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# Using Accounting and Financing to Recover the Value of Natural Capital

by

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# Declaration of Authorship

I, Raul Martinez-Oviedo, declare that this thesis titled, “Using Accounting and Financing to Recover the Value of Natural Capital” and the work presented in it are my own. I confirm that:

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*"If the environment is regarded as a scarce resource, then the deterioration of the environment is also an economic problem."*

Edward B. Barbier (Barbier, 1989).

# *Abstract*

The value of natural capital in countries around the world, including the UK, has been continuously decreasing due to the degradation of natural resources. The lack of accounting and financial mechanisms dedicated to measure and recover the value of natural capital, combined with low investment allocations from private investors, have been a determinant factor contributing to this decline. Given this consideration, the present work defines three objectives in relation to natural capital accounting and finance. First, to investigate the use of natural capital accounts to study changes in natural capital value and identify the major factors impacting the risk of declining natural capital and wealth using the case study of the UK. Second, to analyse the performance of investments in natural capital assets. Finally, to examine the use of Sovereign Wealth Funds as a financial mechanism to dedicate major investments in natural capital. In relation to the first objective, a stochastic model for risk analysis is developed to estimate changes in UKs wealth using data on produced, human, and natural capital asset values reported by UK authorities between 1992 and 2012. Results show that natural capital losses in the UK have been mainly driven by a decrease in value of non-renewable natural capital, together with variations in the value of ecosystem services. Nevertheless, as non-renewable natural capital reach depletion, focus shall be given over coming years to recover renewable natural capital. As part of the second objective, the present work evaluates the performance of investments in real and non-real natural assets and compare it with those of traditional asset classes using time series analysis of historical returns. The obtained results indicate that, when investing in natural capital, investors should focus on real natural assets as their financial benefits are higher than those from equities, bonds, real estate or even some infrastructure assets. Regarding the final objective, this work models the investment portfolio of an oil-based SWF using Norways Pension Fund Global as a case study and employs out-of-sample simulation technique to estimate global efficient portfolios while considering their relationship with oil prices. In this regard, the final results demonstrate that SWFs are able to challenge their current allocation range in natural assets (2-5%) to a higher range (15-20%) while still benefiting from those investments. The overall conclusion from this research suggests that combining the importance of effective natural capital accounts, the financial benefits of natural capital investments, and the role of financial mechanisms such as SWFs is essential to increase the value of natural capital.

## JOURNAL PUBLICATIONS

- Martinez-Oviedo, R. and Medda, F. (2017) *UK's Natural and Wealth accounting.* Working Paper.
- Martinez-Oviedo, R. and Medda, F. (2017) *Real natural assets: The real green investment alternative.* Accepted in the Journal of Alternative Investments.
- Martinez-Oviedo, R. and Medda, F. (2017) Assessing the effects of adding timberland and farmland into resource-based Sovereign Wealth Fund portfolios. *Journal of Economics and Business*, 91, pp. 24-40.

## CONFERENCE PUBLICATIONS

- Martinez-Oviedo, R. and Medda, F. (2017) Real Natural assets: The real green investment alternative. 16th Finance, Risk and Accounting Perspectives Conference. Acrn Oxford, Cambridge, UK.
- Martinez-Oviedo, R. and Medda, F. (2015) Assessing the impact of natural capital on the risk of depleting UK wealth. Regional Studies Association Winter Conference 2015, November, London, UK.
- Martinez-Oviedo, R. and Medda, F. (2014) Building the green economy with Sovereign Wealth Funds. Regional Studies Association Winter Conference 2014, November, London, UK.

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*Raul*

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# Abbreviations

| | |
|---|---|
| **AIC** | **A**kaike **I**nformation **C**riterion |
| **CBI** | **C**limate **B**ond **I**nitiative |
| **CPI** | **C**onsumer **P**rice **I**ndex |
| **DECC** | **D**epartment **E**nergy **C**limate **C**hange |
| **DEFRA** | **D**epartment for **E**nvironment **F**ood & **R**ural **A**ffairs |
| **ET** | **E**cological **T**axes |
| **GBM** | **G**eometric **B**rownian **M**otion |
| **GDP** | **G**ross **D**omestic **P**roduct |
| **GHG** | **G**reen **H**ouse **G**ases |
| **GPFG** | **G**overnment **P**ension **F**und **G**lobal |
| **GSA** | **G**lobal **S**ensitivity **A**nnalysis |
| **LHS** | **L**atin **H**ypercube **S**ampling |
| **LULUCF** | **L**and **U**se, **L**and **U**se **C**hange and **F**orestry |
| **MENE** | **M**onitor of **E**ngagement with the **N**atural **E**nvironment |
| **MVO** | **M**ean **V**ariance **O**ptimization |
| **MPT** | **M**odern **P**ortfolio **T**heory |
| **MR** | **M**ean **R**everting |
| **PES** | **P**ayment for **E**cosystem **S**ervices |
| **PIM** | **P**erpetual **I**nventory **M**ethod |
| **SAA** | **S**trategic **A**sset **A**llocation |
| **SWF** | **S**overeign **W**ealth **F**und |

# Symbols

| **Symbol** | **Name** | **Unit** |
|---|---|---|
| Chapter 4 | | |
| $W_t$ | Total wealth at time $t$ | £mn |
| $C_t^P$ | Produced capital at time $t$ | £mn |
| $C_t^H$ | Human capital at time $t$ | £mn |
| $C_t^N$ | Natural capital at time $t$ | £mn |
| $A^P$ | Set of produced capital assets | |
| $A^N$ | Set of natural capital assets | |
| $I_t^a$ | Investment in capital asset $a$ at time $t$, $\forall a \in A^P$ | £mn |
| $\gamma_t^a$ | Depreciation rate for asset $a$ at time $t$, $\forall a \in A^P$ | |
| $Y_{g,d,t}$ | Lifetime labour income | £ |
| $N_{g,d,t}$ | Number of employed individuals | |
| $E_{g,d,t}$ | Employment rate | |
| $B_{g,d,t}$ | Annual labour income | £ |
| $\Pi_{g,d,t}$ | Probability of upgrading educational attainment level | |
| $h_{g,t}$ | Mortality rate for age group $g$ at time $t$ | |
| $\kappa$ | Productivity growth rate | |
| $\rho$ | Discount rate | |
| $e_t$ | Changes in employment rate at time $t$ | |

| | | |
|---|---|---|
| $D_t$ | GDP growth at time $t$ | |
| $U_t$ | Unemployment rate at time $t$ | |
| $K_t^a$ | Resource rent for capital asset $a$ at time $t$, $\forall a \in A^N$ | £mn |
| $\chi^a$ | Life span of capital asset $a$, $\forall a \in A^N$ | Years |
| $P_t^a$ | Market price for capital asset $a$ at time $t$, $\forall a \in A^N$ | £ |
| $\delta_t^a$ | resource rent ratio at time $t$ for asset $a$, $\forall a \in A^N$ | |
| $S_t^a$ | Production level of asset $a$ at time $t$, $\forall a \in A^N$ | |
| $P_t^o$ | Crude oil market price at time $t$ | £/barrel |
| $P_t^g$ | Gas market price at time $t$ | p/therm |
| $S_t^o$ | Oil production at time $t$ | barrels |
| $S_t^g$ | Gas production at time $t$ | bn therms |
| $q_t^o$ | Oil & gas operating cost | £mn |
| $q_t^d$ | Oil & gas decommissioning cost | £mn |
| $q_t^u$ | Oil & gas user cost of produced assets | £mn |
| $\theta_t^a$ | Industrial output for asset $a$ at time $t$, $\forall a \in A^N$ | £mn |
| $\omega_t^a$ | Intermediate consumption for asset $a$ at time $t$, $\forall a \in A^N$ | £mn |
| $\nu_t^a$ | Compensation of employees for asset $a$, $\forall a \in A^N$ | £mn |
| $\eta_t^a$ | Difference between taxes and subsidies for asset $a$, $\forall a \in A^N$ | £mn |
| $\zeta_t^a$ | Fixed capital consumption for asset $a$, $\forall a \in A^N$ | £mn |
| $\phi_t^a$ | Return to produced assets for asset $a$, $\forall a \in A^N$ | £mn |
| $L_t^T$ | Timberland stocked area at time $t$ | ha |
| $l_{i,t}^T$ | Stock area of timberland associated to age category $i$ at time $t$ | ha |
| $P_t^w$ | Stumpage price of wood at time $t$ | £/m$^3$ |
| $\varphi$ | Volume of timber per area at harvesting age | m$^3$ / ha |
| $M_t$ | Transport fuel cost at time $t$ | £ |
| $Z_t$ | Average hourly wage at time $t$ | £ |
| $F_t$ | Average duration of a visit to recreational sites at time $t$ | h |
| $v_t$ | Annual number of visits to recreational sites at time $t$ | |
| $L$ | UK total land area | ha |
| $\Lambda_t^j$ | Net GHG emissions for land category $j$ at time $t$ | tCO2e |
| $P_t^s$ | Social price of carbon at time $t$ | £/tCO2e |

| | | |
|---|---|---|
| $X_t$ | UK total population at time $t$ | |
| $R^W$ | Risk of declining per capita wealth | |
| $R^N$ | Risk of declining per capita natural capital | |

Chapter 5

| | | |
|---|---|---|
| $\theta^2_{k,t}$ | Liquidity index for company $k$ on a month $t$ | |
| $r_{k,d,t}$ | Return on the stock for company $k$ on day $d$ on a month $t$ | |
| $r^{xs}_{k,d,t}$ | Excess return on the stock for company $k$ on day $d$ on a month $t$ | |
| $r^{mkt}_{k,d,t}$ | Market return on the stock for company $k$ on day $d$ on a month $t$ | |
| $vol^{mkt}_{k,d,t}$ | Volume of stocks traded for company $k$ on day $d$ on a month $t$ | US$bn |

Chapter 6

| | | |
|---|---|---|
| $v_t$ | Fund's market value at time $t$ | US$bn |
| $I_t$ | Cash inflows to the fund at time $t$ | US$bn |
| $C_t$ | Fund's management cost at time $t$ | US$bn |
| $\gamma$ | Percentage of oil revenues allocated to the fund | |
| $e_t$ | Crude oil exports at time $t$ | barrels |
| $p_t$ | Crude oil price at time $t$ | US$/barrel |
| $r^{eq}_t$ | Composite return for equities at time $t$ | |
| $r^{re}_t$ | Composite return for real estate at time $t$ | |
| $r^{na}_t$ | Composite return for natural assets at time $t$ | |
| $N^{eq}$ | Set of equity investments | |
| $N^{re}$ | Set of real estate investments | |
| $N^{fi}$ | Set of fixed income investments | |
| $N^{na}$ | Set of natural asset investments | |
| $\alpha^{eq}$ | Percentage of assets allocated into equities | |
| $\alpha^{re}$ | Percentage of assets allocated into real estate | |
| $\alpha^{fi}$ | Percentage of assets allocated into fixed income | |
| $\alpha^{na}$ | Percentage of assets allocated into natural assets | |
| $\mathbf{w}^{eq}_t$ | Set of weights allocated to equity assets | |
| $\mathbf{w}^{re}_t$ | Set of weights allocated to real estate assets | |

| | |
|---|---|
| $\mathbf{w}_t^{fi}$ | Set of weights allocated to fixed income assets |
| $\mathbf{w}_t^{na}$ | Set of weights allocated to natural capital assets |
| $\mathbf{w}_{G,t}^{eq}$ | Global efficient weights allocated to equity assets |
| $\mathbf{w}_{G,t}^{re}$ | Global efficient weights allocated to real estate assets |
| $\mathbf{w}_{G,t}^{fi}$ | Global efficient weights allocated to fixed income assets |
| $\mathbf{w}_{G,t}^{na}$ | Global efficient weights allocated to natural capital assets |
| $\mathbf{z}_t^{eq}$ | Set of returns for equity assets at time $t$ |
| $\mathbf{z}_t^{re}$ | Set of returns for real estate assets at time $t$ |
| $\mathbf{z}_t^{fi}$ | Set of returns for fixed income assets at time $t$ |
| $\mathbf{z}_t^{na}$ | Set of returns for natural capital assets at time $t$ |

*Dedicated to Nana OTA*

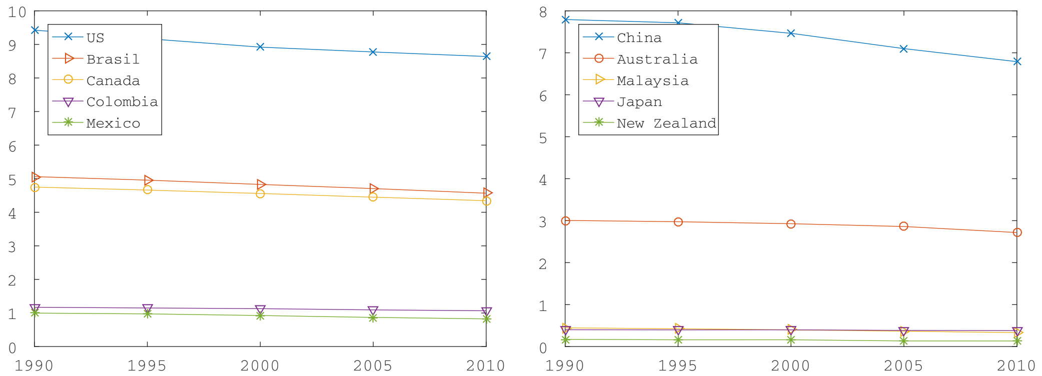
# 1

# Introduction

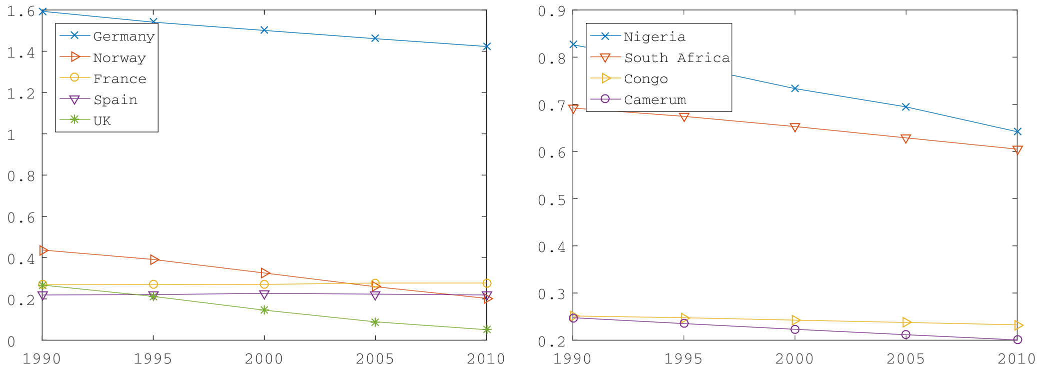
## 1.1 Background

The value of natural capital in countries around the world has been consistently declining over the past decades. In the UK, for instance, the Office for National Statistics's (ONS) initial estimates suggest that natural capital losses in this country were as high as £183 billion (in constant 2014 £s) between 2009 and 2014, indicating a drop of 32.3% in only five years (ONS, 2016c). Similar trends are also found in many other countries. Figure 1.1 shows the trends of natural capital value between 1990 and 2010 in 19 different countries across the Americas, Europe, Asia and Africa, using the most recent estimations provided by the UN University International Human Dimension Programme (UNU-IHDP) and the UN Environmental Programme (UNEP) in the Inclusive Wealth Report (UNEP&UNU-IHDP, 2014). The information from the figure is also given in Table 1.1, which presents the changes in natural capital net value per country and their corresponding percentages. From the values shown in the figure and the table, we can conclude that, with the exception of France, the value of natural capital in the rest of the countries is on downward trajectory. Moreover, when we examine the Inclusive Wealth Report data in detail, we can confirm that this situation is actually shared by the vast majority of countries worldwide.

Many scholars, including Rands et al. (2010); Hails and Ormerod (2013); Barbier (2014b) and Mace et al. (2015), agree that the generalised loss of natural capital



(a) Americas (b) Asia



(c) Europe (d) Africa

FIGURE 1.1: Natural capital values reported by the Inclusive Wealth Report in trillions of constant 2005 US$ (UNEP&UNU-IHDP, 2014).

value is mainly the result of human-induced factors such as overexploitation of natural resources, soil erosion, water pollution, loss of biodiversity, and increasing population. These factor are also recognized by Benwell et al. (2014), who in addition point to the inadequate consideration for nature within decision-making as one of the most important reasons for nature's decline. It has become widely accepted that the lack of accounting and financial mechanisms dedicated to the measurement and recovery of the value of natural capital has contributed to the degradation of nature (Smith et al., 2017; MEA, 2005). Rapacioli et al. (2014), for instance, suggest that because of the absent of proper accounts, natural capital have been largely hidden from the corporative narrative, ignored by most investors, and excluded from government agendas, resulting in declining trends of natural capital reserves. Moreover, Guerry et al. (2015) argue that the value of natural capital is not always clear to decision makers or the public, limiting the adoption of tangible changes in the operation of business and governments. This argument

Table 1.1: Natural capital value change per country, 1990-2010. Source: UNEP&UNU-IHDP (2014).

| **Region** | **Country** | **Value change (in million 2005 US$)** | **% of change** |
|---|---|---|---|
| Americas | US | -784,631 | -8.3% |
| | Canada | -405,394 | -8.5% |
| | Mexico | -172,269 | -17.3% |
| | Brasil | -493,630 | -9.8% |
| | Colombia | -103,471 | -8.8% |
| Europe | Germany | -170,403 | -10.7% |
| | Spain | -90 | -0.0% |
| | France | +8,452 | +3.1% |
| | UK | -216,281 | -81.0% |
| | Norway | -234,100 | -53.6% |
| Africa | Nigeria | -184,234 | -22.3% |
| | Congo | -18,759 | -7.5% |
| | Cameroon | -47,153 | -19.0% |
| | South Africa | -87,100 | -12.6% |
| Asia & Oceania | China | -1,003,511 | -12.9% |
| | Japan | -20,769 | -5.2% |
| | Malasya | -113,155 | -25.4% |
| | Australia | -288,567 | -9.6% |
| | NZ | -38,652 | -22.5% |

is also supported by Zhang et al. (2010) and Jones (2010), who report that in the absence of robust natural capital accounting systems and support investment mechanisms, the valuation of nature stays outside the realm of economic activity and decision-making, and also prevents private enterprise and public authorities from developing strategies to reverse the declining trends witnessed today.

