the boundary for one environmental category (out of eight) – pressure on ecosystems. For the remaining environmental categories, Portugal is outside the boundary for the whole category or in part of the category.

The areas of concern are climate change, ozone layer depletion (for the latitudes between 30N-30S and between 60s-30s), pressure on ecosystems, N and P flows, freshwater use, air pollution (for NMVOC and NH_3 emissions, $PM_{2.5}$ annual concentrations, $PM_{2.5}$ and PM_{10} daily concentrations and O_3 concentrations) and waste production and disposal (for municipal solid waste and total solid waste).

Areas of lesser concern are the ozone layer for the latitudes between 90S-60S (the ozone hole latitude), 60N-30N and 90N-60N, air pollution for $PM_{2.5}$ SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 and NO_2 hourly concentrations, solid sectoral waste disposal. This is because these indicators:

- are in the safe zone and their trend will keep them in the safe zone (for ozone layer depletion for the latitudes between 90N-30N, $PM_{2.5}$, SO_2 and NO_2 emissions, PM_{10} annual concentrations, SO_2 daily concentrations, SO_2 hourly concentrations, solid sectoral waste disposal),
- although still in the uncertainty zone of the boundary, show an improving trend (for ozone layer depletion for the latitudes between 90S-60S, NO_2 hourly concentrations).

We have found that GDP, as it is linked with production and consumption activities, is the main cause of transgressing the boundaries in the biophysical indicators analysed. This is valid for most of the indicators analysed (except for the agriculturally linked indicators such as pressure on ecosystems, water pollution and freshwater use) and assumes particular relevance for the waste production and disposal indicators. For pressure on ecosystems, water pollution and freshwater use, agricultural policy was the main driver, particularly, the policies implemented in the 60s and early 70s and the transition period to the EU policies on agriculture (from 1986).

Policies promoting the decarbonisation of electricity, road transport and waste disposal; energy efficiency measures (for industry and buildings); policies promoting cleaner vehicles and fuels; policies regulated the production and consumption of ozone depleting substances (ODS); policies on waste valorisation have played an important role in partially decoupling the biophysical indicators from GDP.

The results showed that the impacts of generations depend on two factors: (1) the consumption profiles assumed based on the age-distribution of the head of the household (consumption per age group) and (2) the trends observed in the biophysical indicators (impact per year). The combination of these two factors results in the variety of the patterns observed in terms of the impacts of each generation in each biophysical indicator. Because of this variability, we cannot generalise that older generations have higher environmental impacts per capita than younger generations. This only happens for pressure on ecosystems and N and P flows, where the older the generation, the higher their impacts.

Most of the generations analysed had their impacts above the boundary. Apart from a few exceptions, Generation Z is the only one that is within or almost within the boundary in all the biophysical indicators.

For the particular case of climate change, in 2016 Portugal emitted more GHG than the annual GHG budget, which resulted in a progressive reduction of this limit (becoming less available to be emitted until 2100). This results in a citizen (or an age group) in 2016 having a lower emission budget than a citizen of the same age in previous years: -31% compared to a citizen of the same age in 2000, -43% compared to a citizen in 1980 of the same age, -41% compared to a citizen in 1961 of the same age.

There are limitations for the approach followed in this project. These are:

- The biophysical indicators were estimated based on a territorial approach. This means it only accounts for the pressures exerted within national boundaries, not accounting for the impacts of the consumption of imported goods and services,
- Local impacts related with the biophysical indicators are diluted as impacts are analysed in national terms. This is particularly relevant for water (where regional water scarcity (e.g., in the south) is diluted with regions with less scarcity) and air pollution, in particular, air pollution related with traffic, where limits might be transgressed locally, but not when national averages are analysed,
- Some air pollutants, like heavy metals in PM, were not accounted due to lack of data. Given these limitations, the results presented here provide a good indication of the status of the Portuguese territory, but care needs to be made than when air pollution concentrations or water use are within the boundary, that there might be local cases where this might not be observed,
- For air quality indicators, data was only available from 1990 onwards and in some cases, from 2005 onwards. This means that the impact estimated here for older generations is lower than what it is. This is only due to availability of data and not because the generation had lower impacts. This needs to be taken into consideration when analysing the results from the Intergenerational analysis for air quality,
- Older generations, although not within the boundaries in many biophysical indicators, have contributed to the implementation of policies that led to a reduction on these indicators, leaving younger generations with lesser impacts in some indicators. In analysing the results, care needs to be made to consider that older generations have contributed to the implementation of policies that led to a reduction in the biophysical indicators analysed, leaving younger generations with lesser impacts. These aspects are not included in the quantitative analysis performed. This applies to generations C96-C81, C76-61 (Baby Boomers), C56-C41 (generation X) and to a lesser extent, C36-C21 (generation Y).

There is some work to be done for improving Portuguese biophysical impacts, but what we can see is that policies implemented from the 90s onwards have already contributed to reducing these impacts and ensuring the youngest generation (generation Z) has lower impacts than the others.

6.

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7.

TECHNICAL NOTES

7.1
TECHNICAL NOTE 1. ESTIMATION OF BOUNDARIES AND INDICATORS

7.1.1 Results from O'Neill et al. (2018) study

O'Neill et al. (2018) downscaled the planetary boundaries framework to the country level. This was achieved by reformulating some of the boundary definitions and dividing the planetary boundaries by the total population, obtaining per capita boundaries. These per capita boundaries were then multiplied by each country's population to obtain a given country's share of the planetary boundaries. The biophysical pressures were estimated using a consumption-based approach, i.e., accounting for imports and exports.

In the article by O'Neill et al. (2018), the following changes were considered:

- For climate change, the limit considered was the Paris Agreement's objective of stabilizing the global temperature increase at 2°C,
- A proxy indicator, the Human Appropriation of Net Primary Production (HANPP) [5], was used for changes in the land-system and biosphere integrity
- The depletion of the ozone layer was not considered as this issue is already under resolution and it is a matter of time before it is resolved,
- Ocean acidification was not considered because it is driven by CO_2 emissions and these are quantified in the climate change indicator,
- The categories of introduction of novel entities and atmospheric aerosol loading were not estimated (similarly to Steffen et al. 2015, where these were defined, but not quantified),
- The indicators "material flows" and "ecological footprint" were added as additional indicators to complement the key processes of the Earth system mentioned above.

The results from a country level approach show that even in Earth-system processes where globally we have crossed the boundary, there are countries which are still within the boundary. The reverse is also true.

According to O'Neill et al. (2018) (Table 21), Portugal exceeded all seven of the boundaries in 2010.

5 HANPP measures the amount of biomass collected through agriculture and forestry, as well as the biomass that is killed during harvesting but not used, and the biomass that is lost due to changes in land use.

Table 21
Portuguese "planetary boundary" status in 2010, consumption-based approach

Biophysical indicator	Value for Portugal	Per capita boundary	Unit
CO_2e emissions	12.1	1.6	tonnes of CO_2e per year
Phosphorus	5.2	0.9	Kilograms of P per year
Nitrogen	72.9	8.9	Kilograms of N per year
Blue water	240	574	Cubic meters of water per year
eHANPP	2.4	2.6	Tonnes of carbon per year
Ecological Footprint	4.2	1.7	Global hectares (gha) per year
Material Flows	24.3	7.2	Tonnes per year

Source: https://goodlife.leeds.ac.uk (last accessed November 2020).

7.1.2 Climate change

Boundaries for climate change

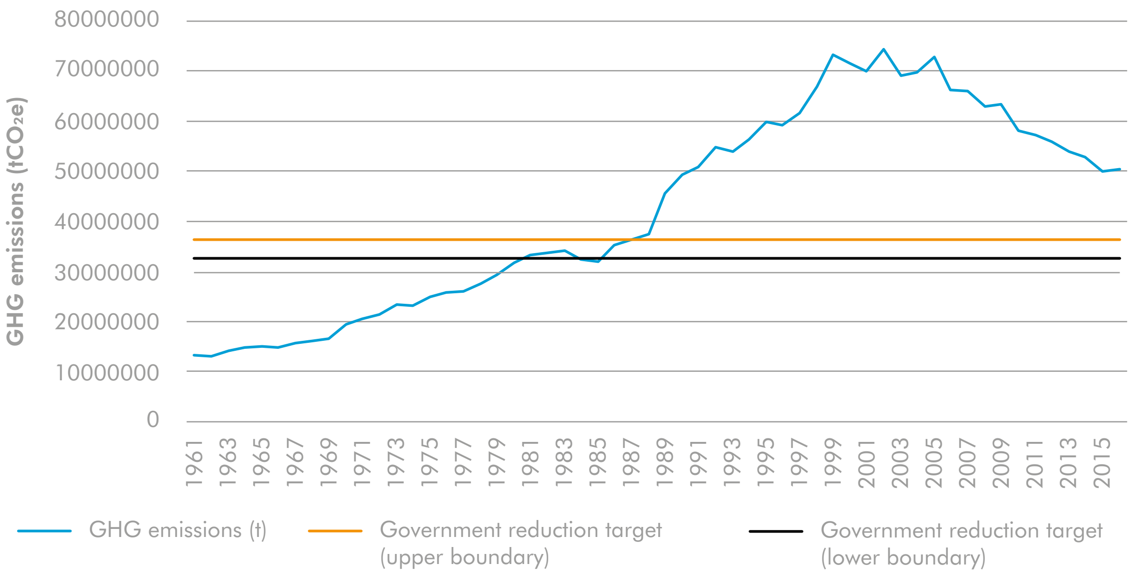
Two boundary types were considered:

- Governmental targets for 2030 and
- The Paris agreement stabilisation goal.