Therefore, as stressed by Helm (2015), if the value of natural capital is to be recovered, actions must be taken to develop and implement natural capital accounts that provide information on the condition of natural resources. In this regards, Bateman et al. (2015) show an example of how monetary valuation of natural assets and ecosystem services can be helpful to this purpose. Moreover, natural capital accounts are an important additional tool for informing on sustainable development (WAVES, 2014). Such accounts allow to identify areas of natural capital deficit that may require intervention or prioritize investments (NCC, 2014a).

The TEEB (2010) recognizes that accounting for natural capital provides a meaningful approach to treat ecosystem impacts as externalities and put sustainability into practice. In addition to natural capital accounts, novel financial mechanisms able to dedicate significant investments in natural capital assets should be also introduced in order to maintain and recover the value of natural capital (NCC, 2014b). Recovering natural capital value and reversing decreasing trajectories are essential to national and regional authorities in their aim to achieve sustainable development goals (Dasgupta, 2010), they are important for the society to secure levels of well-being (Dasgupta, 2004), and they are integral to the long-term decision-making strategies of businesses (NCC, 2016).

Many international organisations, national governments, private sector entities, and academics have nevertheless focused strongly in recent years on creating natural capital accounts and furthering the development of financial mechanism for natural capital. Examples of efforts by international organisations include the introduction of ecosystem assessments, such as the Millennium Ecosystem Assessment (MEA, 2005) and the TEEB report (TEEB, 2010), for identifying and classifying the range of economic benefits derived from nature. In addition, the UN Statistical Commission has introduced the System for Environmental-Economic Accounting (SEEA-CF, 2012) as an international framework to provide guidance on how to quantify natural capital value. Similarly, institutions such as TheWorldBank (2001) and the UNEP&UNU-IHDP (2014) have presented some of the first valuations of natural capital in multiple countries as part of their work to account for the wealth of nations. A number of national authorities worldwide have also developed and implemented their own national natural capital accounting systems. Prominent examples include the national governments of Norway (Alfsen and Greaker, 2006), the UK (ONS, 2012), Australia (BureauOfMethodology, 2013), Sweden (StatisticsSweden, 2015), and Canada (StatisticsCanada, 2016), leading countries in the practical implementation of natural capital accounts. Contributions from the private sector include the Natural Capital Coalition's creation of the Natural Capital Protocol (NCC, 2016), a set of natural capital accounting principles specifically designed for private corporations and businesses. On the academic side, most of the research focused primarily on the study of two different aspects of natural capital: the relationship between natural capital and sustainable development (e.g. Hamilton and Hartwick (2005), Arrow et al. (2012), Arrow et al. (2013), Dasgupta (2010)), and the integration of natural capital accounts into decision-making (e.g. Ruckelshaus et al. (2015), Oosterhuis and Ruijs (2015), Greenhalgh (2015), Hedden-Dunkhorst et al. (2015), Schaefer et al. (2015), Galler et al. (2016)).

Despite the significant progress achieved to date in the study of natural capital, only scant research is dedicated to the specific study of the use of natural capital accounts to assess changes in the value of natural capital over time. A few examples in the literature include Lange (2004), who measures natural capital value changes in Botswana and Namibia; Ollivier and Giraud (2011), who evaluate natural capital trajectories in Mozambique; and Dasgupta (2014), who assesses changes in natural capital value in India. Yet, to the best of our knowledge, no work in the literature has previously addressed this challenge for the specific case of the UK. In addition, the Natural Capital Committee (NCC, 2014a) also recognises that very little research has been carried out to investigate the performance of natural capital investments and on how to develop new approaches for natural capital financing. Investments in natural capital continue to be regarded as alternative investments of secondary importance for private investors when compared to traditional asset classes (i.e., equities, bond instrument or real estate); and this is likely due to the lack of consensus on their financial benefits (see e.g., Olsson (2007), Eichholtz et al. (2012), Chan and Walter (2014), Silva and Cortez (2016)). Moreover, approaches for natural capital investments are still limited in number or do not yet present the most appropriate types of natural capital in which to invest (CLA, 2016). By examining the financial performance of natural capital investments and contrasting their outcomes with those of other financial instruments, we will have demonstrated in the present thesis the attractiveness of natural capital investments to private investors.

## 1.2 Objectives and research questions

In view of the aforementioned considerations, the research conducted here investigates the importance of natural capital accounting in the measurement of changes of natural capital value over time, and in the use of financial mechanisms to invest in natural capital. We examine three specific aspects of natural capital in detail from both a financial and a macroeconomic perspective. First, we analyse the major factors driving changes in the value of natural capital stock and its relationship with other capital assets such as produced and human capital. Second, we study the performance of investments in natural capital and discuss their implications for private investors. And third, we examine the use of Sovereign Wealth Funds (SWFs) as a unique financial instrument for investing in and preserving the value of natural capital. In the present research we identify three specific objectives

- To evaluate changes in natural capital value within the framework of total wealth by considering the UK case study.
- To study the performance of investments in natural asset forms and to compare them with the performance of traditional asset classes (i.e., equities, fixed income, and real estate instruments).
- To investigate the capability of SWFs to act as financial mechanisms for preserving the value of natural capital by dedicating significant investments in natural assets.

The first objective aims to provide an answer to the research questions: What are the main drivers of changes in natural capital value? And how can this information be used to improve natural capital management? Moreover, which natural assets are more exposed to the risk of declining in value? And what are the major factors impacting that risk? To answer these questions and in order to address the first objective, the work presented in Chapter 4 focuses on the wealth composition of the UK and analyses the changes in the value of its natural capital. A stochastic model for risk analysis is developed to estimate changes in the UK's produced, human, and natural capital through the use of data reported by national authorities between 1999 and 2012. The model incorporates some of the most relevant empirical relationships existing among capital assets and macroeconomic variables of interest for which data was available. In addition, the model estimates the risk of declining per capita values of natural capital and wealth and identifies the major factors influencing those risks using sensitivity analysis in future scenarios. Results from this part of the research suggest that the decline of natural capital value in the UK, between 2003 and 2013, has mainly been driven by a loss of non-renewable natural capital, together with variations in the value of ecosystem services. However, as levels of non-renewable natural capital continue to be depleted, attention is expected to be paid over the coming years to recover renewable natural capital.

The second objective addresses the following questions. What are the main financial benefits and challenges associated with natural capital investments? How do these investments need to be attractive and convenient for private investors? Moreover, how do investments in natural capital assets impact an investor's portfolio composed of traditional asset classes (i.e., equity, real estate, fixed income) and other non-traditional assets (i.e., infrastructure)? To this end, we conduct an analysis of price time series, extending from 2000 to 2016, for real and non-real natural assets in Chapter 5. The financial evaluation focuses on estimating the average return, volatility, downside risk, diversification potential, inflation protection, and liquidity risk exhibited by the assets. Optimal portfolios are constructed using Markowitz optimisation models that are periodically updated employing out-of-sample simulation techniques. Our findings reveal, importantly, that investments in real natural assets outperform investments in traditional asset classes. Moreover, it is demonstrated that investments in real natural assets provide higher expected returns, lower volatility, protection against unexpected inflation, reduced downside risk, and lower exposure to liquidity shocks in financial markets compared to traditional portfolios. Thus, real natural assets may be regarded as very attractive for investors. However, the same level of benefits does not hold true for non-real natural asset investments.

Finally, our third objective answers the questions: Can specific financial mechanisms such as SWFs actually support the preservation of natural capital value? Can this emerging type of fund benefit from increased investments of their resource rent in renewable forms of natural capital? As a case study in Chapter 6, we model the investment portfolio of an oil-funded SWF using Norway's Pension Fund Global (the world's largest SWF by 2017). We evaluate the performance of the fund, when including allocations in natural capital, over a nine-year period extending from March 2007 to March 2016. We employ Gintschel and Scherer (2008)'s optimisation method to estimate global efficient portfolios for asset allocation while also considering the relationship between investments and commodity price fluctuations. Results in this case demonstrate that the inclusion of real natural asset investments in the portfolio of an oil-based SWF has a positive effect on the performance of the portfolio. The benefits manifest as higher expected returns, lower volatility, greater savings, and hedging against oil price risk. In fact, results suggest that SWF investors can reconsider their traditional allocation levels in natural assets (2-5%) by raising them significantly (15-20%) and still benefiting from these investments. And in doing so, SWFs would also support other major investments dedicated to the recovery of natural capital value.

## 1.3 Thesis contribution

The main contributions of this thesis are, accordingly, oriented towards increasing the understanding of (i) the major factors driving changes in natural capital value for the specific case of the UK, (ii) the types of natural capital investments that are more attractive to private investors, and (iii) how specific financial mechanisms such as SWFs can be implemented to support significant investments in natural capital.

In this regard, results derived from the work on natural capital and wealth accounting contribute to building a picture of the current condition of the UK's natural capital. Natural capital in the UK represents by far the lowest fraction of wealth in this country when compared to the values of human and produced capital. The majority of the UK's natural capital value is found in the measurement of ecosystem services rather than in non-renewable or renewable natural capital. Additionally, unlike human or produced capital, natural capital values are less associated with variations in the economic performance of the country as reflected in GDP changes. And yet, the value of all forms of natural capital in the UK has been decreasing in the last 10 years, with the rate of decline being particularly fast for non-renewable natural capital. A significant contribution of the present work is the finding that the loss of natural capital value has not been mainly driven by variations in GDP, but rather by the progressive depletion and deterioration of natural capital reserves. This particular contribution confirms the findings reported by the 'Nature and Wellbeing Act' Green paper published by Benwell et al. (2014) on UK's nature condition. Another contribution is that we have identified that future trajectories of aggregate natural capital may be reversed from declining trends, under optimistic scenarios, if the value of ecosystem services is increased. Nevertheless, an apparent overall increase of natural capital due to higher valuation of ecosystem services may mask falls in the value of other natural capital forms. Finally, we also find that as non-renewable natural capital reaches depletion, factors from renewable natural capital such as the output of the agriculture and water industries will overtake in importance those of fossil fuel production for impacting the risk of declining per capita levels of natural capital.

With regard to the second point, it is noteworthy that the thesis findings on natural capital investments contribute by identifying some of the benefits for institutional investors who dedicate major investments in real natural capital assets. Supported by results, in this part of the work, we argue that investments in real natural capital assets will be regarded as an investment option with the same relevance as traditional asset classes, and not as a mere alternative. The present thesis shows that investments in real natural assets can out perform certain assets such as equities, bonds, real estate, and even infrastructure. Moreover, when adding real natural assets into a portfolio composed of traditional assets, financial benefits are observed as higher expected returns, lower volatility, and increased diversification potential. The results obtained in this thesis also contribute to confirming that investments in real natural assets provide hedging against inflation, and in particular against unexpected inflation. Nevertheless, we also emphasise that in order to access the benefits of real natural capital investments, investors should ideally possess long investment horizons and large amounts of capital under management. These two factors still represent the greatest barriers against increasing allocations in real natural assets.

Lastly, the present research on SWFs contributes insights via our demonstration of how these funds can be successfully implemented as natural capital funds to maintain the value of natural capital. SWFs are able to manage the revenues received from non-renewable natural capital exploitation, convert them into a financial wealth form, and reinvest them in renewable natural capital. Thesis results also show that SWF portfolios can significantly increase their allocations in natural capital from current standard levels (3-5%) to a much higher level (15-20%) and still benefit from these investments. By including natural assets as a large fraction of the investment portfolio, an SWF can increase its level of returns, reduce volatility, and hedge inflation against commodity risk. Moreover, we find that these benefits are higher during periods of financial hardship and in circumstances where natural asset investments are carried in replacement of equity investments. Thus, if SWFs push their allocations in natural capital assets to higher levels, these funds are likely not only to improve their performance but also to be reconfigured as a new investment approach for natural capital.

## 1.4 Thesis structure

The structure of the thesis is illustrated in Figure 1.2, and the content of the next chapters is organised as shown below.

In Chapter 2, we provide an overview of the concept of natural capital within the framework of the capital approach to sustainability. The chapter also discusses the importance of natural capital accounting to support decision making and presents

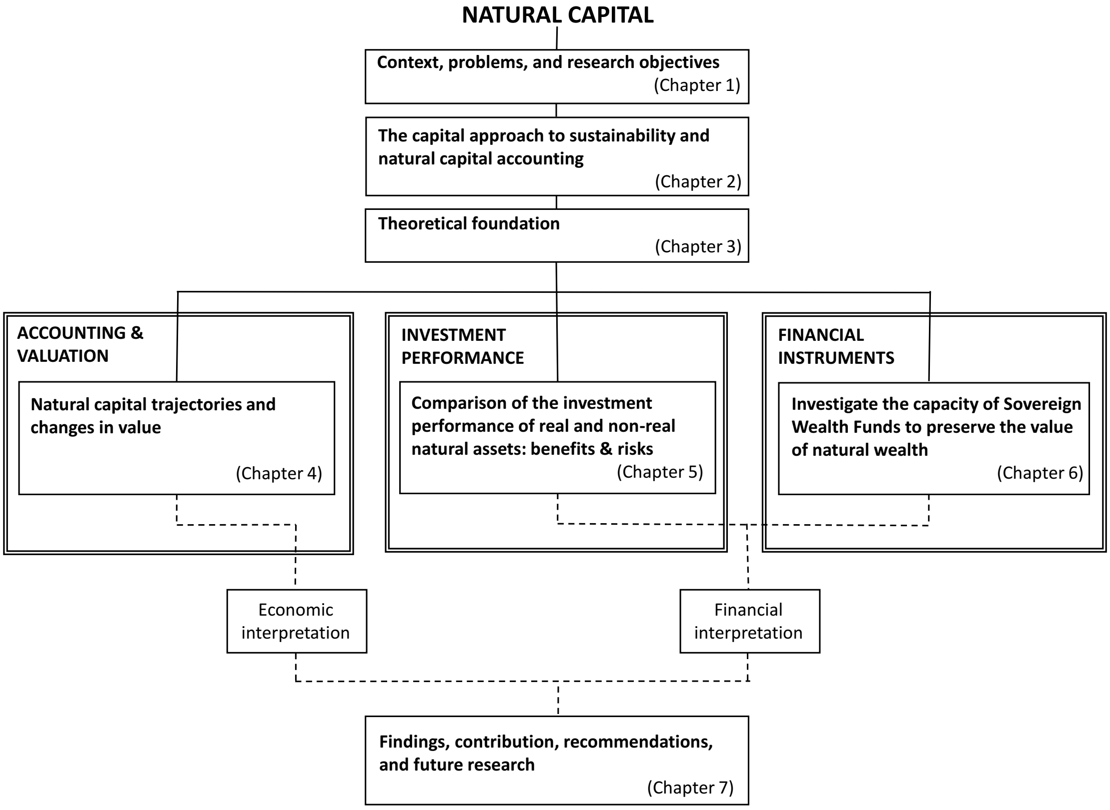


Figure 1.2: Schematic representation of the thesis structure

the latest progress in this subject achieved worldwide and in the UK. In addition, we discuss some of the major challenges faced in natural capital accounting, which is one of the motivations for the present research.

In Chapter 3, we introduce the theoretical foundation for this research. This chapter describes the relevant theoretical concepts, methods, and fundamental definitions underlying the methodologies implemented in the chapters to follow. A description of some of the stochastic processes most commonly used to model commodity prices in natural capital valuation is presented, in addition to an introduction to global sensitivity analysis which we use to estimate the sensitivity of the natural capital model developed in this work. Here, we discuss some of the most relevant relationships in macroeconomic theory and which are also relevant to natural capital value changes. Lastly, we provide a description of the portfolio optimisation techniques for asset allocations.

Chapter 4 presents the analysis of the UK's natural capital accounting and asset valuation. This chapter includes a literature review on wealth accounting and its applications, a description of the methodology followed by a stochastic model for UK wealth, and a discussion of the relationships established among capital assets. The simulation results on assessing the trajectories of natural capital changes are also provided.

Chapter 5 introduces the study on the performance of investments in natural assets. This chapter presents a comparison of the investment performance between non-real and real natural capital assets, focusing in particular on the risk-return characteristic, downside risk, correlation with traditional asset classes, diversification potential, their ability to hedge inflation, and their exposure to shocks in stock market liquidity.

Chapter 6 sets out the analysis of SWFs as instruments for the preservation of natural capital. This chapter introduces a model of an SWF portfolio based on the portfolio of Norway's Government Pension Fund Global and assesses its performance when investing in real natural assets. The capacity of these funds to manage and invest in natural capital is evaluated, and the results describing the significant benefits from these investments are discussed.

Finally, in Chapter 7, we provide a summary of the main conclusions and findings derived from this work. This last chapter discusses the main contributions of the thesis to the literature, introduces the limitations of the work conducted here, and provides suggestions for further research.

# 2

# An overview of Natural Capital

## 2.1 Definition

Natural capital refers to the stock of natural assets and ecosystem services that provide value, directly or indirectly, to people and the economy (NCC, 2014c). The concept of natural capital was first introduced at the end of the 1980's as a result of a more ecologically aware thinking in economics (Akerman, 2003). As explained by Akerman (2003), Pearce (1988) was the first economist to use the expression 'natural capital' to refer to the set of natural resources and services provided by nature. During the 1990's, the emergence of environmental and ecological economics broadly adopted the concept in order to incorporate environmental constraints into economic analysis (Costanza, 1991). And later, in the 2000's, the Millennium Ecosystem Assessment (MEA, 2005) work on assessing the benefits derived from nature, agreed on natural capital as the sum of exhaustible or non-renewable natural resources, renewable natural resources, and ecosystem services. The current application of the term 'ecosystem services' encompasses the different stream of benefits derived from nature that are essential for supporting human wellbeing and economic development. MEA (2005) bundles ecosystem services into four main categories: (i) provisioning services (e.g., food provision, freshwater provision, wood and fiber, fuel, energy, etc.); (ii) regulating services (e.g., climate regulation, food regulation, disease regulation, water purification, etc.); (iii) supporting services (e.g., nutrient cycling, soil formation, primary production, etc); and (iv) cultural services (e.g. aesthetic, recreational, spiritual, educational, etc). Figure 2.1 sets out a schematic representation of the different forms of natural capital.

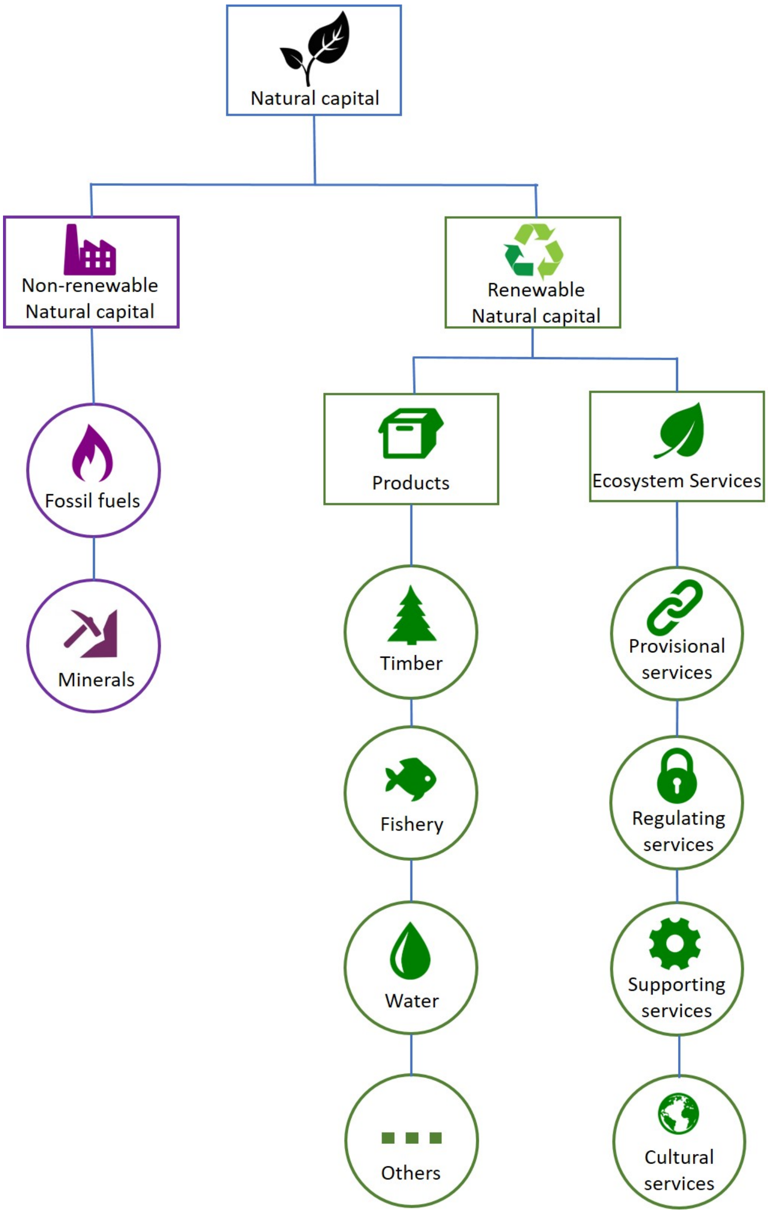


FIGURE 2.1: Natural capital categories
Source: Eden Tree.

Human wellbeing is fully dependent on the services and products provided by natural capital. Nature provides essential life supporting elements including the air we breath, the water we drink, the food we eat, the climate in which we live, and the places and other species that define our environment. Figure 2.2 illustrates the linkages between categories of ecosystem services and several components of human wellbeing. Provisioning services are the products people obtain from ecosystems, such as food, fuel, fibre, wood, fresh water, and genetic resources. Regulating services are the benefits people gain from the regulation of ecosystem processes, including air quality regulation, climate regulation, erosion control, human diseases prevention, and water purification. Cultural services are the non-material benefits people obtain from ecosystems through spiritual fulfilment, cognitive development, reflection, and recreation. And supporting services are those necessary for maintaining all other services, such as primary production, oxygen generation, and soil formation. Changes in these services affect human wellbeing in many ways through impacts on security, the basic material for good life, health, and social and cultural relations. These constituents of wellbeing, ultimately, have an influence on the freedoms and choices available to people. Security may be affected by changes in provisioning and regulating services, which impact supply of food, water and other goods, the likelihood of conflict over declining resources, or the frequency and severity of natural hazards. For example, food shortage has been a serious concern among some Sub-Saharan African nations over the last decade (FAO, 2017), and mangrove forests are a essential to protect coastal residents from storms in Vietnam (Kousky, 2010). The ability to access resources for a good life is related to provisioning services such as food and fibre production and regulating services including water purification. People's health is strongly associated to both provisioning services, including food production, and regulating services such as those influencing the spread of transmitting diseases. Degradation of fishery resources, for example, may derive in a declined protein consumption for local coastal communities (Tidwell and Allan, 2001), and degradation of water and forest resources may increase the burden attributable to malaria in tropical countries (Pruss-Ustun and Corvalan, 2006). Human spiritual values and social relationships are influenced and shaped by changes to cultural services, which impact the degree of human experience. For instance, Osuri et al. (2014) describe how local villages in India preserve sacred groves of forest for spiritual reasons, and Mexia et al. (2018) show how urban parks provide important recreational and social hubs in cities around the world. The capability of people to access to freedoms and make choices is subjected to the degree of existence of all these components of wellbeing. Therefore, maintaining minimum levels of natural capital stock and services is necessary to ensure and enhance multiple factors of human's life.

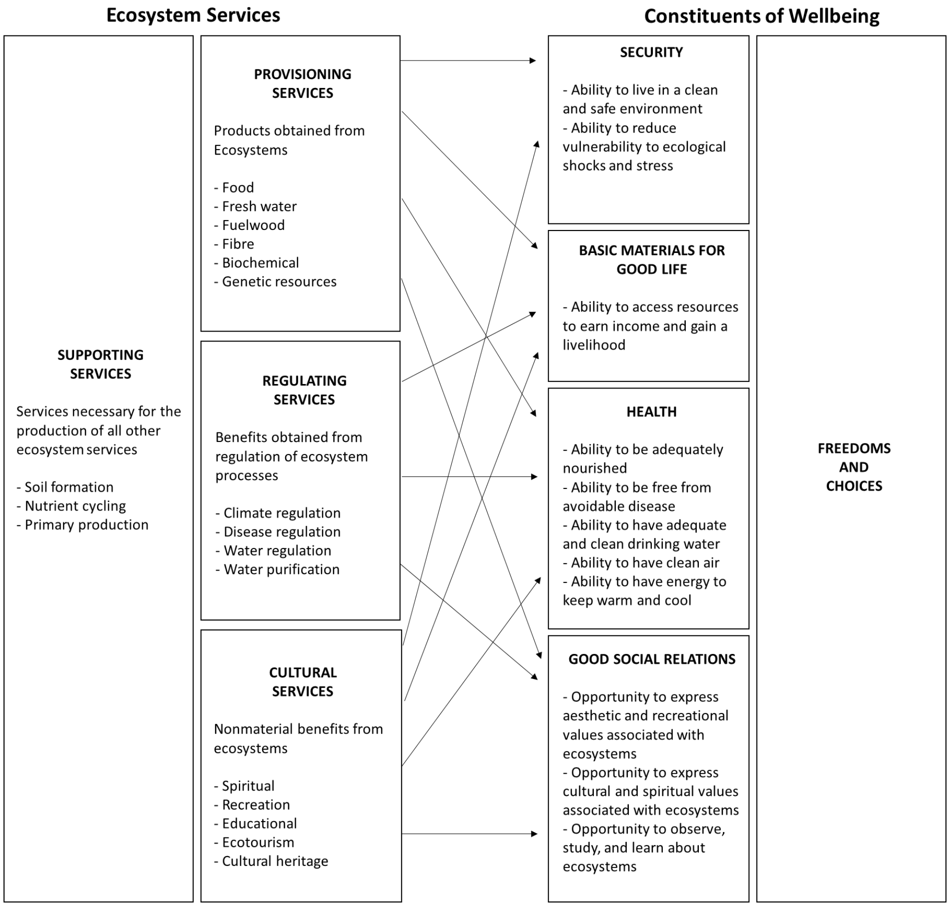


FIGURE 2.2: The role of ecosystem services for human wellbeing
Source: MEA (2005).

In addition to human wellbeing components, countries economic growth and development is also dependent upon the flow of natural capital services. Traditional natural resource-based industries such as agriculture, forestry, mining, energy, fishery or tourism are vital for many countries, particularly for developing economies (Jovic et al., 2016). Moreover, macroeconomic factors such as income and employment, relevant indicators of an economy's health, are also influenced by the condition of natural resources in both developed and developing countries. Changes in natural capital services may also impact the economic performance of nations and their capability to develop urban and industrial centres. Increased production of crops, fishery, forest, and mining products, as well as, ecotourism services have been associated with significant growth in local and national economies, increased employment, and improved labour productivity (Onate-Calvin et al., 2018; Cuellar, 2017; Horsley et al., 2015). Similarly, in regions where productivity has declined due to land degradation, overharvesting, or resource depletion the impacts on local economies and employment can be devastating to those who rely on those services for income. As an example, BSF (2018) describes how the collapse of the Newfound-land cod fishery due to overfishing in the early 90's resulted in the loss of thousands of jobs with an estimated cost of at least $2 billion in income support. Changes in ecosystems may also contribute to increased green-house gas (GHG) emissions which has a significant economic impact, particularly in developed economies (Hamilton, 2017). Furthermore, the ability of developing urban areas may also be compromised due to changes in ecosystem services. Urban development is often threatened by the inability of securing water and air quality provision. Recent examples of this have been witnessed in Cape Town (South Africa), Sao Paulo (Brasil), Mexico City (Mexico), Bangalor (India) or Beijin (China), which are facing the risk of water shortages (BBC, 2018).

The current issue with natural capital is that, unlike other capital forms such as human or produced capital, its value has been steadily decreasing over the years and the stream of services derived from nature are degrading (refer to Section 1.1). The degradation of natural capital value have been primarily driven by an excessive demand for ecosystem services stemming from economic growth, demographic changes, and individual choices. However, this degradation has also been exacerbated by a lack of sufficient knowledge and understanding of the current condition of natural assets and the factors driving changes on natural capital value. Decision makers in the public and private sector often must balance their choices between economic growth and social development with the need of environmental conservation. Nevertheless, current decision-making processes normally exclude or underestimate the value of ecosystem services, leading to a mismanagement of natural assets. Poorly managed natural capital not only results in ecological detriment but also generates social and economic liabilities. At present, the over-exploitation of natural capital is reducing the flow of benefits derived from nature, and therefore, severely impacting economies and jeopardising the ability to deliver sustainable development. For instance, the Truscost-TEEB (2013) report estimates that the global top 10 environmental externalities, including gas emissions, water use, land use, air pollution, land and water pollution, and waste, are costing the global economy nearly US$ 4.7 trillion a year in term of degradation of natural capital. The same source estimates that, in Europe alone, the economic cost of natural capital depletion due to GHG emissions, land use degradation, and water supply scarcity, has been on the order of approximately US$ 337 billion per year. As discussed by Helm (2015), in order to reverse the declining trends of natural capital and save the associated costs, the situation requires the development and implementation of accounting mechanisms and financial approaches dedicated to natural capital. Natural capital accounts are not only essential for capturing the value of natural capital in financial terms, but they are also crucial for tracking changes in the value of natural capital assets over time, and identifying the major factors driving the changes (Barbier, 2014b,a). Likewise, financial approaches aiming to allocate significant investments in natural capital, are fundamental to the recovery of downward-moving values of natural assets (Rands et al., 2010).

## 2.2 Natural Capital and the Capital Approach

The concepts of natural capital and sustainable development are closely related due to the importance of natural resources in delivering development over the long run (Atkinson et al., 1997). When trying to define sustainable development within natural capital economics, two major paradigms emerge: weak sustainability and strong sustainability (Dietz and Neumayer, 2007). The key difference between these paradigms lies in whether natural capital can be regarded as substitutable by other capital forms, especially produced capital. Weak sustainability provides a view in which some environmental assets can be substituted by man-made and human capital. Proponents of this pragmatic paradigm argue that although the three type of capital (produced, human, and natural) are not perfect substitutes, the degree of substitution is not zero. Possible substitutions can be found for natural capital products such as raw materials used for production and consumption (Neumayer, 2000). Weak sustainability stablishes that when non-renewable natural capital is consumed, other assets need to set aside to compensate for what has been used. This may be achieved, for instance, by setting a specific fund for saving purpose or by reinvesting the utility obtained from non-renewables in improving produced and/or human capital instead. However, as discussed by Barbier et al. (1995), the major problem faced by this paradigm is that many life supporting natural assets are impossible to substitute. Moreover, for those that is possible, substitution may become more difficult as resource efficiency becomes higher. Based on this argument, the strong sustainability paradigm, on the other hand, establishes that substitution is not permissible for any form of natural capital, and all natural assets must be preserved. This paradigm places nature as the primary factor of production, and labour and fix capital are secondary, derived from and dependent on nature. According to Helm (2015), the principal problem with the strong sustainability paradigm is that it is extremely rigid as it rules out substitution between natural capital and other factors of production. Therefore, this paradigm goes against any economic development initiative. Given the extreme perspective provided by both approaches, a number of rules have been suggested by economists in order to find a middle ground between these conflicting paradigms and operationalise sustainability. Neumayer (2000) identifies two main schools of thought. One requires that non-renewable resource extraction should be compensated by an investment in renewable resources (e.g. green technologies, timberland, or agriculture). The second requires that a subset of so called ‘critical assets’ (those strictly non-substitutable) remains intact in physical terms for future generations. Regardless their differences, both schools of thought are asset based which have led economists to formulate the ‘capital approach’ in order to adhere natural capital into sustainably measurements.

The concept of natural capital has been endorsed by the ‘capital approach’ for assessing sustainability in development (UN, 2008; Dasgupta, 2009). The capital approach emerged during the search for robust ways of assessing sustainability, and at a time when traditional indicators such as GDP could not provide useful information on sustainable asset management (Costanza et al., 2009, 2014). This approach focuses on measuring the condition of the capital assets that compose the wealth of a region, including human, produced, and natural capital, and that are used as an input factor for production. Figure 2.3 illustrates the focus of the capital approach and compares it with the focus provided by GDP. GDP specifically measures current economic activity in the form of input and out flows, but does not address the condition of the capital stock necessary to maintain levels of production and consumption. On the contrary, the capital approach explicitly measures the condition of capital assets by estimating the monetary value of each capital component. The criteria for sustainability set by the capital approach establishes that sustainable development is a development that ensures non-declining per capita wealth over time (see Polasky et al. (2015); Heal and Kristrom (2005); Dasgupta and Maler (2001); Arrow et al. (2012, 2013)) where wealth is defined as the aggregate value of the stock of human, produced, and natural capital. Thus, the capital approach for sustainability analysis highlights two types of activity in relation to capital assets: (i) estimating the monetary value of the available capital stock, and (ii) tracking changes of the per capita value of capital assets in time.

The major strengths of the capital approach, different from GDP, are that it provides quantifiable criteria for sustainability and also incorporates the value of natural resources, aspects commonly neglected by the GDP approach. But despite the strengths offered by the capital approach, this approach also encounters several limitations in terms of valuation (i.e. practical issues found when valuing the capital stock) and critical capital appraisal (i.e. the degree of substitutability among capital assets) (UN, 2008). Capital accounting requires us to measure shadow prices, and the capital approach assumes that shadow prices can always be measured. However, McFadden (1996) argues that this assumption is not realistic, given that the valuation of all capital assets is not always feasible. McFadden (1996)'s opinion is also supported by Cairns (2013) and Smulders (2012), who point out that the capital approach assumption on shadow prices does not hold

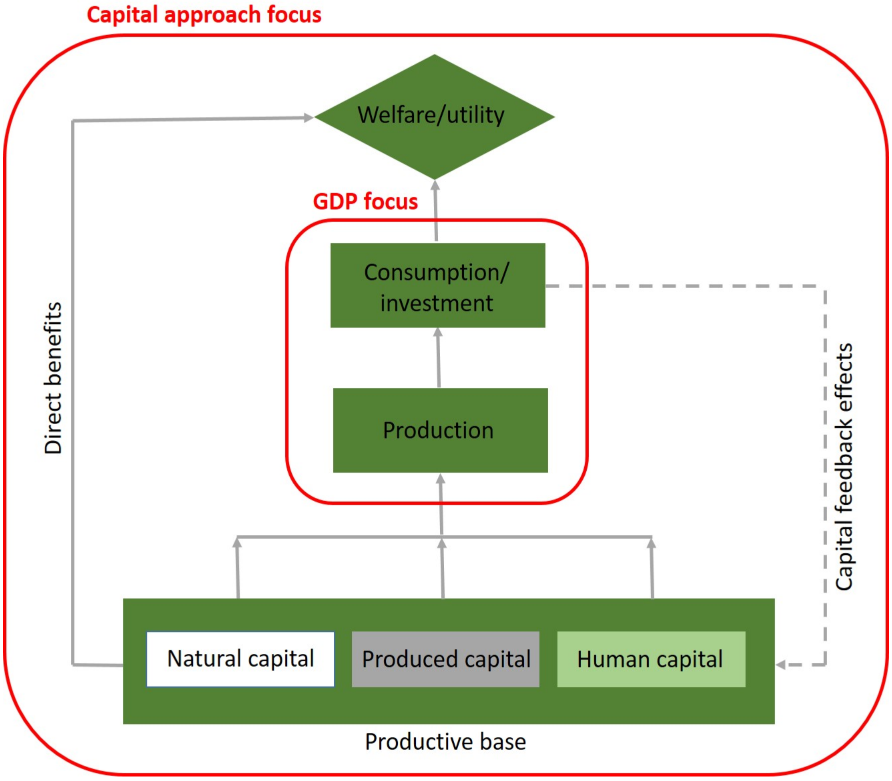


FIGURE 2.3: The three capital model of wealth creation
Source: The Inclusive Wealth Report (UNEP&UNU-IHDP, 2014).

true in many cases. Moreover, the measure of sustainable development provided by the capital approach works under the condition of a high degree of substitutability among capital assets, in line with the weak sustainability paradigm. Stern (1997), nevertheless, argues that in reality, the degree to which various capital stocks, and in particular the stock of natural capital, can be substituted, is limited in accordance with the strong sustainability paradigm. Thus, it would be inadequate to aggregate values of non-critical capital with those of critical capital because information for sustainable development would be lost. Roman and Thiry (2016) also present a critical appraisal of the capital approach in their discussion of the major limitations found in its unrealistic assumptions. Despite the aforementioned criticism and limitations, the capital approach to sustainability continues to be the most viable mean of addressing sustainability issues in development. This approach has been broadly adopted by many international organisations and national authorities around the world for measuring wealth. Therefore, we can assert that the capital approach has motivated the development of natural capital accounting systems for incorporating the value of nature into national wealth accounts and therefore also tracking variations in the condition of natural capital over time. Furthermore, the capital approach prompts the necessity for investment mechanisms capable of maintaining per capita levels of natural capital in order to achieve sustainability.