Boundaries based on governmental targets

The targets announced by government for 2030 are: to achieve by 2030 a level of emissions between 55% and 45% lower than the emissions in 2005. According to this target, Portugal is on the way to meet the targets by 2030 (Figure 54).

Figure 54
Portuguese government's reduction target



Boundaries based on the Paris Agreement temperature stabilisation goal

The Paris Agreement defined a 2ºC world average temperature stabilisation by 2100. This means that there is a budget of GHG emissions that humans can emit to ensure that the target is not surpassed. We have estimated these emissions to be 2 $PtCO_2$.

There are two issues with the operationalisation of this boundary:

- How to allocate this budget to each year,
- How to allocate this budget to each country.

The budget can be allocated to each year considering an equal budget per year, obtaining a fixed yearly budget. Qualitatively, this approach accounts for the evolution of technology. Each person should have the right to emit more in 1960 because the technology was less developed. The world population increased at the same time as technology developed.

Alternatively, the budget can be divided by person.year (sum of total population in all years between 1960 and 2100, data obtained from the UN - Department of Economic and Social Affairs, Population Division, 2019), ensuring each person in each year as the same budget whether they lived in 1960 or in 2100. As the world population has increased from 1960 to the present day and it is expected to continue increasing, the yearly budget is increasing.

The yearly budget needs to be updated every year to account for the excess (or under budget) emissions occurred in the previous year:

- When emissions in a year are higher than the available budget for the same year, the "excess" emissions are discounted from the remaining budget for the next years until 2100.
- When emissions are under the budget available for a particular year, the "emissions" not emitted are credited to the budget for the remaining years until 2100.

The result is that when the budget is surpassed by the emissions, the boundary starts to decrease, when the emissions are under the budget, the budget available increases.

The update of the budget in every year can be conducted globally, based on world emissions and the world budget (i.e., before allocating to each country) or based on each country's emissions performance (i.e., after allocating the global budget to each country). The first option translates the fact that climate change is a global problem, and therefore, it is needed all countries to perform within the boundary to ensure reaching the Paris Agreement goal. The second option puts responsibility for each country in the country itself, linking the country's emissions to its own budget.

The allocation to each country can be done using the per capita boundary (O'Neill et al 2018) and multiplying this boundary by each country's population to obtain each country's budget. Other options have been explored in the literature but not explored in this study. This allocation favours countries with larger population numbers or countries that favour population increase policies. As an alternative, a fixed population could be used, for example, the world's population in 2010, when the estimation of the available budget was conducted. Any demography control policies taken after 2010 (e.g., population growth or immigration promotion policies) will not directly affect the budget available for that specific country.

A summary of the modes of operationalising the Paris Agreement goal is presented in Table 22.

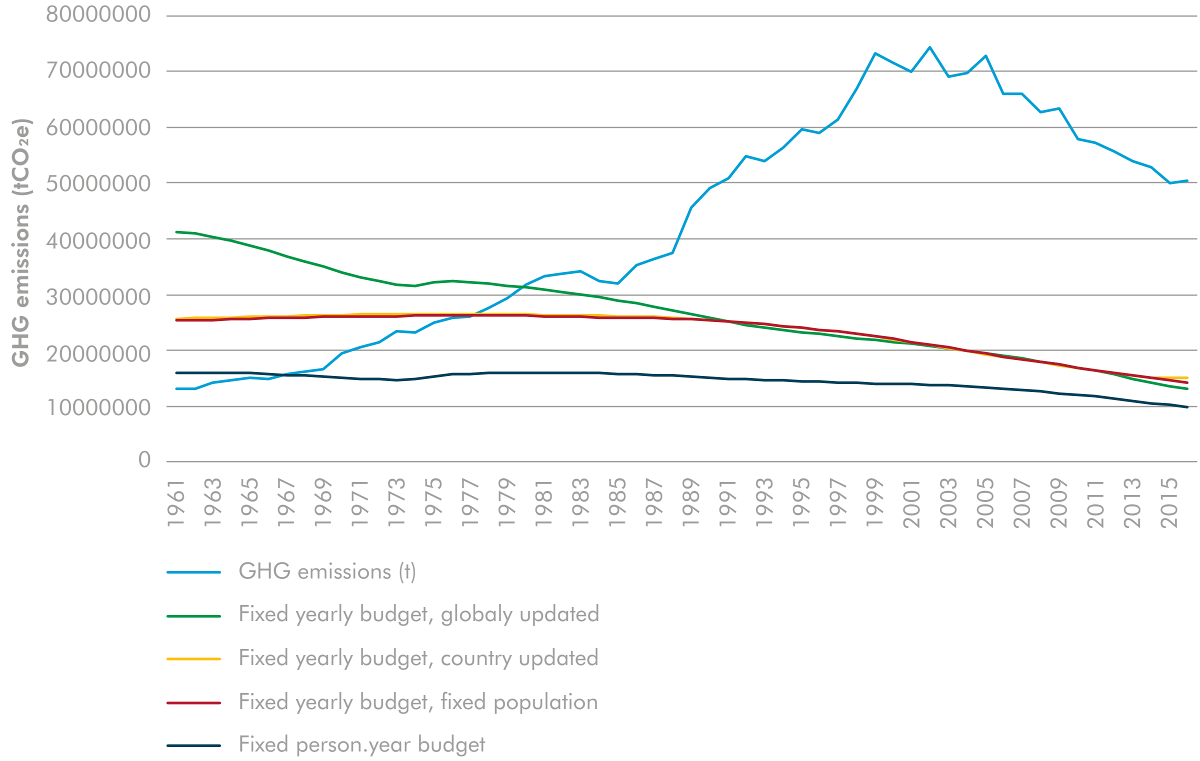
Table 22
Four modes of operationalising the Paris Agreement goal

Boundary name	Allocation to each year	Update of the budget	Country allocation
Fixed yearly budget, globally updated	Fixed yearly budget	World update (before country allocation)	Per capita with real population
Fixed yearly budged, country updated	Fixed yearly budget	Country update (after country allocation)	Per capita with real population
Fixed yearly budget, fixed population	Fixed yearly budget	Country update (after country allocation)	Per capita with fixed population (2010)
Fixed person .year budget	Person.year	World update (before country allocation)	Per capita with real population

Figure 55 presents the results for the four modes of operationalising the Paris Agreement boundary. In all cases Portugal is outside the boundary. The year after which this happens depends on the boundary:

- 1980 for the "fixed yearly budget, globally updated",
- 1978 for the boundaries "fixed yearly budget, country updated" and "fixed yearly budget, fixed population" and
- 1969 for the "fixed person.year budget".

Figure 55
GHG emissions and the four Paris Agreement boundaries



GHG emissions

The data used for estimating the GHG emissions, was as follows:

- For energy emissions: Portuguese consumption of final energy was calculated per energy carrier based on the International Energy Agency (IEA) database. More specifically, the consumption is distributed in the following categories: coal, oil, natural gas, combustible renewables, heat, and electricity. For coal, oil and natural gas, an inefficiency of 10% was considered from the final to primary energy flow stage due to distribution losses after extraction. This 10% was added to the yearly total consumption of each of these carriers. To obtain CO_2e emissions associated with energy, Portugal's final energy consumption was multiplied by 2006 IPCC emission factors for all energy carriers (coal, oil, and natural gas) except for Electricity. To calculate electricity's associated emissions, the natural resources consumed were estimated based on each year's resource mix for electricity production (from National Energy Balances[6]), finally, 2006 IPCC emission factors were applied. Lastly, electricity's associated emissions were summed to the rest previously calculated.
- For agriculture, the time series of GHG emissions from the agricultural sector, nitrogen and phosphorus use were obtained from FAOSTAT (FAO, 2020).

6 Available on http://www.dgeg.gov.pt/

- For remaining emissions (manufacturing industries, households and services and waste sector): emissions obtained from the National Inventory Report (APA, 2019a).

7.1.3 Ozone layer thickness

The ozone hole is the main issues with the ozone layer. The hole was caused by the emission of ozone depleting substances, whose production and consumption have been mitigated and whose emissions are already below 1960 levels (Hegglin et al., 2014). N_2O is the only substance whose emissions are still high. N_2O is a sub-product from agriculture and animal production and is a greenhouse gas. It is a matter of time until the ozone hole issue is resolved. Concentrations of ozone depleting substances in the atmosphere have started to decrease (Hegglin et al. 2014; Montzka et al., 2018) and ozone concentrations are increasing (Hegglin et al. 2014). NASA's data now show that the hole extent is stabilising (NASA Ozone Hole Watch, 2020).

Recently, new evidence is showing that the lower stratospheric ozone at mid latitudes is decreasing, offsetting the progress made towards reducing the ozone hole and the whole thickening of the ozone layer in mid latitudes – between 60º S and 60º N (Ball et al., 2018). The causes of this decline are not yet fully known. Some hypotheses are linked with dynamics of the atmosphere (including the influence of climate change on atmospheric dynamics) and emission of chemicals labelled as VSLS (very short-lived substances) containing chlorine and bromine, whose short life might not be as short as initially thought of.