## 2.3 Natural Capital Accounting

Natural capital accounts are mechanisms able to register the monetary value of natural capital stock and flows, as well as, monitor changes in the value of these assets over time (TheWorldBank, 2016). Accounting can be used to assess the total contribution of ecosystem products and services to human wellbeing, to increase the understanding of the incentives faced by decision-makers, and to evaluate the consequences of actions taken in favour or against the environment (MEA, 2005). Accounting system for natural capital is becoming an increasingly relevant component of the national accounts of a country. The system of national accounts (SNA), developed by the UN Statistical Commission (UNSC), is the international statistical standard for compiling measures of economic activity of nations based on common accounting conventions (SNA, 2009). SNA is used to derive some of the most important statistics for a country, including GDP, household saving ratio, public debt, and consumption. Nevertheless, as suggested by Ochuodho and Alavalapati (2016), there is an increasing recognition that SNA shall also provide an indication of the impact of economic activity on the environment and the services derived from nature. In response to this need, the UN created the UN's System of Environmental-Economics Accounting Central Framework (SEEA-CF, 2012) as a comprehensive accounting framework specifically designed for natural capital.

The development of the SEEA framework marks a significant contribution towards the implementation of natural capital accounting. The framework allows for the full integration of natural capital into traditional SNA, thereby establishing a link between the environment and all sectors of the economy that can be used for policy analysis (Bartelmus, 2014). As Ochuodho and Alavalapati (2016) show, however, few countries have implemented or are currently in the process of implementing natural capital accounting into their national accounts. Prominent examples include Norway (Alfsen and Greaker, 2006), Canada (StatisticsCanada, 2016), Sweden (StatisticsSweden, 2015), Australia (BureauOfMethodology, 2013), and the UK (ONS, 2012). Initiatives for natural capital accounting have also emerged in the private sector with the creation of the Natural Capital Protocol by the Natural Capital Coalition (NCC, 2016). The natural capital protocol provides a methodology for natural capital accounting specifically designed for corporations and businesses. The importance of natural capital accounting is that it contributes to increasing the understanding of the relationship between economic or business activities and the services derived from the environment. Moreover, they help to support better-informed decision making. Public policy makers and private corporations may recognise the role of natural capital if they are able to see the direct impact of the economy or business on nature in real world scenarios.

Although progress has been made in developing and implementing natural capital accounting systems, there are still challenges to be overcome in ensuring natural capital is fully integrated into the economy. Many countries still lack the capacity to implement the SEEA framework (Ochuodho and Alavalapati, 2016). Moreover, in those countries where SEEA has been implemented, natural capital accounts only capture partial estimations of natural assets (e.g. Khan et al. (2014)). Valuing natural capital for accounting purposes is complex (in some cases even impossible), as benefits from nature are in many cases indirect or intangible (Craig and DePratto, 2014). A large amount of data regarding the characteristics and services of nature in a given area is required, and in most cases, data is non-existent or it has only recently started to be collected (Spurgeon, 2014). Most existing valuation methodologies are based on a large number of assumptions that may be considered unrealistic. Added to these challenges, Ochuodho and Alavalapati (2016) also point out that research on the implementation of natural capital accounts is scarce in the literature. Hence, there is still a minimal understanding of how natural capital accounting can be used to link policy making and economic activity with the impact on natural resources. To target this research gap, in Chapter 4 we provide an analysis of the use of natural capital accounting to quantify changes in natural capital value using the case study of the UK. In this analysis, a model for natural capital accounts is used to investigate the drivers of past and future trajectories of natural capital value while assessing the risk of its decline.

## 2.4 Natural Capital and Commodity Prices

A wide range of methodologies have been developed to attempt to quantify the benefits of natural capital and ecosystem services as part of the green accounting approach (SEEA-CF, 2012; Khan et al., 2014). The methodologies are particularly well developed for provisioning services and natural assets for which markets exist, although progress has also been made in improving the ability to value regulating, and other services (Dietz and Neumayer, 2007). As will be discussed later in Chapter 4, the choice of valuation technique for any particular natural asset depends on the characteristics of the assets and the data available. Most of the methodologies used in estimating the change in value of the flow of benefits provided by non-renewable natural capital involve estimating change in the physical quantity of the assets and their market price. A common problem in valuation with market price based methods is that prices in many cases are affected by factors not necessarily related to the natural capital condition. This is particularly the case for natural capital products such as oil, gas, minerals, agricultural and timber products, which valuation depends on commodity prices. Commodity price behaviour can be complex as prices are commonly influenced by several factors that can induce instant changes in their path (Hansen and Gross, 2018). Some of the most important factors that can cause changes in commodity prices in the short term, include supply and demand dynamics, political and social shocks, weather conditions, international trade, and transport costs. Also, in the long-run commodity prices can be affected by interest rates, inflation, exchange rates, energy consumption, and technological developments that impact productivity. Moreover, commodities are often subjected to market speculation, which is in some cases an additional factor of price change (Robles et al., 2009). Economists and researchers have always been interested in analysing and forecasting commodity prices for modelling purposes. Representing future price movements are important for developing econometric models, including those used in natural capital valuation. Commodity prices are characterized by some distinct features including mean reversion process, stochastic volatility, and non-normal residuals. These features enable the elaboration of mathematical models that approximate the behaviour of commodity prices. Some of the most distinctive models, discussed in more detail in Section 3.1, are: The Geometric Brownian Motion (GBM) and Mean-Reversion (MR) stochastic processes. These two models are commonly used in the methodologies implemented for natural capital valuation that are commodity price-based (UNEP&UNU-IHDP, 2014). Below, we provide a general overview of some relevant commodity prices of interest for the work develop in the coming chapters.

### Oil & Gas

Figure 2.4 below shows the historical prices registered for the West Texas Intermediate (WTI) and Brent, two of the main crude oil price indicators. Oil prices rapidly rose from $20's per barrel in the early 90's to over $130/bbl in late 2008 after which prices suddenly collapsed to the rage of $40-45/bbl during 2009. From late 2009, prices recovered to fluctuate around a $100/bbl during 2011-2013 and collapsed again at the beginning of 2014. As the market has continued to rebalance in recent years, oil prices has started to rise slowly once more. Crude oil prices are in general very volatile, subjected to variation in the global demand (primarily from non-OPEC countries and China) and the production with the compliance by the Organization of the Petroleum Exporting Countries (OPEC) and non-OPEC producers. The price of crude oil has been also influenced over the years by levels of inventory and supply surpluses, political events, and regional conflicts. In recent years, the disruption of the markets caused by the introduction of new fracking technology also drove prices down for a period of time. Furthermore, during the second half of 2017, prices for the US WTI did not rise in tandem with Brent because of Hurricane Harvey, a natural disaster that impacted up to one-quarter of US refinery capacity and reduced refinery crude demand. Geopolitical risk is also a factor often impacting prices as it has been recently witnessed with threatened exports from several producing counties (e.g., Libya, Nigeria, and Venezuela), and from transit country disputes (e.g., pipeline exports from Kurdish region in northern Iraq). On the political arena, cuts in production promoted by OPEC and non-OPEC countries confronting increased production (notably in the US shale) has also shaped the price path of this commodity in recent years.

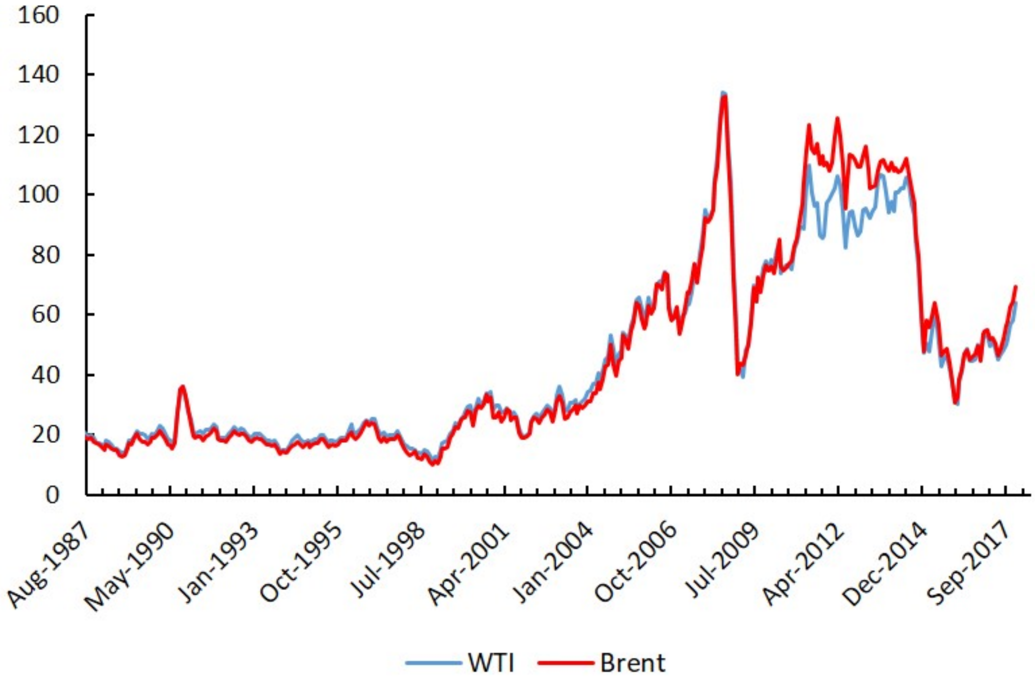


FIGURE 2.4: Historical prices of crude oil (in US$/barrel)
Source: US Energy Information Administration (EIA).

Natural gas prices have also been characterized by a high volatility over the past 15 years, as shown in Figure 2.5. Major peaks around $10/thousand cubic feet in the price of US gas were registered in early 2001 and 2003, mid 2005 and 2008, and at the beginning of 2014. After 2014, the price seemed to stabilise in the range of $3.4 per thousand cubic feet. Perhaps to a lesser degree but still similar to the case of crude oil, gas prices are also greatly subjected to variation in the domestic and global demand, rising or declining exports from producer countries, as well as, to the conditions of the geopolitical context at some point. In the gas market, weather plays a key role is shaping prices defining variations according to seasonal conditions (e.g., mild or severe winter) and the capacity of countries to restock and deliver supply on time.

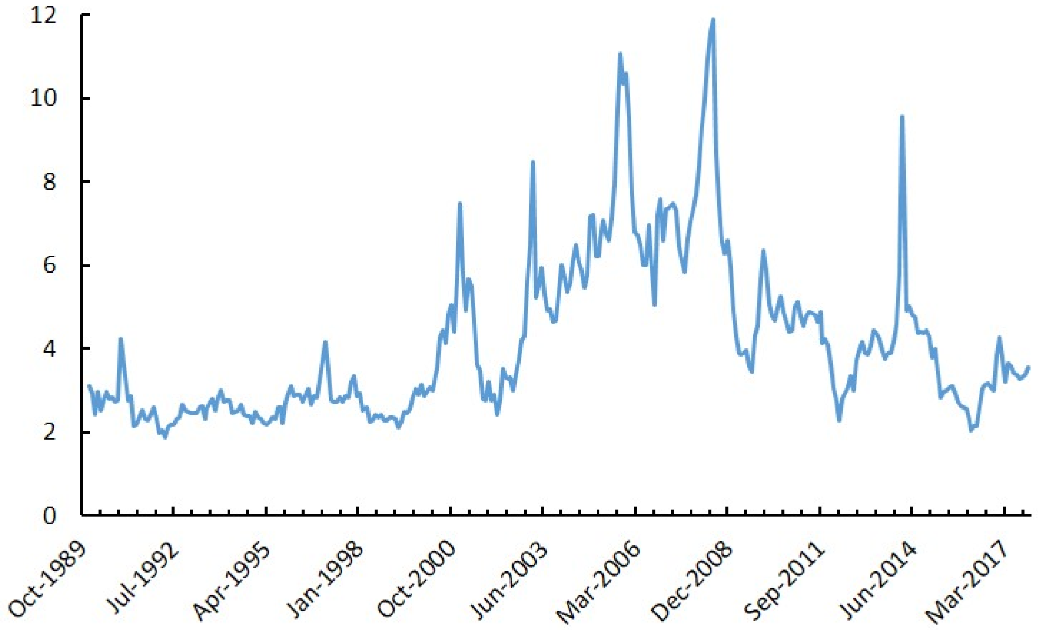


FIGURE 2.5: Historical prices for Natural Gas in the US market (in US$/thousand cubic feet)
Source: US Energy Information Administration (EIA).

### Agriculture

Agriculture commodities comprise grains (e.g., corn, wheat, soybeans, rice, coffee), food and fibre, and livestock meat. Figures 2.6 and 2.7 show the trend followed by the price of some of the main cereals and live meat products over the last decade, respectively. In the case of grains, prices experienced a relatively high level during the period 2011-2013. From early 2014, prices of these commodities started to decline. Live meat products, including cattle, chicken, and pig, have followed a similar tendency to that showed by grains, with dropping prices after 2014. The price of agricultural commodities is generally driven by levels of production, market supply, and consumption in the form of food or biofuel. The decline observed for agricultural commodities in recent years, for example, have been attributed to the well supplied condition of most food markets around the world and a lower impact of biofuels, which had helped to booming prices of grain in the past. In addition, this particular type of commodities is also subjected to disruptive weather conditions and the materialization of El Nino y La Nina weather cycles. For instance, UNECE-FAO (2017) reports that the global production of wheat in 2017 experienced an upward trend to reach 751 million metric tons, given the favourable weather conditions experienced in wheat producer countries (e.g., Kazakhstan, Russia, and Ukraine) on that year. On the contrary, global rice production in the same year receded compared to wheat due to more adverse weather conditions registered in some Asian producer countries (e.g., China, Vietnam, and Thailand). Another significant factor affecting agricultural commodity prices is the influx of speculative investments. As discussed by Robles et al. (2009), sharp increases of agricultural commodity prices cannot be explained only by supply and demand fundamentals. The authors claim that speculation, expectations and hysteria drove up prices and increased volatility on commodity markets during the 2000's.

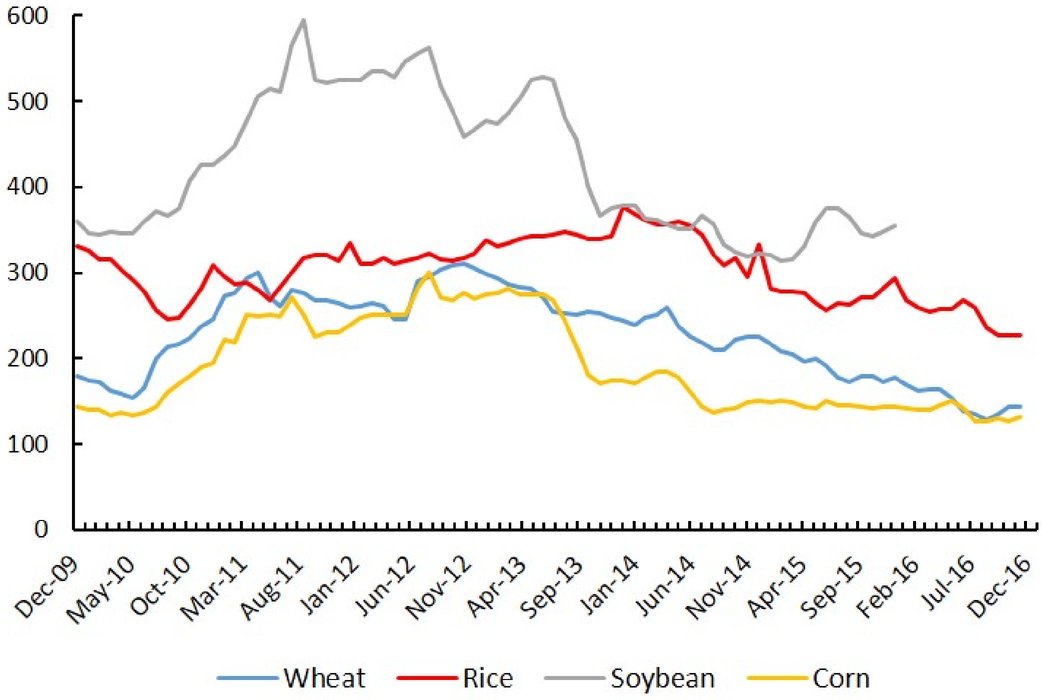


FIGURE 2.6: Historical prices for cereal products in the US market (in US$/tonne)
Source: Food and Agriculture Organization of the UN (FAO).