Given that:

- stratospheric ozone layer depletion is a global issue, resembling climate change (and therefore, a country-level analysis might reveal little of significance),
- there are no data that provide Portuguese emissions of ozone depleting substances (UNEP, 2015), apart from N_2O data (APA, 2019a),
- the ozone hole is stabilising,
- the causes of a decrease in lower stratospheric ozone concentrations at mid latitudes are still unknown (and therefore, difficult to attribute responsibilities to each country),

we only analyse this biophysical indicator at the planetary level. We analyse the thickness of the layer at mid latitudes, the latitudes involving Portugal. We compare the latitudinal changes in the ozone layer thickness in these sections of the planet and compare them with the boundary presented by Steffen et al. (2015). Data for this analysis was obtained from NASA Ozone Watch (NASA Ozone Watch, 2020; Hegglin et al. 2014; Montzka et al., 2018).

7.1.4 HANPP in Portugal

We estimated HANPP following Krausmann et al.'s (2013) method. HANPP can be expressed as

$$HANPP = HANPP_{luc} + HANPP_{harv}$$

where $HANPP_{luc}$ is the net primary production (NPP) lost due to land use change from potential natural vegetation, and $HANPP_{harv}$ is NPP harvested (or otherwise killed) from currently prevailing vegetation (NPP_{act}). $HANPP_{luc}$ was calculated as the difference between NPP_{act} and NPP_{pot} (where NPP_{pot} was obtained from Haberl et al., 2007, and NPP_{act} on cropped area was extrapolated from $HANPP_{harv}$). As outlined above, $HANPP_{harv}$ on cropland comprises harvested crops as well as all belowground biomass and aboveground leftover biomass after harvest. $HANPP_{luc}$ on grassland assumes that the conversion of forests to grassland results in a 20% reduction of NPP. $HANPP_{luc}$ on forest and wilderness areas is equal to NPP_{pot}. $HANPP_{harv}$ on cropland comprises used and unused biomass extraction. $HANPP_{harv}$ on grazed areas is calculated based on feed demand which is a function of the number of animals. $HANPP_{harv}$ of forests is equal to the harvest of wood.

All land use areas, cropland production, number of animals and wood extraction required to calculate HANPP were obtained from FAOSTAT (FAO, 2020).

7.1.5 Water pollution

National nitrogen and phosphorus use data were obtained from FAOSTAT (FAO, 2020).

7.1.6 Blue water withdrawal

Blue water withdrawal was obtained from the Eora Global Supply Chain Database (Lenzen et al., 2012).

7.1.7 Emissions and concentrations of atmospheric pollutants

Annual emissions data for air pollutants were obtained from the Portuguese National Inventory Report's Annex I (APA, 2019a).

For air pollutants concentrations, data were obtained from the national air quality monitoring network. This network provides hourly values for most of the pollutants. Values were averaged by 1-year, 1-day or 8-hour values according to each pollutant guidelines/ceilings. For some pollutants, the number of times (hours, days, 8-hour periods, year) the concentrations were above the ceilings in a year were considered, to compare with their respective EU ceilings.

Values for heavy metals in PM_{10} (As-Arsenic, Cd-Cadmium, Ni-Nickel and Pb-Lead) and benzo-(a)-pyrene in PM_{10} were not estimated as there were not enough data to have good estimations.

The approach followed here, although coherent with the planetary boundaries' framework, has a few limitations in terms of the purpose of the study:

- Morbidity and mortality rates, linked with pollutants, would represent better the boundary. Although some of these data are available for some pollutants for humans, they are not available for all pollutants for humans, and they are also not available for the ecosystems,
- Exposure rates, rather than emissions or concentrations in the atmosphere, would be a better second approach (in the absence of morbidity and mortality rates); however, measuring exposure is not easy (Faria et al., 2019): (1) activity patterns of subgroups of the population vary across the day, week and year, and therefore, exposure can vary, as well as the impacts on the health of those more sensitive and (2) people spend approximately 90% of their time indoors, rendering indoor air quality more relevant for population exposure than ambient concentration levels. Because of this, there is not yet enough knowledge and data to be able to measure air pollution in terms of exposure in the way required by this project. It is expected that in the future the approach would go in the direction of measuring the exposure rather than emissions or concentrations,
- Concentrations in the atmosphere would be a better third approach, which is the approach that we are following whenever data (and limit values) are available in this form. This approach has a few limitations compared to the first two approaches described above. According to Faria et al. (2020), there is a

significant variability in some pollutant concentrations within the territory (even within a city), including hotspots that are often not covered by the air quality networks,

- Finally, there are other pollutants that could have relevance for "air pollution", but they are not included because there is either not enough data available (i.e., systematic collection of data to analyse trends, e.g., for heavy metals in PM10) or there is not yet knowledge on the damage certain pollutants can have (e.g., indoor sources of pollution). It is expected that in the future, new pollutants might be added to the category.

7.1.8 Waste production and disposal

Limits for waste production and disposal

The Portuguese National Plan for Waste Management 2011-2020 (PNGR 2011-2020) defines four targets for solid wastes:

1. A limit on solid waste production: 20% reduction on total waste production from 2009 to 2020. This boundary is set to reduce the environmental impacts related with waste management.
2. Minimum level of integration of resources in the economy – 70% of total waste to be recycled by 2020 (PNGR 2011-2020). This limit is set to reduce the environmental impacts of certain forms of waste management (namely, landfill and incineration).
3. A limit on waste disposal: 62% reduction from 2009 to 2020. This boundary was set to reduce the most environmental unfriendly waste management practices.
4. A boundary on GHG emissions from the waste sector: reduction of emissions to the value of 5.68 $MtCO_2e$ by 2020 (20% reduction from 2005)..

For the present study, we have selected targets 1 and 3. This was because (1) targets 2 and 3 are dependent, therefore, we have selected the one that provided a ceiling instead of a minimum standard; and (2) as the waste sector only contributes with 6.8% (in 2017) of total GHG emissions (APA, 2019a), we have considered that this target is not as significant as the remaining.

Data on total waste produced was not available because data on sectoral wastes was not available. For this reason, partial limits for municipal solid wastes were defined based on the national limits:

- 20% reduction on municipal solid waste production from 2009 to 2020
- 62% reduction from 2009 to 2020 of municipal wastes going into landfill.

Data sources for waste production and treatment

Data used for waste production and disposal were:

- Municipal solid waste production, 1990-2018: National Inventory Report (APA, 2019a),
- Sectoral solid waste disposal, 2008-2014: National Statistics Office (INE),
- Waste disposed: National Inventory Report (APA, 2019a).

Total waste produced is estimated by the sum of MSW and SSW production.

7.2 TECHNICAL NOTE 2. DESCRIPTION OF EXPLANATORY VARIABLES

7.2.1 Sectors Contributing to the indicators

The results presented here result from our analysis of the literature of the biophysical indicators.

Climate change

In 2018, most of the GHG emissions in Portugal came the use of fossil fuels (>80%). According to APA (2019a), GHG emissions from Portugal in 2018 were as follows:

- 26.6% from the energy industries (production of fuels, heat, and electricity),
- 25.6% from transport,
- 11.2% from the energy use in manufacturing industries,
- 11.1% from other processes in industrial processes,
- 10.1% from the agriculture sector,
- 6.8% from the waste sector (solid waste and wastewater treatment) and
- 6.7% from the energy use in services, commerce, buildings, and agriculture.

So, for climate change, energy industries, transport, manufacturing industries and the agriculture sector (which includes animal production) are the main sources of GHG emissions.

Ozone layer depletion

Most of the ozone depleting substances (ODS) are emitted from the use and disposal of equipment containing these substances, such as air conditionings, refrigeration units and extinguishers. The use of ODS in this equipment have been regulated as well as their maintenance and disposal. The only ODS that has not been regulated in N_2O, whose main source is agriculture (from nitrogen-based fertiliser use in agriculture, APA, 2019a).

Pressure on ecosystems

Our estimation of pressure on ecosystems was made using land use areas and their potential biomass content (section 7.1.4). This means that pressure on ecosystems is linked with agricultural land, forest land and grazing land.

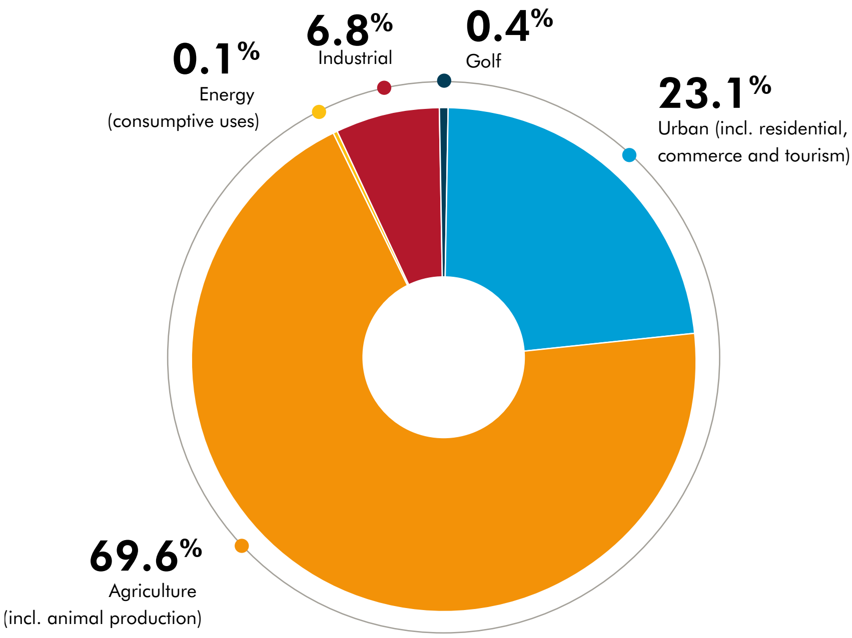
Water pollution

N and P emissions are linked directly with the use of nitrogen and phosphorus base fertilisers.

Freshwater use

According to the National Plans for water basin management (PNGBH), freshwater use is mostly linked with agriculture (70%). Urban uses, which include residential, commerce and tourism represent 23% of water consumption (Figure 56).

Figure 56
Water uses in Portugal for 2007



Source of data: Planos Nacionais de Gestão de Bacias Hidrográficas (PNGBH)

Air pollution

For air quality explanatory hypothesis, we have used the following sources for a start in our investigation:

- National inventory report (NIR), APA (2019a), covering Portugal.
- European Environment Agency's report on air quality for 2019 (EEA, 2019), covering the EU.
- World Health Organisation's website on ambient (outdoor) air pollution (https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health, last accessed: September 2020), covering the world.

These sources identified potential relationships between air pollutants and socio-economic drivers (see Table 23). We have identified variables within these drivers and explored the relationships between them and the air pollutants. We were then able to provide explanatory hypotheses for the pollutants' trends.

Table 23
Drivers for air pollutants

Source:	WHO [(a)]	EEA [(b)]	NIR [(c)]
Geography:	World	EU	Portugal
$PM_{2.5}$	Fuel combustion (cooking, heating, transport)	Household and services; Industrial processes and product use; Road transport.	Industrial activities
PM_{10}	Fuel combustion	Households and services; Industrial processes and product use; Agriculture; Road transport;	-
SO_2	Fuel combustion (coal and oil); Smelting of mineral ores	Energy production and distribution; Energy use in manufacturing industry; Households and services; Industrial processes and product use	Power generation; Energy use in industry
CO	-	Households and services; Energy use in manufacturing industry; Road transport; Industrial processes and product use	-
NO_2	Fuel combustion	Road transport; Energy production and distribution; Households and services; Energy use in manufacturing industry	Road transport; power generation; Industrial processes and product use (pulp & paper, glass, iron and steel, ceramics); Energy use in general
NMVOC	-	Industrial processes and product use; Household and services; Agriculture	Power generation; Energy use in manufacturing industry; Industrial processes and product use
O_3	Vehicles; Industry; Solvents	-	-
NH_3	-	-	Fossil fuel combustion; Industry (nitric acid production); Agriculture

(a) WHO (2018); (b) EEA (2019); (c) APA (2019a).

We have considered APA (2019a) sectors for analysis and have used the remaining data sources for pollutants not covered by APA (2019a), giving preference for EEA (2019) as the geographic area covered is similar to Portugal than the one from WHO (2018).

Waste production and disposal

According to APA (2019a), the main drivers for waste production are GDP and for waste disposal are GDP and waste policies on waste treatment.

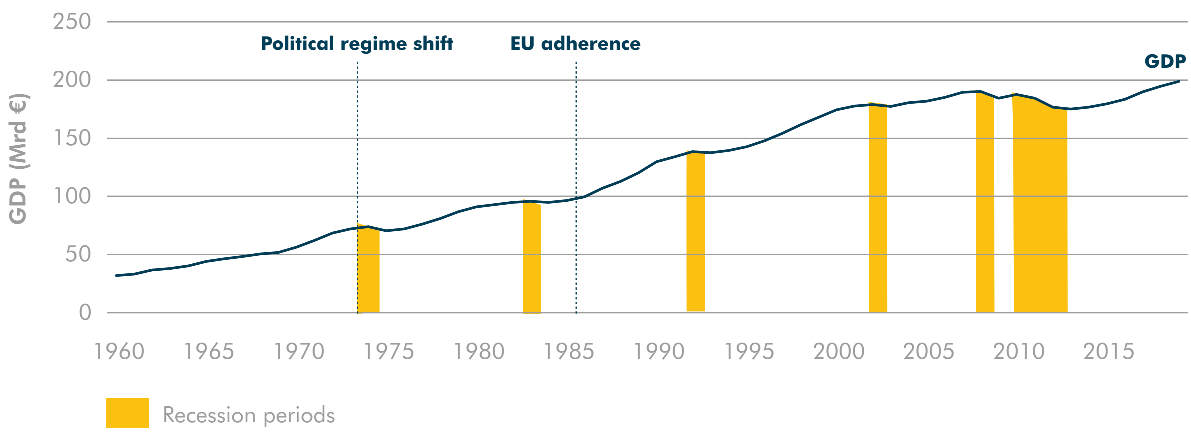
7.2.2 Overview of GDP dynamics

During Portuguese economic history there has been several periods of economic recession and of economic growth. Figure 57 presents these periods of recession and growth.

Recession periods happened in 1974-75 (coinciding with the political regime shift from dictatorship to democratic regimes), 1983-84, 1992-93, 2002-03, 2008-09 and 2010-13. The later one was the longest and more severe recession and included a financial rescue from the European and World banks and IMF. The private consumption index decayed from 101.1 in 2010 to 89.7 in 2013 (Aguiar-Conraria, 2020). During this recession period, Europe has also started a recession, which prolonged the recession in Portugal.

In terms of economic growth, Portugal has been growing between the 60s and 2000, with some recession periods in between. This growth has not been at the same rate, and there were two periods where this growth rate was higher: between 1986-90 (coinciding with the Portugal joining the EU) and between 1995-2000. Between 2000 and 2010, Portuguese GDP has been close to stagnation, with the exception of the two periods of recession.

Figure 57
Portuguese GDP between 1960-2018



Source: AMECO database. Recession periods: Reis (2020).

7.2.3 Relationship between GDP and subsectors of activity

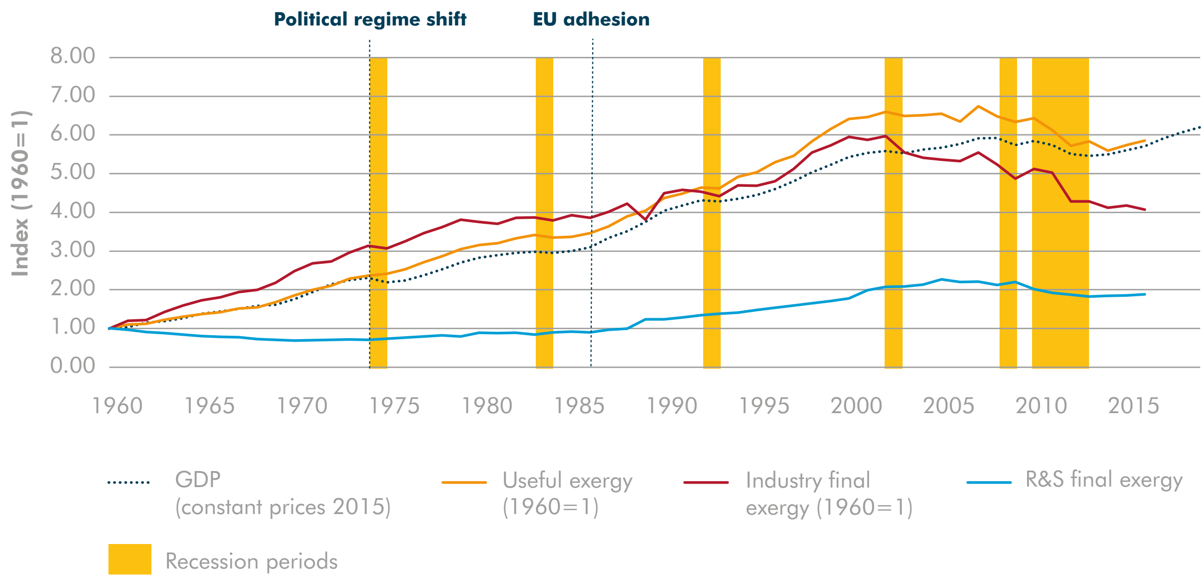
Figure 58 presents the variation of GDP and its relationship with useful[7] exergy[8] of the economy and the final energy from industry and services and residential. The relationship between GDP and useful exergy of the economy has been explored in Serrenho et al (2016), and we can see that recession periods and periods of rapid economic growth are reflected in the useful exergy of the economy.

Industry final exergy consumption also follows the periods of recession and economic growth, with the exception of the period starting in 2003, where final exergy consumption in industry continues to decline until 2009, a year just before the last recession. This can be explained partially with the energy efficiency measures imposed to industry (and explored in section 7.2.6).

Residential and services seem only to be affected by the last recession (having started one year before the recession, in 2009) and by the rapid GDP growth periods.

Figure 58

GDP, useful exergy, and final exergy from industry and residential and services



GDP – gross domestic product. R&S final exergy – final exergy from households and services.

In terms of transport, Figure 59 presents a summary of the evolution of the different road transport variables and GDP. Between 1985 and 2000, economic growth has led to increased purchase power by families and an increase in the number of vehicles and road travel (APA, 2019a), which can be observed by the increase in energy use from road transport. At the same time, government has made increasing investments in road infrastructure up until 2010 (EUROSTAT).