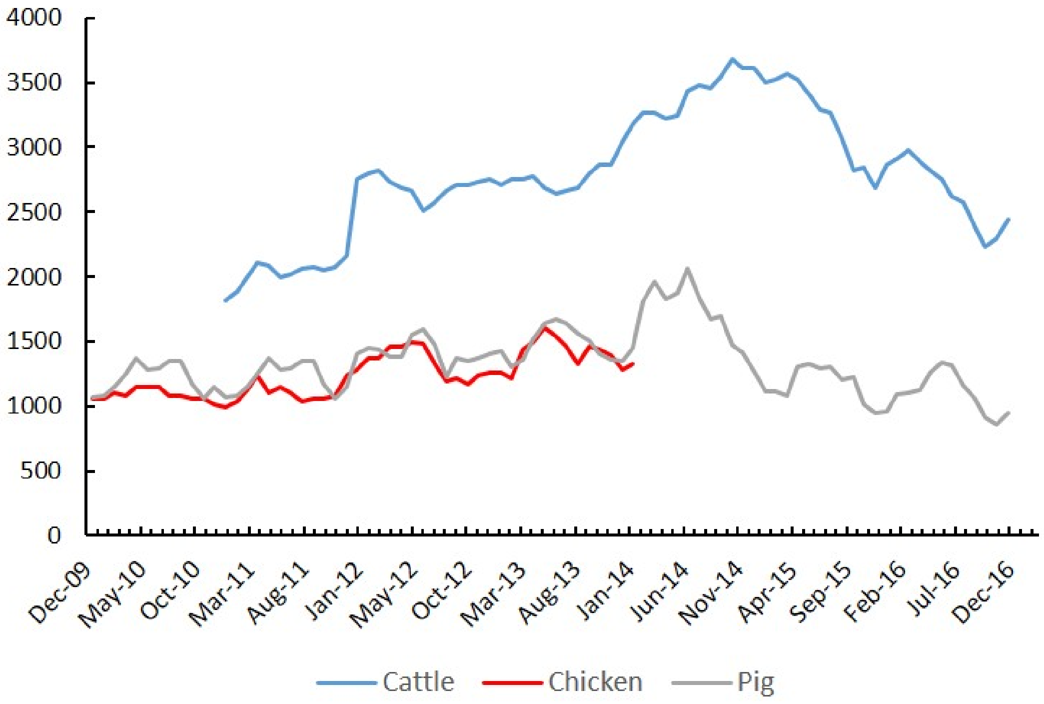


FIGURE 2.7: Historical prices for live meat in the US market (in US$/tonne)
Source: Food and Agriculture Organization of the UN (FAO).

### Timber

Timberland commodity is an important component of many global economies. The quality of life in both developed and developing countries is dependent upon the use of products derived from timber. As global population increases, the consumption of timber related products also increases due to its use in construction, fencing, packing, furniture, paper and magazines. The level of demand for forest products in combination with the global supply of timber has significantly shaped the prices of this commodity over the past 20 years. Factors that can shift the demand of forest products vary widely and include trends in housing markets, levels of investment in construction and real estate developments, consumption of wood-based panels, paper products, wood energy materials, and the availability of substituent. As an example, the expansion of the US house market in 2016-2017 contributed to increase the demand of sawn softwood, which rose prices in turn (UNECE-FAO, 2017). The supply side is similarly affected by factors such as the availability of harvested timber, trees' growth rate, the degree of land use changes, and the rate of forest loss. Production is greatly associated to coniferous forest (softwood) in North America (US and Canada), northern Europe (Russia, Germany, Finland, Sweden, and Baltic States) and to tropical hardwoods in Brazil and Indonesia. In addition to demand and supply factors, the price of timber is also often affected by public policies, governmental actions, and trade agreements. For instance, in April 2017, the US government announced tariffs of 3-24% on imported lumber from Canada, which resulted in an 6.4% price increase in timber products traded in the US market (Emrath, 2017). In Europe, the results from the Brexit referendum in June 2016, had implications on the price of forest products traded in the European market and in other regions. Moreover, the Comprehensive Economic and Trade Agreement (CETA) signed between Canada and EU in September 2014 contributed to reduce the price of several forest products that were subjected to tax and other barriers to market access (GAC, 2018). Unlike other commodities, the price of timber in global markets has exhibited a predominant upraise trend during the last 16 years even during periods of low economic growth. Figure 2.8 illustrates, as an example, the price of coniferous standing wood as commercialized in the UK market. Construction output in the UK has been growing swiftly in the last five years (FIM, 2015). Output in 2014 increased by 7.4% compared to 2013, and it is expected to growth in the next years too. An increased UK demand for timber in combination with higher levels of construction investments around the Eurozone after 2015 has contributed to the rise of timber prices in this particular market.

## 2.5 Natural Capital and Macroeconomic

The value of natural capital is affected not just by fluctuations in commodity prices but also by variations in the value of other capital forms, such as human and produced capital. The condition of all capital assets found in a particular region are normally shaped by macroeconomic factors that define the economy of the region. For instance, the value of human capital is subjected to economic indicators such as employment and unemployment rates, wages, levels of education in the population, life expectancy, inflation, GDP growth, among many others. Similarly,

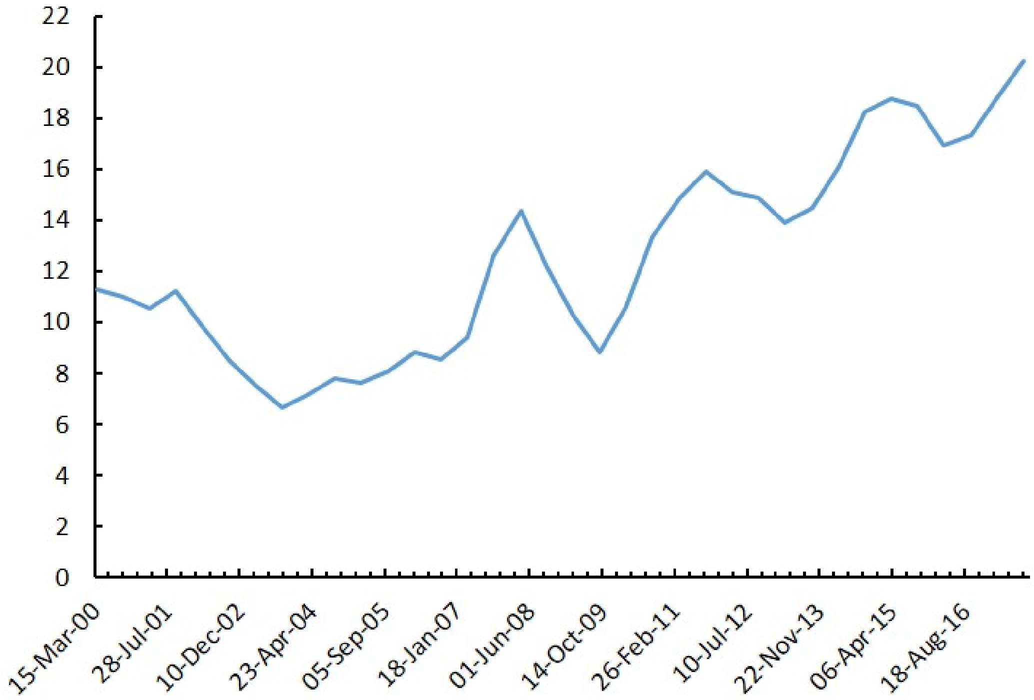


FIGURE 2.8: Historical prices of conifer wood for the GB market (in 2016 £/m3)
Source: Food and Agriculture Organization of the UN (FAO).

the value of produced capital is influenced by levels of investment in infrastructure assets, real estate development plans, ICT equipment installation, machinery acquisition, and the development of many other fix structures. Natural capital valuation, therefore, must take into account the different relationships existing between natural assets and major macroeconomic variables. Macroeconomic theory studies and models the relationship between these variables and characterize them in a way that can be incorporated into economic models (Blanchard, 2011). Most of the relationships are based on the empirical observation of the specific data associated with a given region during a certain period of time. This section presents a review of some of the empirical relationships studied in macroeconomic theory that are relevant for the analysis introduced in Chapter 4. The reviewed relationships include that one between unemployment rate and GDP growth, also known as Okun's Law; the relationship between changes in employment rate and GDP growth; and the relationship between unemployment rate and wages. The application of these relationships extracted from macroeconomic theory in the research work here conducted is described in Appendix C, where the data utilized to create them and the regression coefficient computed are also presented. Below, a description of each of the relationships of interest is provided.

### 2.5.1 Changes in unemployment and output growth (Okun's Law)

Okun's law defines the relationship between changes in unemployment rate and the rate at which output (i.e. GDP) growths. This relationship is established using the linear model

$$u_t - u_{t-1} = -\beta(g_t - \bar{g}), \tag{2.1}$$

where $u_t$ denotes the unemployment rate at time $t$, $g_t$ is the output growth (in percentage) experienced at time $t$, $\bar{g}$ is the normal growth rate of the economy, and $\beta$ is the rate at which growth in excess of normal growth translates into decreases in unemployment. The normal growth rate refers to the rate of output growth needed to maintain a constant unemployment rate. This is given by adding up the employment growth rate and the labour productivity growth rate. Equation (2.1) shows that an inverse linear relationship is set between changes in unemployment rate and GDP growth. In practice, this relationship is commonly estimated using linear regression models.

As an example, Figure 2.9 plots the quarter changes in unemployment rate vs. output growth registered in the UK between June 1971 and March 2013. The figure also includes the regression line that best fit the data points. The relationship defined by the line, in this case, is given by

$$u_t - u_{t-1} = -0.12(g_t - 0.8\%),$$

from this expression, we find that for the UK, the normal growth rate is 0.8%, which means that the output growth has to be no less than 0.8% quarterly (i.e. $0.8\% \times 4 = 3.2\%$ p.a.) to prevent the unemployment rate from rising. In addition, $\beta$ equals 0.12, indicating that an output growth of 1% in excess of the normal

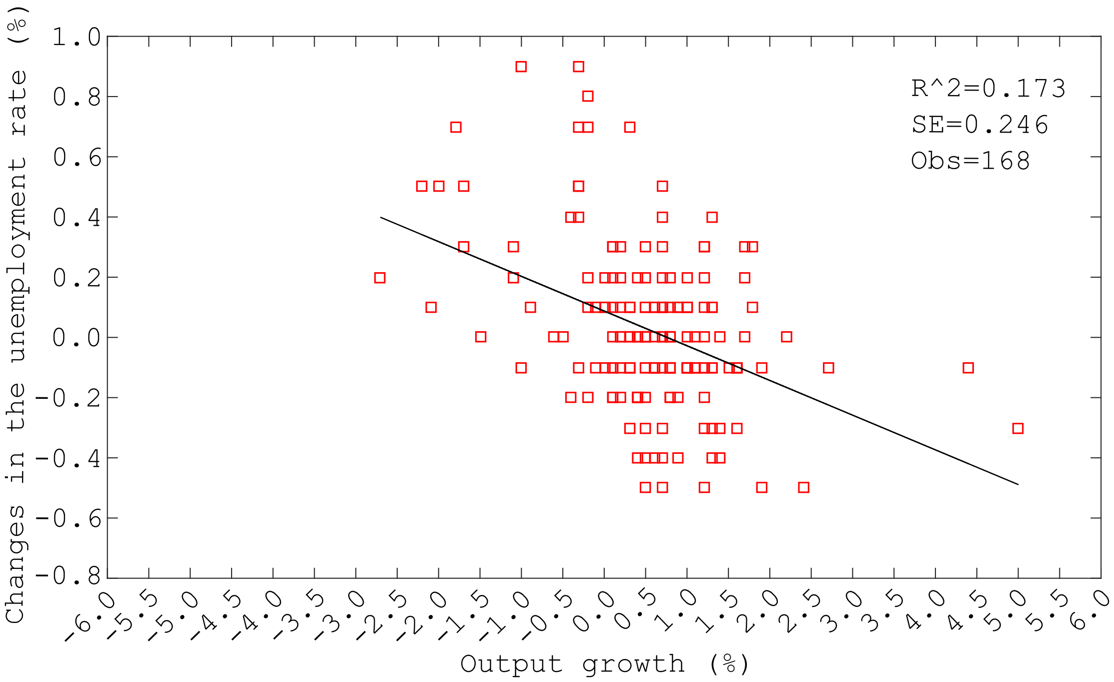


FIGURE 2.9: Quarter changes in unemployment rate and GDP growth in the UK, June 1971 - March 2013

growth rate leads to a 0.12% reduction in the unemployment rate. The regression model registers an R-squared value of just 0.173 and a standard error of 0.246, suggesting that only 17% of the variability of the unemployment rate is explained by the linear model established with GDP changes. Yet, the regression coefficients are statistically significant at 0.01%. Despite its name, the Okun's Law is not a law as conceived in physical science, but rather it is an approximation to represent the relationship between GDP growth and unemployment based on empirical observations. Therefore, relatively low R-squared values are generally expected (Ball et al., 2014).

### 2.5.2 Employment rate and economic growth

Another relationship of significant interest in macroeconomics is the one established between movements in economic activity, represented by GDP growth, and movements in the labour market represented by the employment growth. This relationship is important to understand to what extend economic growth can translate into job growth. The employment rate is commonly considered a lag indicator of economic growth (Dumitrescu et al., 2009; Akkemik, 2007; AustralianBureauofStatistics, 2006). The reason for this is that employment starts to react to economic growth once growth has already been well established for several periods. Firms normally remain hesitant to hire more workers until they are convinced that the economic growth will be maintained. Based on this premise, Seyfried (2005) studies the relationship between employment and economic growth in detail, supporting the idea that employment lag behind GDP growth. The results from this work indicate that economic growth does not only has an immediate effect on employment, but also some of the effects may be lagged for several periods of time before they are felt. Therefore, the author proposed two models. The first one considers the possibility of persistence in employment growth, which means that periods of positive growth in employment are more likely to be followed by further increases in employment and vice-versa. This is given by

$$e_t = \beta_0 + \beta_1 e_{t-1} + \gamma_0 g_t + \varepsilon, \tag{2.2}$$

where $e_t$ is the employment rate at time $t$, $g_t$ is the growth in GDP and $\varepsilon$ represents the error term in the model.

The second model tries to capture in addition the time it takes for employment to respond to economic growth, thus taking the form

$$e_t = \beta_0 + \beta_1 e_{t-1} + \gamma_0 g_t + \gamma_1 g_{t-1} + \gamma_2 g_{t-2} + \gamma_3 g_{t-3} + \varepsilon. \tag{2.3}$$

In practice, the specific lag structure of the model is very case dependent and it must be adjusted in accordance to the particular empirical data studied, following a criterion such as the Akaike Information Criterion (AIC). The AIC is a measure of the quality of a statistical model for a given dataset and provides a mean for model selection (Aho et al., 2014; Akaike, 1974). The criterion deals with the trade-off between the goodness of fit of the model and the complexity of the model. Given a set of candidate models for fitting the data, the preferred model is the one with the minimum AIC value.

### 2.5.3 Unemployment and real wages

Classical and modern economics recognise that levels of unemployment can restrict wages. According to Gregg et al. (2014), there are at least three potential reasons for that. First, when unemployment is high, workers tend to have a reduced margin to claim higher wages because of scarce availability of better job offers from other employers. Second, high unemployment also means that there are more people to compete with to get a replacement job; therefore, in fear of losing their jobs, workers may cede wages to secure job positions. And finally, higher unemployment means that there are much more applicants per job opening, and firms have the possibility to secure better qualified labour for lower wages.

One of the first relationships between unemployment and wages was established by Phillips (1958) and Samuelson and Solow (1960) that became known as the *Phillip Curve*. This relationship was established between unemployment and nominal (not adjusted for inflation) wage changes under the premise that lower unemployment leads to higher nominal wages. However, this relationship broke down in 1970 after the recession experienced in the US that saw high unemployment coinciding with high inflation (Blanchard, 2011). Newer theoretical and empirical evidence shifted the focus to suggest that unemployment regulates the growth rate of real wages (i.e. adjusted for inflation), instead of nominal wage changes. This new focus associate low unemployment not only with higher wage growth, but with a mechanism in which lower unemployment also leads to higher good and service prices, and thus, higher inflation called the *wage-price spiral.* The literature recognizes this approach as the current most common way to study the relationship between wages and unemployment. Although, new evidence presented by Gali (2011) seems to suggest that variations of the Phillips curve relationship are re-emerging with some plausible theoretical underpinning.

Based on the aforementioned context, Gregg et al. (2014) introduces a model to represent the relationship between unemployment and wages. The model relates changes (in percentage) in unemployment and the log of real wages, where a one period lagged unemployment term is included to reduce the potential for current economic conditions to be driving unemployment and wages movement simultaneously. Hence, the model takes the form

$$\log(w_t) = \alpha_0 + \alpha_1 t + \beta_0 \log(u_{t-1}) + \beta_1 \log(u_t) + \varepsilon_t, \tag{2.4}$$

where $w_t$ is the real wage at time $t$, $u_t$ is the unemployment rate and $\varepsilon$ is an error term. The particular structure of this model allows to capture the short-run effect that unemployment has over real wages through the parameter $\beta_1$. In addition, a lag effect on unemployment is also considered measured by the coefficient $\beta_0$; and a trend effect is added being controlled by the coefficient $\alpha_1$.