7 Useful is the stage of energy after the final energy. Final energy is the energy that typically is paid for, e.g., electricity, natural gas, diesel, and gasoline. Useful energy is the conversion of this energy into what we needed for, for example, light, heat, mobility.

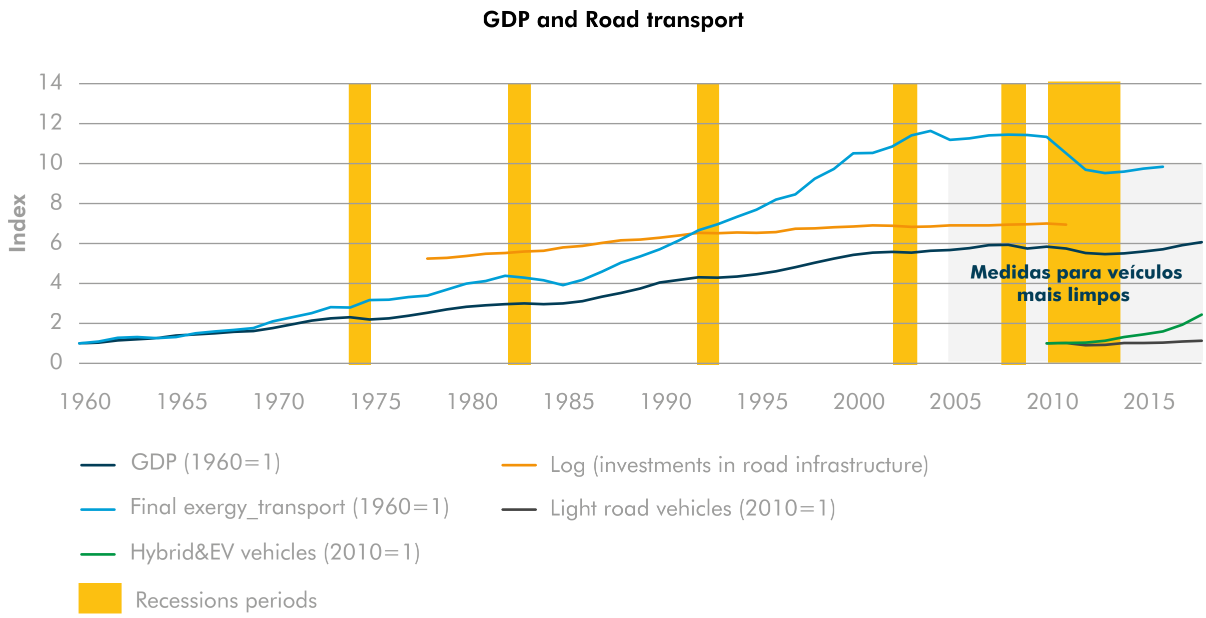
8 Exergy is the maximum amount of energy that can (thermodynamically) be ever converted into work. There will always be a part of energy that cannot be converted to work. This amount is anergy. Anergy + Exergy = Energy.

Between 2000 and 2010 there was economic stagnation, this is reflected in the energy use by road transport, leading to conclude this stagnation has reduced some economic activity linked with transport and families reduced their use of private vehicles. Manufacturing industries were also affected by this stagnation (Figure 58), whose final exergy decreased during this period, affecting road freight transport. Government investments in road transport infrastructure continued to rise during this period. It is also in this period that liquid biofuels and catalytic converters are introduced.

The last economic recession hit Portugal in 2010 and lasted until 2013. During this period, families reduced their road travels, industrial activity was reduced (reducing road transport) and government cut on road infrastructure investments. Energy use decreased as a result. The number of alternative vehicles (i.e., hybrid and electric vehicles) started to increase during this period, a result from mobility policies, removing taxes from these sorts of vehicles.

From 2014, in line with the recovery from the economy, we start to see an increase in the numbers of vehicles and on the use of liquid biofuels.

Figure 59
Road transport indicators, 1960-2018

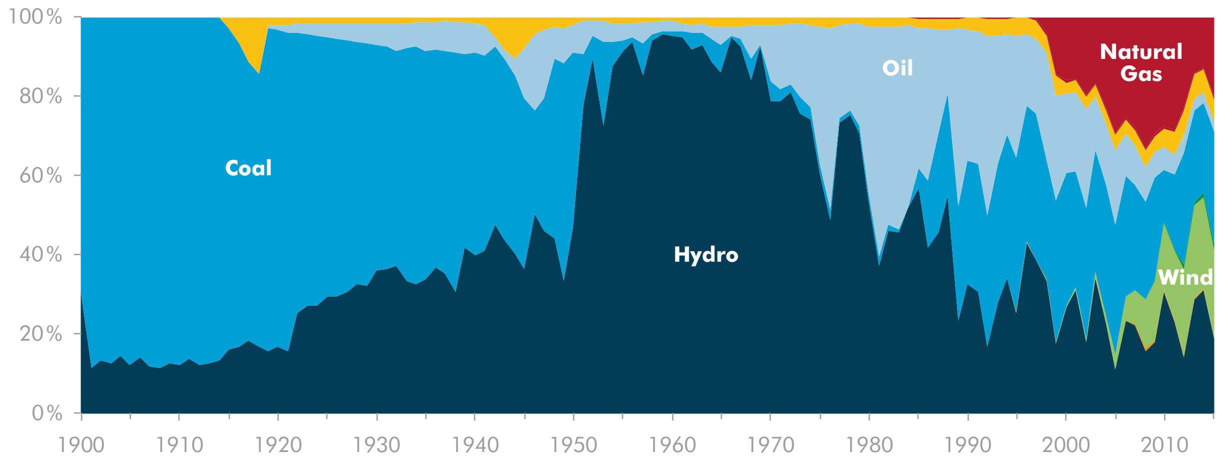


Source of data: GDP: Ameco database; Investments in road infrastructure, light road vehicles and hybrid and electric (EV) road vehicles: EUROSTAT; Final exergy from transport: own calculations based on the IEA energy statistics.

7.2.4 Electricity mix in Portugal – historical overview

Figure 60 presents the electricity mix of Portugal from 1900 to 2014. Between 1900 and 1950, coal was the main source of energy for electricity. Between the 1950 and mid-1970s there were large investments in hydropower, reducing the use of coal. Hydropower became the major electricity source during that period. From the mid-70s to the late 1990s, coinciding with the re-introduction of democracy in Portugal, oil was added to the electricity mix and coal made a came back. In the late 1990s, natural gas was introduced in Portugal and in electricity production through combined cycle power plants, mostly replacing the oil used in the electricity mix.

Figure 60
Electricity mix in Portugal, 1900-2014



Source: Felício et al. (2019)

From 2005 onwards there was a massive investment in renewable sources of energy, in particular wind energy, which contributed to a reduction in coal use. Besides the direct funding linked to the installation of new renewable sources of electricity, other incentives were provided during this period to promote renewable sources of energy. These were:

- A special regime for renewable sources of electricity, with feed-in tariffs to renewable sources of electricity (and combined heat-power, CHP) and a guarantee that renewable sources had priority in the electricity grid to satisfy demand (until 2013),
- The European Union Emission Trading Scheme (EU-ETS), which penalised fossil-based electricity,
- The RECS – renewable energy certificate system, for micro-electricity generation.

From 2013 onwards the electricity market in Portugal was liberalised (with a transition period between 2007-2013). This represented a move from the previous government-single company control to an open market. This allowed new companies to invest in electricity production in Portugal. This period marked the end of the feed-in tariffs for renewable electricity sources.

Between 2010 and 2013, with the investments in shale gas in the US, US became an exporter of coal, flooding the market with coal. As a result, coal prices went down. This happened at the same time as the EU-ETS market crashed, which prices of CO_2 between 2 and 5 EUR/ton. This crash resulted from the economic recession, where industrial activity decreased and licences for CO_2 emissions were not being used, resulting in excess of licences being traded within the EU-Trading Scheme, leading the price of CO_2 down. These two factors (price of coal as a raw material and CO_2 prices from burning coal) made the use of coal cheaper than natural gas, leading to a reduction in the use of natural gas in the electricity mix, to give place to coal.

Figure 61 presents the carbon intensity of electricity and the fossil fuels used in electricity generation. The use of oil has been being eliminated from the electricity mix, being substituted by natural gas. The use of coal has been constant until 2006. From 2006, renewable sources of electricity and the reduced energy demand from economic recession in 2010 led to a reduction in coal use. This decrease was rapidly changed to an increase in the use of coal between 2012 and 2017, the period where the price of using coal was lower than natural gas.

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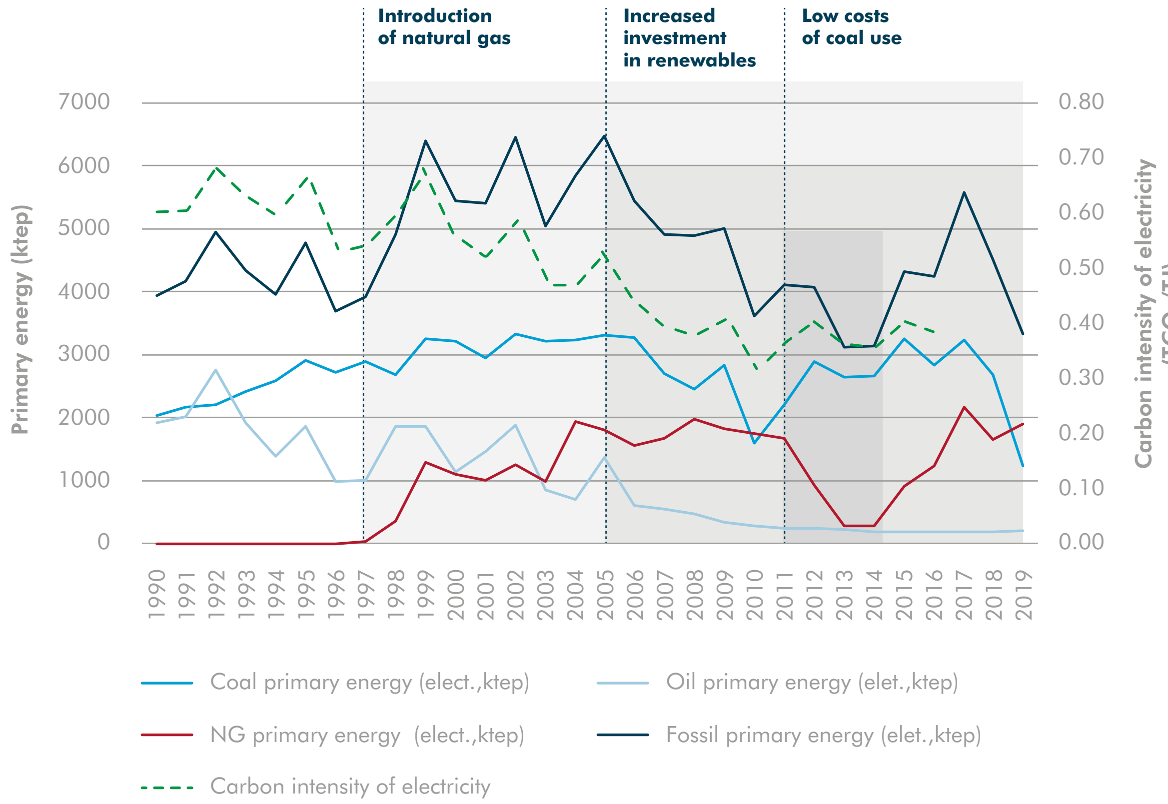
Figure 61

Fuels used in power generation and carbon intensity of electricity



Data sources: fossil fuels – national energy balances from DGEG; carbon intensity of electricity – Felício et al (2019).

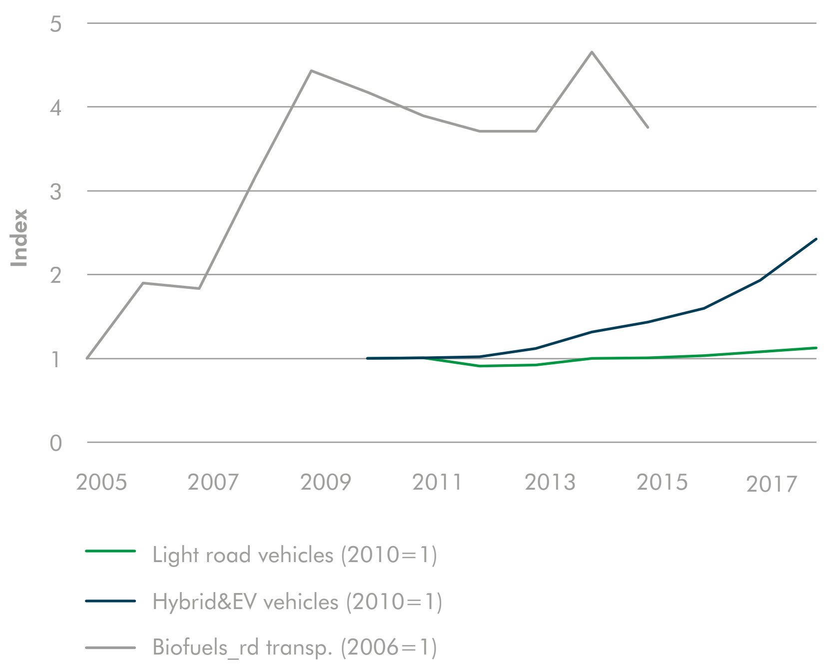
7.2.5 Policies for cleaner Transport and mobility

Several measures have been adopted by government to reduce the use of fossil fuels in cars, namely:

- the inclusion of a CO_2 component in annual circulation tax (from 2007 onwards) and in the vehicle purchase tax,
- incentives for vehicle abatement and replacement (from 2008 to 2010),
- introduction of biodiesel in diesel from 2005 onwards (targets: 6% in volume by 2009, 7% by 2010, and so on until 2020). Figure 62 shows how the use of biodiesel has been increasing in Portugal from 2005 onwards,
- introduction of exemptions to fuel tax for biofuels, public transport and hybrid and electric vehicles (from 2010, Portaria 139/2009). Figure 62 shows how the numbers of these vehicles have been increasing from 2010 onwards,
- Investment in public transport, and
- Investments in road infrastructure.

Figure 62

Biodiesel incorporation in fuels, number of hybrid and electric (EV) and light road vehicles in Portugal



Data sources: number of vehicles – EUROSTAT; biofuels in road transportation – national energy balances from DGEG.

7.2.6 Energy efficiency measures

Energy efficiency measures in industry included:

- Introduction of natural gas in Portugal (from 1997 onwards),
- feed-in tariffs for CHP production (from 1999 onwards, DL 538/99 and Portaria 60/2002),
- the Intensive Energy Consumption Management System (SGCIE, DL 71/2008),
- amongst others.

Residential and services (including commerce and institutional) had a few energy efficiency measures, in particular, measures targeting energy efficiency in buildings. These include:

- Regulation on energy in buildings from 2006 (SCE - DL 78/2006, RCCTE - DL 80/2006; RSECE - DL 79/2006 from 4th of April), which included the compulsory installation of solar thermal energy in new buildings, and energy certification of buildings,
- Incentives for substitution of incandescent lights (from 2008),
- Incentives for micro-electricity generation (from 2008),
- Incentives for substitution of washing machines, installation or substitution of (non-double glazed or poorly insulated) windows, installation of thermal insulation, and installation of heat pumps for water heating,
- The new legislation for buildings (DL 58/2013), which will have a major impact on the energy consumption in new (residential, commercial, and service) buildings and buildings going through major renovations.

7.2.7 International agreements on ozone depleting substances (ODS)

Ozone depleting substances are present in many technologies used by modern societies such as refrigerant in air conditioning and refrigeration units and extinguishers. Regarding the regulation of the production and consumption of these substances, there are two main international agreements: the Vienna Convention (1985) and the Montreal Protocol (1987). The later has had five revisions, and the latest one in 2016. Table 24 presents a summary of the international agreements on ODS. Table 25 presents the targets that resulted from these agreements.

All of these targets are reflected in the industry, which had to find substitutes for the substances used as refrigerants and in extinguishers, and for households and services which had to maintain and dispose properly of refrigeration and air conditioning units to ensure the ODS do not escape into the atmosphere.

Table 24
Summary of main international agreements on ODS

Agreement	Summary
Vienna Convention (1985)	The countries of the world agreed the Montreal Protocol on Substances that Deplete the Ozone Layer under the Convention
Montreal Protocol (1987)	Set targets for the phase out of CFCs and freeze halons production and consumption
London Amendment (1990)	Changed the ODS emission schedule. Methyl chloroform was added to the list of controlled ODS
Copenhagen Amendment (1992)	Accelerated the phaseout of ODSs and incorporated an hydrochlorofluorocarbons (HCFC) phaseout
Montreal Amendment (1997)	Included the phaseout of HCFCs in developing countries, as well as the phaseout of methyl bromide in developed and developing countries
Beijing Amendment (1999)	Tightened controls on the production and trade of HCFCs. Bromochloromethane was also added to the list of controlled substances
Kigali amendment (2016)	Phase down the production and consumption of hydrofluorocarbons (HFCs) because these substances were adopted by industries in moving away from ozone-depleting substances and they are potent greenhouse gases damaging to the earth's climate.

Table 25
ODS targets

Substance	Base level	Target in developed countries
CFCs (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115)	1986	100 % reduction by 1 January 1996 (with possible essential use exemptions). Applicable to production and consumption.
Halons	1986	100 % reduction by 1 January 1994 (with possible essential use exemptions). Applicable to production and consumption.
Other fully halogenated CFCs (CFC-13, CFC-111, CFC-112, CFC-211, CFC-212, CFC-213, CFC-214, CFC-215, CFC-216, CFC-217)	1989	100 % reduction by 1 January 1996 (with possible essential use exemptions). Applicable to production and consumption.