## 2.6 Natural Capital Investment Approaches

The diverse features of natural capital assets require the consideration of different types of investment approaches in order to appropriately match the intrinsic characteristics of natural assets (Helm, 2015). In this regard, the Asian Development Bank (ADB, 2015) combines investment approaches in natural capital into two broad categories. The first category refers to investments aiming to directly protect and enhance renewable natural capital. The second category refers to investments for the improvement of resource-use efficiency in the case non-renewable natural capital. Renewable natural capital requires direct investments to increase its value in terms of quality and quantity. Whereas non-renewable natural capital cannot be increased, it can only be diminished as it is produced. Therefore, investment approaches, in this case, should be designed to improve the efficiency of the processes used to produce these resources. In the context of sustainability, this is formulated in the Hartwick-Solow rule (Hartwick, 1977; Solow, 1974). The rule establishes that the depletion of non-renewable natural resources shall be compensated by reinvesting the rent obtained from depletion into another alternative capital form. For example, the rent from non-renewables can be invested in education and health, to increase levels of human capital. Similarly, the rent can be invested in non-renewable natural capital to maintain aggregated levels of natural capital.

Various investment approaches for natural capital have been implemented by authorities in different countries to preserve the value of their natural assets. Prominent examples include central government investments, the use of non-government organisations (NGO's), market-based mechanisms, fiscal instruments, and private investments. Each of these mechanisms offers advantages and disadvantages.

Liu et al. (2008) describes the example of the Central Government approach implemented in China. The author discusses how the central government approach has provided significant results in terms of natural capital recovery. However, this approach may also cause financial hardship in some local governments due to the limited diversification of the source of funding. Nino-Murcia (2006) describes the experience of using NGOs to fund natural capital projects in India. The study shows that the NGO approach can be successfully implemented, but tends to have a reduced impact which is limited to the local level rather than the national level. Thus, this approach suffers from a severe scope limitation. Market-based mechanisms also referred to as Payment for Ecosystem Services (PES), aims to design services out of the ecosystems (i.e. water provisioning, farming, biodiversity conservation or carbon sequestration) that can be sold to companies and markets that must meet environmental targets (Farley and Costanza, 2010). This approach has been successfully implemented in China (Yin et al., 2014), Welsh (Wynne-Jones, 2013), Costa Rica (Rosendal and Schei, 2014) and Ecuador (Bremer et al., 2014). Despite its international popularity, the approach can involve political ambiguity and financial risk for local communities (VanHecken and Bastiaensen, 2010). Fiscal instruments in the form of environmental taxes (ET) are relatively easy to implement and have been fairly widely implemented in Europe (e.g., Ercolano et al. (2014)) and South America (e.g., May et al. (2002)) to protect natural assets. However, the implementation of environmental taxes is frequently limited by problems of political and social acceptability (Dresner et al., 2006). Private investments, as described by Brand (2002) for the case of Australia, seek to construct investment portfolios which include natural capital assets that may be financially attractive to private investors. Natural capital portfolios can be profitable and attractive, but in order to be built, they also require the verification of the financial performance of natural assets with the help of substantial information that is not always available (Cremers, 2013).

A major limitation shared by all the aforementioned investment approaches is that they mainly address investments in renewable natural capital, but do not consider the contributions from the depletion of non-renewable natural resources. From this perspective, these mechanisms are not fully in line with the Hartwick-Solow rule. Therefore, further financial approaches able to provide compensation for the depletion of non-renewable natural capital are still needed (NCC, 2014a). Such mechanisms must be capable of dedicating all, or part of, the net receipts from non-renewable liquidation to finance investments in renewable natural capital. Only in this way, would these mechanisms be in accordance with the Hartwick-Solow rule. Interestingly, with the recent and rapid emergence of Sovereign Wealth Funds (SWF) as global investors, an opportunity is foreseen to use these funds as an alternative approach to finance and manage natural capital (Helm, 2015). SWFs are government owned investment vehicles that, in most cases, receive inflows from nonrenewable natural capital rent (e.g., oil, gas, minerals) and invest in highly diversified portfolios (IWG, 2008). These funds have the capability to convert non-renewable natural capital into another form of a financial capital substitute in order to preserve its wealth over time. A prime example of this approach is Norway, which has been a leading country in incorporating its SWF to preserve its natural capital value and contribute to developing its sustainable development strategy of the country (MinistryOfFinance, 2008a). If renewable natural asset investments are significantly incorporated into SWF investment portfolios, these funds may be able to act as a natural capital financial mechanism that addresses investments in renewable natural capital while considering the contribution of non-renewable natural capital depletion. There is, however, still limited research on the use of SWFs to invest in natural capital assets and on assessing the impacts that these investments may have on their portfolio performance. With this lack of research in mind, the work presented in Chapter 6 is dedicated to the study of the effects of natural capital investments on SWF portfolio performance. The return and risk profile of the SWF is assessed under multiple investment portfolios, thereby demonstrating that SWFs can indeed dedicate significant investments in natural capital assets and benefit from these investments.

## 2.7 Natural Capital in the UK

The UK has positioned itself as a leading country in the discussion and implementation of natural capital accounting and financing mechanisms for sustainability (ONS, 2015). The initial strategy for addressing the natural capital accounting challenge in this country was set out in the UK Natural Capital Roadmap 2012 (ONS, 2012), and later extended in the 2015 Natural Capital Roadmap Review. The UK roadmap defines the policies and actions to be taken, over the time span 2012-2020 in order to create and implement a natural capital accounting system that can be fully integrated into the SNA of this country by 2020. To date, UK authorities have produced the first estimates of natural capital value, first introduced in 2012 and since then reported by the Office for National Statistics (ONS). The UK national government also established in 2012 the Natural Capital Committee (NCC) as an independent advisory body to government on the subject of natural capital management (NCC, 2014c). In addition, the Department for Environment, Food & Rural Affairs (DEFRA) has contributed to the development of the UK National Ecosystem Assessment (UKNEA, 2014), the UK land cover and land use accounts (Miles et al., 2014), and the UK carbon emission by land use category (Buys et al., 2014) in order to support the work of accounting for natural capital value.

The initial UK natural capital accounting system is in accordance with SEEA framework and provides partial estimates of UK natural assets using methodologies still under revision (Khan et al., 2014). Natural assets currently accounted in the UK system include: the non-renewable natural capital of fossil fuel reserves (i.e. oil & gas), mineral reserves and coal; the renewable natural capital of timber resources, fisheries and water supply; and the non-provisioning ecosystem services of outdoor recreation and net greenhouse gas sequestration. These are more natural assets than have been considered in other natural capital accounting systems, including the TheWorldBank (2006) and UNEP&UNU-IHDP (2014). However, many other important natural assets for which valuing methodologies do not yet exist remain excluded from the accounts. To name a few, for instance there is biodiversity, cultural heritage, and aesthetic experience, but there are many others. Although partial, the initial estimates in the UK confirm that natural capital value in this country has been consistently declining since it was first measured in 2009. Figure 2.10 presents the trajectory of the UK's natural capital value between 2009 and 2014, as reported by the Office for National Statistics (ONS, 2016c). From the figure, we can see that natural capital passed from an approximate total estimate of £566 billion (in 2009 constant price) in 2009, to less than £383 billion in 2014, representing a 32.3% decline over a period of five years. The rapidly declining rate of natural capital has motivated UK authorities to increase their understanding of the factors driving changes in the value of natural assets. Analyses using natural capital accounting systems have allowed for the extraction of information about the condition and factors influencing the values of natural capital.

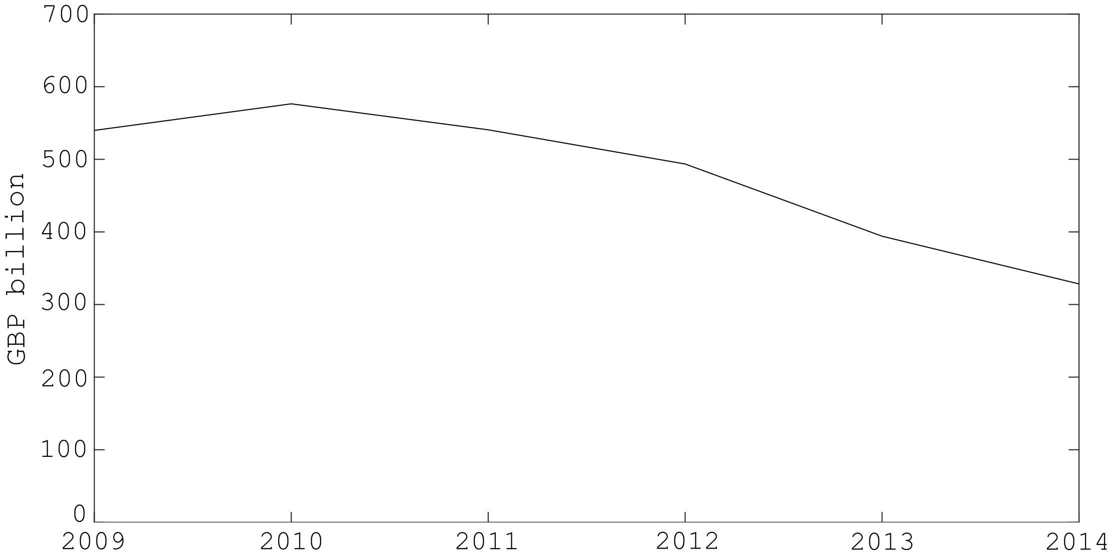


FIGURE 2.10: UK natural capital monetary estimates reported by national authorities between 2009 and 2014, in millions of constant 2014 £. Source ONS (2016c).

In so far as natural capital financial approaches are concerned, environmental taxes have been traditionally implemented in the UK mainly in energy, transport, pollution and resource production, each having different results on environmental benefits and the economy (Webster and Ayatakshi, 2013; Abdullah and Morley, 2014; Martin et al., 2014). Only in 2014, revenues from environmentally related taxes stood at £44.6 billion (ONS, 2014). The traditional tax approach is also being complemented by more innovative approaches emerging in recent years. At the national level, for example, the UK Government has committed to a 25-year plan of 'targeted investments' to restore the UK's natural capital (BES, 2015). Moreover, the UK has already developed the Green Investment Bank as a financial initiative to fund green infrastructure projects with minimum environmental impact across the UK (GIB, 2016). Furthermore, the possibility of creating an SWF to manage the rent from the potential exploitation of shale gas resources has been debated in the House of Commons (UKParliament, 2016). At regional level, local authorities have begun to formulate their own natural capital investment strategies for the future. Examples include the investment strategy developed by authorities in Surrey (SurreyNaturePartnership, 2015) and Dorset (DorsetLocalNaturePartnership, 2016) for the recovery of their renewable natural capital, and the green infrastructure investment plan designed for London to improve the condition of non-provisioning ecosystem services (GreenInfrastructureTaskForce, 2015).

The information on the UK natural capital condition, combined with research efforts of the NCC and DEFRA, have allowed these institutions to identify three relevant areas where research is imperative on the topic of UK natural capital accounting and financing. First, the impact that natural capital accounting has on understanding the main drivers of natural capital decline. Second, the assessment of how investments in natural capital assets offer attractive financial benefits for investors. And third, the study of the use of new financial mechanisms that can be adapted to manage and fund natural capital. The work presented in Chapters 4, 5 and 6 addresses, respectively, each of these research areas. Chapter 4 examines natural capital accounting in the UK to identify the changes in the value of natural capital in this country. Chapter 5 analyses the performance of natural capital investments. Lastly, Chapter 6 studies the ability of SWFs to act as investment vehicles for natural capital. The next chapter will introduce the theoretical concepts used in the methodologies employed in each of the analysis presented in this thesis.

# 3

# Theoretical framework

This chapter presents a description of the theoretical concepts used in the methodologies implemented in the following chapters for the analytical work conducted on natural capital. The content in the chapter starts by describing some stochastic processes commonly used to model natural assets pricing. Then, a review of the global sensitivity analysis in presented which will be used in Chapter 4 to assess the impact that the condition of natural assets has on UK total wealth. In addition, some of the empirical relationships broadly studied in macroeconomic theory and that are of interest for establishing links between natural capital condition and macro-economic variables are discussed. Later, a description of Mean-Variance portfolio optimization technique is presented which will become relevant to study the performance of natural capital investments in Chapter 5. Finally, the theoretical framework to model and assess the performance of commodity sourced Sovereign Wealth Funds (SWFs) portfolios is explained. This framework will be required to examine the ability of SWFs to invest in natural capital in Chapter 6.

## 3.1 Stochastic processes for commodity pricing

For the monetary valuation of natural capital, SEEA-CF (2012) framework recommends as a first option that natural capital should be valued based on their price in existing markets when possible. When markets do not exist, valuation should be done based on the value assets would have if markets existed. For example, the valuation of protected land (not tradeable) must be based on what the land would be sold for on the open market. Alternatively, when market information is completely unavailable, projecting the levels of service flows and their real prices over an accounting lifetime and applying a discount rate to generate a net present value would be a desirable approach. In the case of non-renewable natural capital, most assets (e.g. oil, gas, minerals, coal, etc) have well established markets where they are commonly traded at prices that change according to market conditions. Valuing these types of assets requires having information on the market price and its changes over time. Nevertheless, when studying future scenarios price paths can be modelled using stochastic processes to generate random trajectories that could potentially describe the future trend of the commodity prices. In financial modelling, Geometric Brownian Motion (GBM) and Mean Reverting (MR) are two of the most popular stochastic processes used to model commodity prices (Meade, 2010; Helyette and Fong, 2009; Lutz, 2009; Postali and Picchetti, 2006; Schwartz, 1997). Thus, these processes are frequently considered for valuing non-renewable natural capital (see for instance UNEP&UNU-IHDP (2014)). Other stochastic processes also exist that provide a most complex representation of asset prices, including Arithmetic Brownian Motion (ABM), Fat-tails (i.e. GARCH, Variance Gamma, ABM with normal jumps) and Mean-Reverting with Fat Tails. However, for the sake of the analysis conducted in Chapter 4, it is beyond the scope of this research to look at all them in detail. Brigo et al. (2007) provides a comprehensive description of these stochastic processes. Below, the GBM and MR of interest for this work are described with examples of their applications in natural capital valuation provided.

### 3.1.1 Geometric Brownian Motion

The GBM process describes the stochastic behaviour of an asset instantaneous price, $S(t)$, as follows

$$dS(t) = \mu S(t)dt + \sigma S(t)dW(t), \tag{3.1}$$

where $W$ follows a stochastic process called Wiener process that is characterized by presenting independent increments that are normally distributed, such that $dW(t) = \varepsilon\sqrt{dt}$, where $\varepsilon$ is a random draw from the standardized normal distribution. This characteristic implies that the model is a Markov process, in which the computation of future asset prices depends only on the current asset price and not on past values. The constant $\mu$ is called the drift parameter and it controls the trend of the GBM trajectory. Meanwhile, $\sigma$ is another constant called the volatility parameter that controls the random noise embodied in the trajectory.

Equation (3.1) can be solved using Ito's calculus (Oksendal, 2010; Karatzas and Shreve, 1997), implying that

$$d\ln S(t) = \left(\mu - \frac{\sigma^2}{2}\right)dt + \sigma dW(t). \tag{3.2}$$

Providing a time subscript to each variable in Equation (3.2) and integrating over the time interval $0 - T$, with $T > 0$, we can write

$$\int_{t=0}^{T} d\ln S(t) = \int_{t=0}^{T} \left(\mu - \frac{\sigma^2}{2}\right)dt + \int_{t=0}^{T} \sigma dW(t), \tag{3.3}$$

which solution is given by

$$\ln S(t) - \ln S(0) = \left(\mu - \frac{\sigma^2}{2}\right)T + \sigma[W(T) - W(0)]. \tag{3.4}$$

Taking the exponential in both sides of Equation (3.4) and rearranging, the solution to the GBM process can be expressed as follows

$$S(T) = S(0)\exp\left[\left(\mu - \frac{\sigma^2}{2}\right)T + \sigma\varepsilon\sqrt{T}\right]. \tag{3.5}$$

Equation (3.5) shows that asset prices in GBM are given by a log-normal distribution, while the logarithmic returns $\ln(S(T)/S(0))$ are normally distributed. The mean and the variance of $S(t)$ are given by

$$\mathrm{E}[S(T)] = S(0)\exp(\mu T),$$

and

$$\mathrm{Var}[S(T)] = \exp(2\mu T)S(0)^2[\exp(\sigma^2 T) - 1]$$

respectively.

The calibration of the model to find the value for parameters $\mu$ and $\sigma$ is commonly done using the maximum likelihood method to fit historical time series (Smith, 2010; Brigo et al., 2007). This method finds the parameter estimates that maximise the likelihood of the model given the observed data. The probability of observing a particular data sample, assuming the process holds the Markov property, is represented as a function $\zeta(\mu, \sigma)$ of the form

$$\zeta(\mu, \sigma) = f_{\mu,\sigma}(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f_{\mu,\sigma}(x_i),$$

where $f_{\mu,\sigma}$ is the probability density function. Maximum likelihood estimates the values of $\mu$ and $\sigma$ that maximise the likelihood function. Since the result of the product of density functions could be small, the function is usually transformed into a log form as follows

$$\zeta^*(\mu, \sigma) = \log \zeta(\mu, \sigma) = \sum_{i=1}^{n} \log f_{\mu,\sigma}(x_i).$$

The maximum of the log likelihood is commonly found numerically using optimization algorithms.