Substance	Base level	Target in developed countries
Methyl chloroform	1989	100 % reduction by 1 January 1996 (with possible essential use exemptions). Applicable to production and consumption.
HCFCs	1989 HCFC consumption + 2.8 % of 1989 CFC consumption	Freeze: 1996 35 % reduction by 1 January 2004 65 % reduction by 1 January 2010 90 % reduction by 1 January 2015 99.5 % reduction by 1 January 2020, and thereafter consumption restricted to the servicing of refrigeration and air-conditioning equipment existing at that date 100 % reduction by 1 January 2030 Applicable to consumption
HCFCs	Average of 1989 HCFC production + 2.8 % of 1989 CFC production and 1989 HCFC consumption + 2.8 % of 1989 CFC consumption	Freeze: 1 January 2004, at the base level for production Applicable to production
HBFCs	Year not specified	100 % reduction by 1 January 1996 (with possible essential use exemptions). Applicable to production and consumption.
Bromochloromethane	Year not specified	100 % reduction by 1 January 2002 (with possible essential use exemptions). Applicable to production and consumption.
Methyl bromide	1991	Freeze: 1 January 1995 25 % reduction by 1 January 1999 50 % reduction by 1 January 2001 75 % reduction by 1 January 2003 100 % reduction by 1 January 2005 (with possible essential use exemptions). Applicable to production and consumption

7.2.8 Agricultural policies

Policies during the dictatorial regime

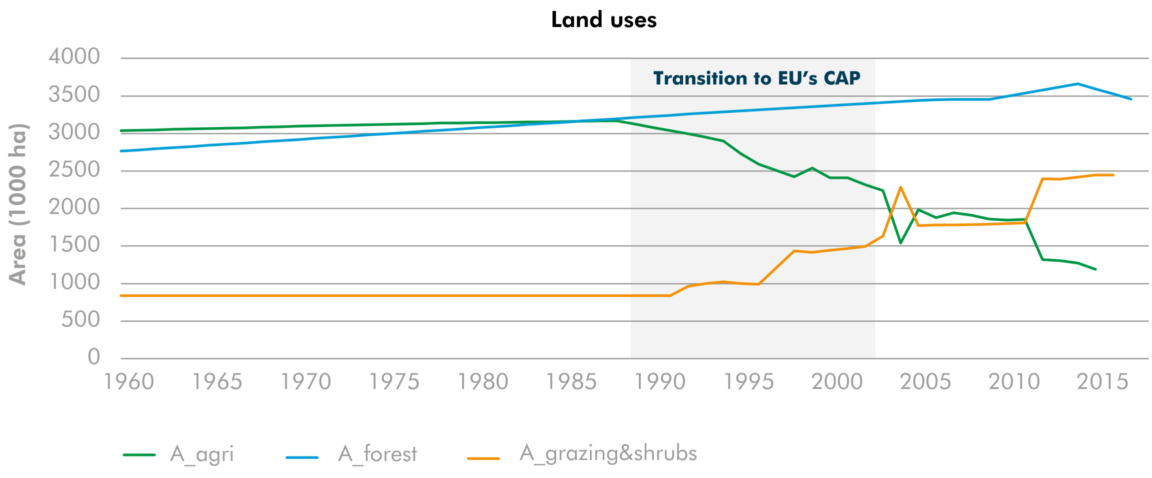
During the 50s and 60s, agriculture did not provide much income to the population in rural areas, leading to a migration of population either to the cities or to outside the country (Carmo et al. 2017). This led to an increase in abandoned areas (decrease in agricultural areas).

In the 60s and 70s, the government promoted a series of agricultural reforms, abandoning the “cereal campaign” that was in place. These reforms aimed at increasing income from agricultural activities by investing in forestry, in particular in community areas (the “baldios”), which might have contributed to a decrease in the number of extensive graze of animal, namely, sheep; investing in more profitable crops and animal production; and investing in mechanising and irrigating agriculture. The reforms failed to increase the rural population but helped maintaining the agricultural area relatively stable and increasing agricultural productivity.

As a result, between 1960 and 1974:

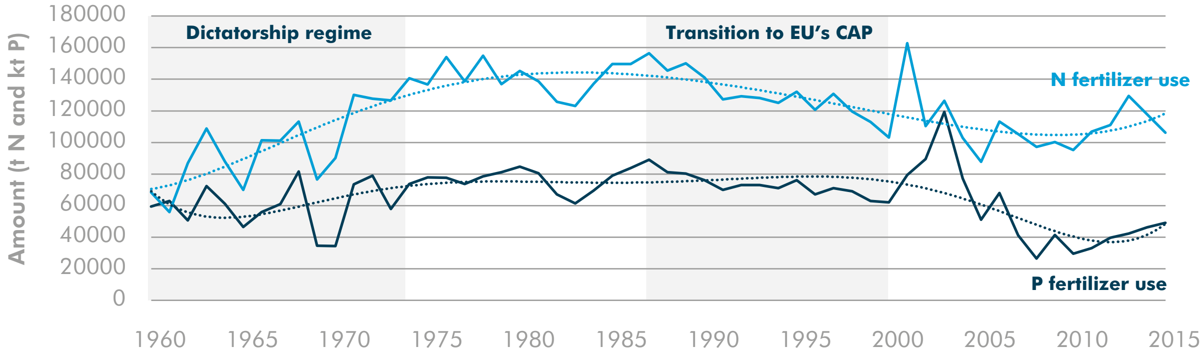
- Agricultural areas remained stable, not decreasing (Figure 63).
- Nitrogen and phosphorus fertiliser use increased, as a result of the intensification of agriculture (Figure 64).
- Wheat yields increased (Figure 65) and machinery use in agriculture have increased greatly (Figure 66).
- The number of cattle (dairy and non-dairy), goats and swine increased, but the number of sheep decreased (Figure 67).

Figure 63
Trends in land uses in Portugal



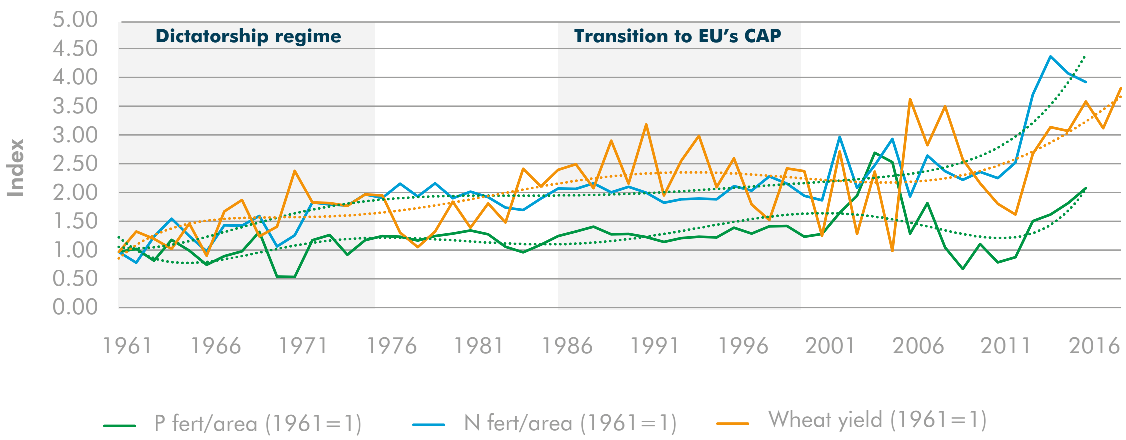
Source of data: COS for forest areas, FAOSTAT for remaining areas.
Note that agricultural and grazing areas remain fairly constant until the 80s, which could be due to low quality of data available. Grazing areas include shrubland and pastures.

Figure 64
Trends in fertiliser use in Portugal



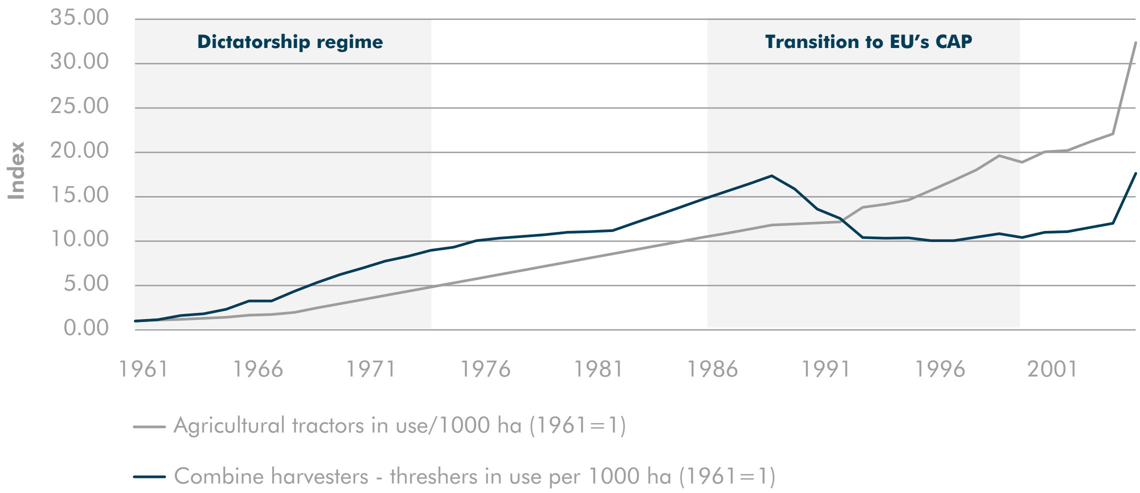
Source of data: FAOSTAT.

Figure 65
Trends in intensification of agriculture – fertiliser and crop yields per 1000 ha



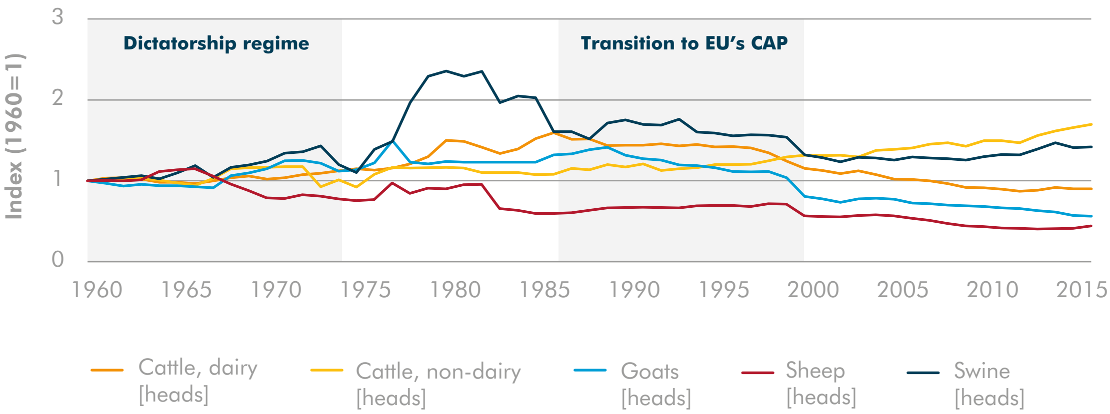
Source of data: own calculations based on FAOSTAT.

Figure 66
Trends in intensification of agriculture – machinery use per 1000 ha



Source of data: own calculations based on FAOSTAT.

Figure 67
Animal production



Source of data: FOASTAT.

Agricultural policies from the EU

Portugal joined the EU in 1986. The transition to the EU's CAP was a process that included a period for harmonising the prices of Portuguese produce with the EU prices of produce, as well as a series of alterations to the regulatory structures in Portugal (Anon. 2004). The transition period was set as the following:

- a 10-year transition period (later extended until the year 2000) to harmonise the prices of products whose price was higher than those from the remaining EU. This covered cereals (including wheat), rice, milk, and meat products. For this, EU has introduced subsidies for those products, with a decreasing trend through time, ending the subsidies in 2000 (Anon. 2004),

- a 7-year transition period for harmonising the products whose prices were lower than the ones within the remaining EU. This was the case for oils, processed fruit and vegetables and sugar.

In 1992, EU introduced a major reform to the CAP. This reform included the internationalization of EU agricultural markets that occurred in 1993, reducing its internal market protection. There was a cut on subsidies towards agriculture (Anon. 2004), except for agri-environmental measures.

During this period, the agricultural area started to decrease (Figure 63) together with nitrogen and phosphorus fertiliser use (Figure 64). Grazing areas started to increase (as a result from the abandonment of agricultural areas). Forest areas started to stabilise. Animal production, namely cattle (dairy) and goats (Figure 67), started to reduce in part due to the decreasing subsidies from the EU and the internationalisation of EU markets. As milk and meat production was subsidised by the EU, with decreasing subsidies, producer took this opportunity to invest in non-dairy cattle production, which is more intensive form of animal production.

After 2000, EU subsidies to Portuguese agriculture have greatly fallen. EU's CAP was then focused on promoting competitiveness, the environment (with income-oriented measures) and rural development. Land use areas maintained their trends (Figure 63), with agricultural areas decreasing. Wheat producer prices started to increase and then stabilise (Figure 65), and wheat yields, and nitrogen fertiliser use started to increase after a decrease, meaning that despite the agricultural area reductions, there has been an intensification of agriculture. Animal production maintained the trends observed in the transition period, with the increase in cattle (non-dairy) and decrease in the remaining types of animals (Figure 67). Exception is for swine production, which started to stabilise.

In the years 2003 and 2005 have had a large area affected by forest fires and following 2005 the government have imposed strong measures for forest fire prevention.

In sum, the Portuguese entrance into the EU brough major changes to the Portuguese agriculture, the main effects were:

- a reduction in the production on dairy cattle, swine, and goat,
- a decrease in agricultural areas and fertiliser use,
- a decrease in wheat prices and nitrogen use during the transition period, and from which Portugal started to recover in recent years,
- a stabilisation of forest area, avoiding its continuous decrease.

7.2.9 Waste policy in Portugal

According to APA (2019a) and PERSU (strategic plan for solid urban waste), the main factors affecting waste production, treatment and disposal were:

- the amount of waste generated follows the variations in GDP, due to the increase in consumption patterns and industrial activity.
- Introduction and uptake of waste collection and treatment systems.

Until late 90s, landfilling remained almost exclusively the main waste treatment practice. From 1999 onwards, separation of waste more than doubled (PERSU) and waste collection systems have increased from 40% in the 60s to 100% in 2000 (because the systems increased and because the population moved to cities, where the systems were in place).

According to PERSU, from 1999 onwards, incineration plants were also introduced:

- 1999 two waste incineration units (MSW) started their operation,
- 2001/2002 MSW incineration plant in Madeira,
- 2015 MSW incineration plant in the Azores.

From 2002, uncontrolled municipal solid waste disposal (dump sites) was eliminated.

From 2005 onwards, the increase in biogas burning from landfills (reducing methane emissions from landfill, a GHG).

Between 2007 and 2016, a new strategic plan for urban solid waste (PERSU II) was implemented. This plan foreseen the construction of mechanical and biological treatment and recovery organic units, with a view to the recovery and recycling of the biodegradable waste fraction and their diversion from landfill, as well as the reinforcement of the equipment for the recovery of the multi material fraction of waste.

In 2010, economic crisis and efforts from PERSU and PERSU II reduced the amount of wastes.

In 2014, with the economic recovery, waste production seems to increase, allied to increase in tourism which increases GDP and MSW.

From 2014, the new national plan for waste management (PNGR 2014-2020) was implemented. This plan aimed at the promotion of the use of waste as a resource, giving priority to the upstream activity of the chain of value and the integration of the Urban Waste Prevention Program. Furthermore, it supports a significant increase in separate collection and recycling and promotes the progressive elimination of direct landfilling.

7.3 TECHNICAL NOTE 3. ALLOCATION APPROACHES FOR THE INTERGENERATIONAL ANALYSIS

7.3.1 Alternative allocation approaches analysed in this study

Impact allocation by living population (allocation approach 1)

The allocation of impacts by living population allocates the impacts to each person that happen to live in a certain year with a certain impact. All population is included, from birth to 85 years of age. The result is 25 birth-cohorts.

Each biophysical indicator per year was divided by the total population in the same year, obtaining each biophysical indicator per capita and per year.

Based on the years that each birth-cohort lived, it was possible to allocate this per-capita indicator to each age group of each cohort (based on the year each age group of each cohort lived). These results are per capita, representing the impact allocated to an average citizen that lived in a particular year.

Impact allocation by working population (allocation approach 2)

The allocation of impacts by working population allocates the impacts to each person that happen to work in a certain year with a certain impact. Only working population is included. For simplicity, it was assumed that working population was the population between 15-64 years of age.

Each biophysical indicator per year was divided by the total population between ages 15 to 64 in the same year, obtaining each biophysical indicator per capita and per year.

Based on the years that each birth-cohort worked, it was possible to allocate this per-capita indicator to each age group of each cohort (based on the year each age group of each cohort lived).

Comparison of the three allocation approaches

Table 26 and Figure 68 present the impacts of each generation with each allocation approach. From the Intergenerational analysis we can see that almost all generations have had a period in their lives when their impact was high, mostly because they have lived, worked or were a head of the household during the period from 1995 to 2016 where GHG emissions were the highest.

In the approach 1, all generations had a period of their lives that they lived during the period with high GHG emissions. This means that all generations have high impacts in a period from their lives. The generation Pre-WWII Baby Boom is the one that presents the lowest impacts overall as this generation, although it lived through periods of increasing GHG emissions and the period of higher emissions, it also lived in a period of lower GHG emissions, diluting the average GHG emissions per capita per year from this generation. Generation Y and Generation Z present the highest impacts. This is because these generations lived all their lives in a period with high GHG emissions, so when averaging the impact through their lives there is no period of lower emissions to dilute the high impacts. Part of Generation Z correspond the members that have not yet entered into working age and already have a high impact in terms of GHG emissions.

In the approach 2, where impacts are allocated to the working population only, all generations had a period of their lives that they worked during the period with high GHG emissions. This means that all generations have high impacts in a period of their lives. The generation with the lowest GHG emissions' impact is Generation Z, as this generation have worked little yet, and therefore, has little impacts allocated to the generation. The generation with the highest average impact is Generation X as this generation has worked most of their lives through a period of high GHG emissions.

In approach 3 (the one selected for this study), youngest generations have lesser impacts and older generations higher impacts (Table 26). Only the generations *Pre-WWI Babby Boom*, Baby Boomers and Generation X were in a period of higher consumption when the emissions were the highest. Overall, Pre-WWII Baby Boom presents the highest average impacts closely followed by *Babby Boomers*. These generations have longer periods of their lives where they lived, worked, and consumed during high Portuguese GHG emissions.

Table 26
GHG impacts per capita for each generation, by allocation approach

Approach	Pre-WWII baby boom	Baby Boomers	Generation X	Generation Y	Generation Z
A1	3.3	4.1	4.7	5.5	5.4
A2	2.6	3.9	6.1	5.3	1.9
A3	5.8	5.6	4.0	1.7	0.0

The peaks in GHG emissions for each generation have been being lower and lower from generation to generation (Figure 68), being the highest for Baby Boomers and the lowest to Generation Y (Generation Z has not reached its peak yet). For the latter generation, the peak already occurred when they reached between 30-34. Baby Boomers present the highest impacts per capita from their 30-60 years of age.

Figure 68
GHG impacts by age, per generation

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