### 3.1.2 Mean-Reversion

Mean reversion is the property of the stochastic process to tend to revert to a certain constant value with limited variance around it (Brigo et al., 2009). This characteristic embodies the argument that when commodity prices are too high (or too low), demand will reduce (increase) and supply will increase (reduce), rebalancing the price again and reverting it to a mean value (Smith, 2010). This feature has made MR to be widely used to model interest rates and commodities. One of the most popular MR models is the Ornstein and Uhlenbeck (1930) (O-U) process. In this process, the logarithmic returns $X(t) = \ln[S(t)/S(t-1)]$ is described by

$$dX(t) = \lambda(\mu - X(t))dt + \sigma dW(t)$$

where $dW(t)$ is again the Wiener process, $\mu$ is a constant describing the long run mean the process tend to revert to, $\sigma$ is the volatility of the process, and $\lambda$ is another constant controlling the speed of mean reversion. The solution to the MR stochastic differential equation between two time instants $t_i$ and $t_{i+1}$, with $0 \leq t_i < t_{i+1}$, can be obtained from the solution to the Ornstein-Uhlenbeck SDE, as

$$X(t) = \mu(1 - e^{-\lambda(t_{i+1}-t_i)}) + e^{-\lambda(t_{i+1}-t_i)}X(t_i) + \sigma e^{-\lambda t_{i+1}} \int_{t_i}^{t_{i+1}} e^{\lambda u} dW(u). \tag{3.6}$$

Taking $\Delta t = t_i - t_{i-1}$, Equation (3.6) can be written as

$$X(t_i) = \mu(1 - e^{-\lambda \Delta t}) + e^{-\lambda \Delta t}X(t_{i-1}) + \sigma\sqrt{\frac{(1 - e^{-2\lambda\Delta t})}{2\lambda}}dW(t_i), \tag{3.7}$$

where $dW(t_i) \sim N(0,1)$. The conditional mean and variance for the O-U process can be derived from Equation (3.7), and are given by

$$\mathrm{E}[X(t)] = \mu + (X(\tau) - \mu)e^{-\lambda(t-\tau)},$$

and

$$\mathrm{Var}[X(t)] = \frac{\sigma^2}{2\lambda}\left(1 - e^{-2\lambda(t-\tau)}\right),$$

respectively.

It can be observed that as time increases, the mean tends to converge to the value $\mu$ and the variance remains bounded, thus, implying mean reversion. Despite the popularity of the O-U process to model asset prices, the model has the major pitfall that it can give negative estimates. This is an inappropriate feature for modeling non-negative asset prices. However, when applied in computational models, negative values can be prevented by adjusting convenient levels for the mean and the standard deviation of the process. Or simply, by substituting those negative value by a minimum non-negative value acceptable for the model.

The parameters $\mu$, $\sigma$ and $\lambda$ in the O-U model are normally estimated using least square regression and maximum likelihood technique (Smith, 2010; Brigo et al., 2007). The equation describing the solution to the MR process can be rewritten in the following linear form

$$X(t_i) = a + bX(t_{i-1}) + c\epsilon(t_i),$$

with

$$a = \mu(1 - e^{-\lambda\Delta t})$$

$$b = e^{-\lambda\Delta t}$$

$$c = \sigma\sqrt{\frac{(1 - e^{-2\lambda\Delta t})}{2\lambda}}$$

and $\epsilon(t_i)$ represents the error term in the form of Gaussian white noise. The coefficients $a$, $b$ and $c$ can then be calibrated using a least-square linear regression model of the time series $X(t_i)$. By solving the three equations system, it can be reduced to the following expressions for the parameters $\mu$, $\sigma$ and $\lambda$ respectively

$$\mu = \frac{c}{(1 - b)}$$

$$\sigma = \frac{c}{\sqrt{(b^2 - 1)\Delta t / 2\ln(b)}}$$

$$\lambda = -\frac{\ln(b)}{\Delta t}$$

Calibration through least-square regression technique is recognized to provide good estimates for $\mu$ and $\sigma$, but it is poor in estimating $\lambda$ (Yu, 2012). In order to improve the accuracy in estimating $\lambda$, Phillips and Yu (2005) introduce a more sophisticated 'jackknifing' technique used in more advanced applications.

## 3.2 Global Sensitivity Analysis

Global sensitivity analysis (GSA) is a particular sensitivity analysis technique that studies how the uncertainty of the output of a mathematical model can be associated with the different sources of uncertainty in the model inputs (Saltelli et al., 2004). GSA is useful to know how much of the variation of a model output is attributed to the variations of a particular input (or group of inputs) in the model. As part of the analysis presented in Chapter 4, a mathematical model for the UK national wealth and natural capital is presented. It is the interest of this research to identify which input parameters (given by variables associated to the stage of natural capital condition) are more influential over the model output (given by aggregated values of natural capital and total wealth). This information will be useful, for example, to identify which natural assets or macroeconomic variables are more influential on introducing changes in natural capital and wealth values. Thus, providing information on the major drivers of natural capital change for the UK case.

A number of different sensitivity analysis methodologies are available in the literature. Some of the most popular approaches for sensitivity analysis are based on partial derivatives. These methodologies focus on estimating the sensitivity of an output $Y_j$ versus an input $X_i$, as the derivative $\partial Y_j / \partial X_i$. Derivative-based approaches have the advantage to be easy to implement and they result very computationally efficient. Nevertheless, derivative-based approaches are greatly limited when the model inputs are uncertain and when the model is not linear (Saltelli et al., 2008). In consequence, derivatives only provide information at the base point where they are computed and do not attempt to explore the full input space. Another simple but very useful form of sensitivity analysis is to build scatter plots of the output variable against individual input variables. Scatter plots can be used to investigate the behaviour of models and they allow to order input factors by their influence on the output. However, scatter plots are less convenient in models involving many input factors. This introduces the challenge of how to analyse factors succinctly without having to look at many scatter plots. Another problem with this methodology is that it does not allows capturing the sensitivities resulting from sets of input variables.

Despite overcoming the aforementioned pitfalls, global sensitivity analysis still faces other limitations. The method can be complex to implement and confusing to explain when the model has a large number of input variables (Kennedy, 2007). Moreover, highly complex model are also more computational demanding, requiring longer time to run a GSA. According to Saltelli et al. (2008), the main drawback of GSA is the slow convergence rate to the estimators, which can lead to a high computational cost when the number of input parameters increases. In addition, GSA assumes the set of input variables in a model are independent. Hence, when inputs are correlated, some ambiguities arise in the definition of the sensitivity indices given by GSA (Rabitz, 2010). The particular issue of GSA for dependent inputs has been widely discussed in the literature (Chastaing et al., 2012; Gauchi et al., 2010; Li et al., 2010; Xu and Gertner, 2007; Jacques et al., 2006), however, it remains to be a major pitfall. Therefore, the convenience of using GSA depends on considerations such as: the computational cost of running the model, the number of input factors, linearity features of the model, consideration of interactions among variables in the model, and the purpose of the analysis.

The mathematical model utilized in Chapter 4 for natural capital valuation is in general complex and involve a reasonable number of input factors (around 18). Moreover, the model is non-linear and the variation effect on the model output may very likely be the result of the combination of multiple input variables rather than just one. Therefore, given the limitations of the derivative-based and scatter plot approaches, and considering the computational resources available in this research, GSA has been chosen as the sensitivity analysis technique to be implemented in the natural capital study presented in this thesis. A summary of this technique is provided as follows.

GSA was firstly introduced by Sobol (2001). This approach decomposes the output uncertainty to the uncertainty of different inputs in the model and their combinations (Saltelli et al., 2008). Therefore, the variance of the model output is decomposed as follows

$$V(Y) = \sum_{i} V_i + \sum_{i<j} V_{i,j} + \sum_{i<j<m} V_{ijm} + \cdots + V_{1,2,\ldots k}$$

where $V_i$ is the fraction of the output variance attributed to the marginal factor $X_i$, $V_{ij}$ is the fraction of the output variance due to the interactions between input factors $X_i$ and $X_j$, $V_{ijm}$ is the fraction of the output variance resulting from the interaction among the factors $X_i$, $X_j$ and $X_m$, and $k$ is the total number of input factors.

The GSA approach establishes that the variance of the model output can be used to compute two sensitivity indices to characterize the effect of an input over the uncertainty of the output. The first index is known as the *first-order sensitivity index* ($S_i$) of the input factor $X_i$, and it is given by

$$S_i = \frac{V_{X_i}(E_{X_{\sim i}}(Y \mid X_i))}{V(Y)}$$

where $E_{X_\sim}(Y \mid X_i)$ is the expected value of the output $Y$ when the input parameter $X_i$ is fixed to the value $x_i$. The term $V_{X_i}(E_{X_{\sim i}}(Y \mid X_i))$, therefore, refers to the variance of the expectation of $Y$ conditioned by $X_i = x_i$, measured over all possible points $x_i$. The term $X_{\sim i}$ denotes the set of all input factors except $X_i$ and $V(Y)$ is the variance of the output.

The value of $S_i$ always lies between 0 and 1. The higher its value, the greater the influence of $X_i$ over the output. Similarly, a low value of $S_i$ indicates unimportant variables. For additives models, that is a model for which it is possible to separate the effects of its input variables in a variance decomposition framework, the relationship $\sum_{i=1}^{r} S_{Z_i} = 1$ holds. While for non-additive models, the first order terms do not add up to 1, i.e. $\sum_{i=1}^{r} S_{Z_i} \leq 1$. The difference $1 - \sum_i S_i$ is an indicator of existing interactions in the model.

The second index is referred as the *total effects sensitivity index* ($S_{T_i}$) of factor $X_i$, expressed as

$$S_{T_i} = 1 - \frac{V(E(Y \mid X_{\sim i}))}{V(Y)} = \frac{E(V(Y \mid X_{\sim i}))}{V(Y)},$$

where the term $V(E(Y \mid X_{\sim i}))$ is the variance of the output expectation when conditioned on all factors but $x_i$. The total effect index can be expressed as a linear combination of the contribution to the output variation due to factor $X_i$ (i.e. the first order effect) and all higher-order effects resulting from the interaction between sets of input factors (Saltelli, 2002; Saltelli et al., 2008), as follows

$$S_{T_i} = S_i + S_{ij} + S_{ijm} + \cdots + S_{ijm\ldots k},$$

therefore, total indices can provides information on how much the factor $X_i$ is involved in interactions with any other input factor of the model by looking at the difference $S_{T_i} - S_i$. A null value of $S_{T_i}$ (i.e. $S_{T_i} = 0$) implies that $X_i$ is non-influential and it can be fixed anywhere in its distribution without affecting the variance of the output. The sum of all $S_{T_i}$s is always greater than 1, and it is equal to 1 if the model is perfectly additive.

The advantages of the GSA approach compared to other approaches is that it works for all models independently of the degree of linearity. Moreover, it summarizes all the relevant information about the influence of an input factor over the output of a model in a set of $2k$ indices normalized between 0 and 1. This avoids the need of having to reproduce a large number of scatter plots in models with a large number of input factors. In addition, the set of indices also captures information about the combined effects of a set of input factors by providing information about their interactions.

Sensitivity indices for GSA can be computed using a number of different methods, including Monte Carlo based methods, metamodels (Zuniga et al., 2013), scatter plots smoothing techniques (Storlie and Helton, 2008; Chan et al., 2013) and Fourier amplitude sensitivity testing (FAST) (McRae et al., 1982), among others. Out of them, Monte Carlo-based procedures are probably the most commonly implemented. The most sophisticated Monte Carlo-based procedure available today in the methodology attributed to Saltelli (2002), which represents an extension of the original approach introduced by Sobol (1990) and Homma and Saltelli (1996). This methodology is summarized as follows:

1. Generate a $(N, 2k)$ matrix of random numbers, where $N$ is the number of Monte Carlo samples and $k$ is the number of input parameters, and define two data matrices $A$ and $B$ each containing half of the samples such that

$$A = \begin{pmatrix} x_1^{(1)} & x_2^{(1)} & \dots & x_i^{(1)} & \dots & x_k^{(1)} \\ x_1^{(2)} & x_2^{(2)} & \dots & x_i^{(1)} & \dots & x_k^{(2)} \\ \vdots & \vdots & & \vdots & & \vdots \\ x_1^{(N-1)} & x_2^{(N-1)} & \dots & x_i^{(N-1)} & \dots & x_k^{(N-1)} \\ x_1^{(N)} & x_2^{(N)} & \dots & x_i^{(N)} & \dots & x_k^{(N)} \end{pmatrix}$$

$$B = \begin{pmatrix} x_{k+1}^{(1)} & x_{k+2}^{(1)} & \dots & x_{k+i}^{(1)} & \dots & x_{2k}^{(1)} \\ x_{k+1}^{(2)} & x_{k+2}^{(2)} & \dots & x_{k+i}^{(2)} & \dots & x_{2k}^{(2)} \\ \vdots & \vdots & & \vdots & & \vdots \\ x_{k+1}^{(N-1)} & x_{k+2}^{(N-1)} & \dots & x_{k+i}^{(N-1)} & \dots & x_{2k}^{(N-1)} \\ x_{k+1}^{(N)} & x_{k+2}^{(N)} & \dots & x_{k+i}^{(N)} & \dots & x_{2k}^{(N)} \end{pmatrix}$$

2. Define a matrix $C_i$ formed by all columns of $B$ except the $i$-th column, which is taken from $A$:

$$C_i = \begin{pmatrix} x_{k+1}^{(1)} & x_{k+2}^{(1)} & \dots & x_i^{(1)} & \dots & x_{2k}^{(1)} \\ x_{k+1}^{(2)} & x_{k+2}^{(2)} & \dots & x_i^{(2)} & \dots & x_{2k}^{(2)} \\ \vdots & \vdots & & \vdots & & \vdots \\ x_{k+1}^{(N-1)} & x_{k+2}^{(N-1)} & \dots & x_i^{(N-1)} & \dots & x_{2k}^{(N-1)} \\ x_{k+1}^{(N)} & x_{k+2}^{(N)} & \dots & x_i^{(N)} & \dots & x_{2k}^{(N)} \end{pmatrix}$$

3. The model output is computed for all the input values in the sample matrices $A$, $B$ and $C_i$, obtaining three $N \times 1$ vectors:

$$y_A = f(A) \qquad y_B = f(B) \qquad y_{C_i} = f(C_i),$$

4. The first order index and the total effect index are estimated as follows:

$$S_i = \frac{V[E(Y \mid X_i)]}{V(Y)} = \frac{y_A \cdot y_{C_i} - f_o^2}{y_A \cdot y_A - f_o^2} = \frac{(1/N)\sum_{j=1}^{N} y_A^{(j)} y_{C_i}^{(j)} - f_o^2}{(1/N)\sum_{j=1}^{N} (y_A^{(j)})^2 - f_o^2}$$

and

$$S_{T_i} = 1 - \frac{V[E(Y \mid X_{\sim i})]}{V(Y)} = 1 - \frac{y_B \cdot y_{C_i} - f_o^2}{y_A \cdot y_A - f_o^2} = 1 - \frac{(1/N)\sum_{j=1}^{N} y_B^{(j)} y_{C_i}^{(j)} - f_o^2}{(1/N)\sum_{j=1}^{N} (y_A^{(j)})^2 - f_o^2}$$

where

$$f_o^2 = \left( \frac{1}{N} \sum_{j=1}^{N} y_A^{(j)} \right)^2$$

The accuracy of the estimates for $S_i$ and $S_{T_i}$ will depend on the number of runs $N$ chosen. The selection of $N$ should be done considering that the error associated with the Monte Carlo estimates is proportional to $1/\sqrt{N}$, which indicates that if the analyst wishes to reduce the error by a factor of 10, $N$ must be increased by a factor of $10^2 = 100$. As a rule of thumb, the analyst should select a number for $N$, such that $N >> 2k$; and the sampling points used to build matrices $A$ and $B$ should be generated using Latin Hypercube sampling (LHS) technique (Iman et al., 1980; Mckay et al., 1979) to assure a better distribution of samples in the sampling space. However, the analyst should also take into consideration that the computational cost of this approach is $2N$ runs of the model to generate the matrices $A$ and $B$, plus $k \times N$ to estimate the output vector for the matrix $C_i$. Therefore, the total cost is that of $N(k + 2)$ runs.

## 3.3 Mean-Variance Portfolio Optimization

The analysis on the performance of natural capital investments presented in Chapter 5 requires to build and test investment portfolios composed by a diverse range of assets. It is the interest of the work presented in this chapter to compute optimal portfolios of investments that maximizes returns and minimizes level of risk in order to identify the financial benefits of natural capital investments. A popular approach broadly adopted for modelling investment portfolio is the Mean-Variance approach for portfolio optimization. In modern portfolio theory, mean-variance optimization (MVO) approach is the mathematical framework to estimate the optimal portfolio of assets that maximizes the expected return for a given level of risk that is proxied with the variance. Mean-variance was initially introduced by Markowitz (1952, 1959), and it became also known as Markowitz portfolio optimization. In this approach, the portfolio risk is measured by estimating the covariance of the asset classes or the correlation among them. Given a portfolio conformed by $N$-risky assets, the portfolio return, $r_p$, is given by

$$r_p = \sum_{i=1}^{N} w_i z_i, \tag{3.8}$$

where $w_i$ represents the weights allocated to the individual asset $i$ and $z_i$ is the expected asset return. The variance of the portfolio is defined as

$$Var_p = \sum_{i=1}^{N} w_i^2 \sigma_i^2 + \sum_{i=1}^{N} \sum_{j \neq i} w_i w_j \rho_{ij} \sigma_i \sigma_j, \tag{3.9}$$

where $\sigma_i$ is the variance of the $i$-th asset, $\rho_{ij}$ is the correlation coefficient between assets $i$ and $j$, and $\sigma_i$ is the standard deviation of asset $i$.

Markowitz optimization determines the efficient portfolio as the set of weights that allows obtaining the maximum expected portfolio return for a given level of variance. Or similarly, the portfolio that minimizes the risk (i.e. the variance) for a specific target return. The collection of efficient portfolios is normally plotted in a risk-expected return space to create the efficient frontier, which presents the best possible returns for a given level of risk. The efficient frontier is a hyperbolic shaped curve that encloses all the non-efficient portfolio in it (Merton, 1972).

A matrix representation is frequently used for the estimation of the efficient frontier. If we represent the portfolio weights using a $N \times 1$ vector $\mathbf{w}$ and the set of returns of the $N$-risky assets by the vector $\mathbf{z}$, the optimization problem in Markowitz Mean-Variance approach can thus be defined as

$$\mathbf{w}^* = \underset{\mathbf{w}}{\operatorname{argmin}}\, \mathbf{w}^{\mathrm{T}} \boldsymbol{\Sigma} \mathbf{w} \tag{3.10}$$

subject to achieving the target return $r_p$, such that $\mathbf{z}^{\mathrm{T}}\mathbf{w} = r_p$ and to the constrains $\mathbf{1}^{\mathrm{T}}\mathbf{w} = 1$, where $\boldsymbol{\Sigma}$ is a $N \times N$ matrix with the covariance of the risky assets.

MVO relies on the assumption that asset returns are normally distributed, and only returns, variance and covariance are needed to derive the optimal portfolio. Therefore, if skewness or kurtosis exist in the returns, these would not be captured in the model (Francis and Kim, 2013). Moreover, MVO is based on expected values and variance to model investor preferences, which mean making mathematical assumptions about the future that in many cases will not represent actual investor preferences in practice. This lead to several problems, for instance, expected values fail to take account of new circumstances that did not exist in the historical data (Low et al., 2016); it implies increasing absolute risk aversion, which means that as an investor wealth increases, its risk aversion also increases (Francis and Kim, 2013); and it implies investors are indifferent to negative profits which it is not realistic. Another weakness of MVO is that the technique faces problems of robustness and sensitivity of the optimal portfolio weights to changes in the input parameters (Fabozzi et al., 2007). This results in a weight allocation that places too much weight to assets with higher expected return, and zero allocations to assets with lower expected return. Despite its several drawbacks and weaknesses, MVO is still the optimization approach for portfolio allocation most widely adopted among practitioner given its simplicity and convenience.

## 3.4 Asset Allocation for Oil-sourced Sovereign Wealth Funds

In the analytical study introduced in Chapter 6, it is required to model the portfolio of investment of an oil-funded SWF to determine optimal allocations in a set of investment assets. The Mean-variance portfolio optimization approach described in the previous section is not sufficient to address the problem of determining optimal allocations in a commodity source portfolios. Unlike other type of investment portfolios, oil-funded SWFs shall consider optimal allocations that take into account for the risk of the assets respect to oil prices. In this sense, optimal assets will be not those assets that maximize returns and minimize the portfolio risk only, but those that also minimize the risk with the commodity price that is funding the fund. As a result, an extra level of complexity is added to the problem of estimating optimal portfolios for SWFs.

The theoretical framework developed by Gintschel and Scherer (2008) addresses the optimal asset allocation problem for oil-sourced Sovereign Wealth Funds (SWFs). This framework differentiates a country's wealth into two main components: a fraction, $\omega$, that represents the value of subsoil assets (e.g. oil reserves); and a remaining fraction, $(1-\omega)$, that represents the value of above-ground assets in the form of an SWF that is invested in financial securities. Oil resources are determined by the size of oil reserves $x_o$, in million barrels, and the price per barrel $p_o$. The total value of oil resources is therefore, $x_o p_o$, and changes in oil prices determine their expected return $r_o$, and risk $\sigma_o$ that the country wants to diversify. The value of above-ground assets is given by the market value of the fund $v_f$, which is invested in a portfolio of N-risky securities with weights $\mathbf{w}$, such that $\mathbf{1}^{\mathrm{T}} \cdot \mathbf{w} = 1$. The return of the N-risky assets over the period of analysis is given by the vector $\mathbf{z}$, and their covariances are provided by the matrix $\mathbf{\Sigma}$. The return on the portfolio is $r_p$. Therefore, the change in total wealth (i.e. oil reserves and financial assets) is given by $r = \omega r_o + (1-\omega) r_p$, where $\omega = x_o p_o / (x_o p_o + v_f)$ is the value of oil reserves relative to aggregated wealth. The exposure of financial assets to oil risk is captured by the oil sensitivity of the asset's returns collected in a vector $\mathbf{b}$, whose elements $b_i = Cov(z_i, r_o)/\sigma_o$. In consequence, the oil exposure of a financial portfolio $\mathbf{w}$, is defined as $\mathbf{w}^{\mathrm{T}} \cdot \mathbf{b}$.

Following the standard definition, an optimal asset allocation is defined by a portfolio that minimises variance for a given expected return. Gintschel and Scherer (2008) distinguish between two possible choices for the optimal portfolio: a locally efficient portfolio and a globally efficient portfolio. A locally efficient portfolio neglects the commodity risk of a country. In the standard mean-variance framework, as commonly applied in practice, the locally efficient portfolio is obtained by solving the problem

$$\mathbf{w}^* = \operatorname*{argmin}_{\mathbf{w}} \mathbf{w}^{\mathrm{T}}\mathbf{\Sigma}\mathbf{w} \tag{3.11}$$

subject to achieving a target expected return $\mu$, such that $\mathbf{z}^{\mathrm{T}} \cdot \mathbf{w} = \mu$, and to the constrains $\mathbf{1}^{\mathrm{T}} \cdot \mathbf{w} = 1$. The solution to this problem is denoted by $\mathbf{w}_L(\mu)$ which is efficient in isolation.

A global efficient portfolio $\mathbf{w}_G(\mu)$, on the contrary, takes into consideration the commodity risk and it yields to an efficient combined portfolio that minimizes the variance of changes in aggregate wealth given by

$$Var(r) = \omega^2\sigma_o^2 + (1-\omega)^2\mathbf{w}^{\mathrm{T}}\mathbf{\Sigma}\mathbf{w} + 2\omega(1-\omega)\sigma_o^2\mathbf{w}^{\mathrm{T}}\mathbf{b} \tag{3.12}$$

subject to the constrains $\mathbf{1}^{\mathrm{T}}\mathbf{w} = 1$ and $\mathbf{z}^{\mathrm{T}}\mathbf{w} = \mu$. It is worth noticing that the solution of the global portfolio has the same expected return $\mu$ as the locally efficient portfolio, independently of the expected oil price change. This avoid the need of making further assumptions on the expected oil price change. It can be proven (see Gintschel and Scherer (2008) and Bertoni and Lugo (2013)) that for any desired return $\mu$, the globally efficient portfolio can be expressed as a linear combination of the locally efficient portfolio and a hedge portfolio $\mathbf{w}_H$ as follows

$$\mathbf{w}_G = \mathbf{w}_L(\mu) + \frac{\omega}{(1-\omega)}\mathbf{w}_H \tag{3.13}$$

where

$$\begin{aligned}\mathbf{w}_H =&\sigma_o^2\{-\boldsymbol{\Sigma}^{-1}\mathbf{b}+\boldsymbol{\Sigma}^{-1}\mathbf{z}\frac{1}{\Delta}[(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})-(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})]\\&+\boldsymbol{\Sigma}^{-1}\mathbf{1}\frac{1}{\Delta}[(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z})]\}\end{aligned} \tag{3.14}$$

is a zero- net investment, zero-expected return hedge portfolio, and $\Delta = (\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1}) - (\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1})$. Thus, for any target return the globally efficient portfolio can be derived from a locally efficient portfolio using the hedge portfolio $\mathbf{w}_H$.

Excluding some special cases, such as when commodity is riskless (i.e. $\sigma_o = 0$), when its risk is orthogonal to the risk of financial assets (i.e. $\mathbf{b} = 0$) or when the country does not want to diversify its commodity risk (i.e. $\omega = 0$), it is found that the locally efficient and the globally efficient portfolios are different. In general, for a given level of return, $\mathbf{w}_G(\mu)$ will have a higher stand-alone risk and a lower Sharpe ratio than $\mathbf{w}_L(\mu)$. An oil-funded SWF aiming to diversify oil risk will not invest in the locally efficient portfolio, but rather, it will invest in the globally efficient portfolio that takes into account the sensitivity of financial assets with oil $\mathbf{b}$. Assets exhibiting high sensitivity with oil risk tend to be underweighted, and the sensitivity to commodity risk can be more tolerated in assets with higher expected returns. Therefore, when analysing the performance of an SWF, it should be done considering the globally efficient portfolio, otherwise, results would provide consistently incorrect conclusions (Bertoni and Lugo, 2013).

# 4

# Natural capital and wealth accounting

A Fundamental interest in a country development strategy is having information about the condition of its natural capital over time. Natural capital accounting systems have already been developed and implemented in several countries (see e.g., BureauOfMethodology (2013); StatisticsSweden (2015); StatisticsCanada (2016)) with the objective of tracking changes on the value of natural capital assets and identifying the major factors affecting those changes. Information about the value of the stock of natural resources and drivers of change is a prerequisite for informed decision-making (Guerry et al., 2015; Greenhalgh, 2015). This information also allows for the estimation of the total wealth of a country that can then be used to assess the sustainability of development (Dasgupta, 2010; Arrow et al., 2012; Polasky et al., 2015). The value of natural capital is a fundamental component of the wealth of a nation, which is the result of aggregating the value of the stock of produced, human, and natural capital assets. A necessary condition for delivering sustainability is the preservation of enough per capita wealth, including its natural capital component, for future generations (Costanza and Daly, 1992).

Awareness of the importance of natural capital and wealth accounting, has guided international efforts, led primarily by The World Bank with its *Where is the Wealth of Nations?* report (TheWorldBank, 2006) along with the *Inclusive Wealth Report* published by UNEP&UNU-IHDP (UNEP&UNU-IHDP, 2014), to estimate the value of wealth and its components in countries around the world. The studies conducted by the above sources reveal two striking observations about the wealth composition of developed economies: first, that natural capital normally represents a very small fraction of national wealth compared to other capital forms, e.g., human and produced capital; and second, the value of natural capital has been declining steadily in the last decades. A wealth composition that is largely composed of elements of produced and human capital, under conditions of financial shock, exposes per capita wealth trajectories to the risk of decline. The 2008 financial crisis, for instance, severely impacted the levels of human and produced capital in developed and developing economies, and in doing so, dragged down aggregate values of wealth. The 2008 financial crisis yielded a high default rate in the United States subprime home mortgage sector, precipitating an international banking crisis that collapsed a number of the world largest investment banks (French et al., 2009; Kehoe et al., 2008). Natural capital, on the contrary, is an element of wealth which is less exposed to economic fluctuations since its value is less dependent on economic stability. Nevertheless, different forms of natural capital including non-renewable and renewable natural assets and ecosystem services, as already mentioned, continue to decline due to the persistent depletion and degradation of natural capital stock.

The aforementioned context reflects the specific case for the United Kingdom. The UK is an example of a leading nation in the implementation of natural capital and wealth accounts, that has successfully been able to track changes in the value of its capital stock over time (ONS, 2015). The first estimates of natural capital in the UK were introduced by the Office for National Statistics (ONS) in 2012, and values for natural assets have been reported since 2009. Similarly, estimations of human capital were initiated in 2004 and values on produced capital have been accounted for since 1952. The UK's specific data also shows that per capita values of human and produced capital were severely affected by the 2008 financial crisis (ONS, 2016a; TheBlueBook, 2014); whereas the value of natural capital has been experiencing significant losses, again, mainly due to the decline of non-renewable natural capital components (Khan et al., 2014). The fall in natural capital value and the fluctuations of human and produced capital have motivated authorities in the UK to investigate how capital asset management, and in particular natural capital, affects the risk of subsequent declining trajectories for their values. Moreover, it has also become relevant to identify the main factors driving those trajectories.

In line with this interest, this Chapter presents an analysis of the UK's wealth composition and assesses the risk of registering declining trajectories of per capita value of natural capital and wealth. The main objectives of this analysis are, first, to examine the trajectories registered for natural capital and wealth in the UK between 2003 and 2013, and identify which factors are driving the changes in their values. Thereafter, we study the effect of the 2008 financial crisis on the trajectories of each capital component of wealth. Lastly, we assess the risk of declining per capita natural capital and per capita wealth over the period 2015-2020 in order to identify the main factors influencing those risks. In this chapter we aim to enhance the understanding of how natural capital and wealth accounting systems generate useful information on the condition of capital assets and their changes in the specific case of the UK. To assess the risk of subsequent declining trends of natural capital and wealth values, we develop a stochastic model for the UK's wealth and then run Monte Carlo simulations. The model has the capability to estimate wealth components and their changes, using the methodologies for wealth accounting implemented by UK government agencies. Our extensive collection of empirical data is drawn from publicly available datasets. The model also accounts for some of the most relevant relationships existing among capital assets and macroeconomic variables of interest such as GDP changes. A significant contribution of this chapter is to provide a quantitative tool to track changes in the monetary value of natural capital assets in the UK over the years within the examined period. The monetary valuation of the different natural assets takes into account aspects of quantity and quality of the underlying asset, as well as, other factors such as market price, inflation, and economic growth in order to provide an estimation of its value. By providing a monetary estimation of the value of natural capital, the developed tool can identify increasing and decreasing trajectories, as well as, rates of change which allow comparison among different natural asset classes.

The content of this chapter is organized as follows. Section 4.1 presents a compilation of related works on this subject. Section 4.2 introduces the methodology used for wealth accounting and the stochastic model developed for the risk assessment. Section 4.3 provides the results of wealth composition, natural capital trajectories, risk assessment based on scenario evaluation, and our sensitivity analysis. Finally, in Section 4.4, we summarize the main findings and conclusions of the research conducted here.

## 4.1 Related work on natural capital and wealth accounting

Natural capital accounting has become a fundamental component of the 'capital approach' to measure changes in wealth over time (Atkinson et al., 2014). Early works of Solow (1986); Maler (1991); Pearce and Atkinson (1993) and Asheim (1994) discuss the importance of 'greening' accounting systems by incorporating natural capital accounts and providing a more comprehensive picture of capital asset management in modern economies. The measurement of natural capital value, as part of the aggregated wealth of nations, is also supported by the works of international organisations. Prominent examples include the creation of the System of Environmental-Economic Accounts (SEEA-CF, 2012) by the UN Statistical Commission and the development of national wealth accounting approaches by The World Bank (TheWorldBank, 2006) and the United Nations University-International Human Dimension Programme and United Nations Environmental Programme (UNEP&UNU-IHDP, 2014). The approaches for wealth accounting introduced by the World Bank and the UNEP&UNU-IHDP are currently the two major alternatives widely adopted for estimating wealth and its components, including natural capital. Estimations in the World Bank approach are based on the theoretical work of Hamilton and Hartwick (2005), where wealth is estimated as the present value of future consumption and is broken down into various capital forms, i.e. natural capital, produced capital and intangible capital which encompasses human, social, and institutional capital. Conversely, the alternative approach to wealth accounting adopted by UNEP&UNU-IHDP is based on the theoretical framework of Arrow et al. (2012, 2013) which estimates wealth as the aggregated value of produced, human, and natural capital components.

Both approaches for wealth estimation differ in the implementation of their methodologies for valuing capital assets. Nevertheless, the basic idea behind both approaches is the same. Wealth results from aggregating the monetary value of produced, human, and natural capital components. Moreover, the value of wealth and its capital components are divided by population in order to obtain per capita estimates. A sustainable management of capital assets requires that levels of aggregated per capital wealth do not decline over time (Polasky et al., 2015; Heal and Kristrom, 2005; Dasgupta and Maler, 2001). Therefore, both approaches focus on analysing changes (i.e. growth rates and variations in the composition) in the per capita value of wealth and its components over time that are reported in monetary values in real terms.

Based on the aforementioned approaches, a number of works in the literature focus on changes in natural capital and wealth value in different countries. TheWorldBank (2001), for instance, has estimated values of wealth and its components in 120 countries over three years (1995, 2000 and 2005). While the Inclusive Wealth Report 2014 published estimates of changes in wealth and all of its components for 140 countries over the period 1990-2010 (UNEP&UNU-IHDP, 2014). Moreover, Dasgupta (2014) has analysed the composition of wealth accumulation in India and studied the trajectory of the country's natural capital over the period 1995-2000. The study of Dovern et al. (2014) applies wealth and natural capital accounting to develop a sustainability index to rank 100 cities in Germany. Ollivier and Giraud (2011) assessed the sustainability of Mozambique's development path between 2000 and 2005 using the Arrow et al. (2012) methodology for wealth and natural capital estimation. Likewise, Lange (2004) also used the Arrow et al. (2012) approach to measure the per capita value of natural capital and national wealth in Botswana and Namibia, contrasting the development paths of both countries over the period 1980-2001, over which time different natural capital policies were adopted. In Barbier (2013), a case study implements natural capital accounting to track changes in the value of mangroves in Thailand between 1960 and 2010. Engelbrecht (2014) used The World Bank approach to evaluate sustainability in OECD countries between 1995 and 2005. Lastly, in Engelbrecht (2016), differences in wealth and natural capital valuation in OECD countries are compared using the two different approaches for wealth estimation. All of the above studies show consistent declines in natural capital values in the different countries.

In the UK, significant efforts have also been made to introduce natural capital accounting as an integral part of wealth accounts (UKNEA, 2014; ONS, 2012). Estimations of produced capital components have traditionally been reported in the UK National Accounts since 1952, and more recently natural and human capital estimates have emerged to be incorporated into the national accounts. The first methodology for the estimation of natural capital in the UK was introduced by Khan et al. (2014). The methodology is based on The World Bank's approach for wealth measurement. However, it has been extended to include further natural capital assets and ecosystem services that are not considered in The World Bank estimates. Despite the UK having implemented estimates of its different wealth components, no previous work in the literature has yet gathered this information together to study changes in natural capital value and aggregated wealth in this country when following their own adopted approach. Moreover, most of the works found in the literature limit to the report of estimates of natural capital and wealth changes based on historical data. The present work goes a step further and not only evaluates the historical trajectories of UK's wealth and natural capital, but also introduces projections into the future based on different scenarios. Particular focus is given to identifying the drivers of changes in wealth and natural capital value and assessing the risk of declining their respective values.

## 4.2 Methodology

### 4.2.1 Stochastic model for wealth and risk analysis

The model built for wealth estimation and risk assessment is based on the different methods adopted by the Office for National Statistics (ONS) in the UK to estimate the value of wealth components. Those methods are compiled together to create a single model to track changes in total wealth over time. In addition, a number of empirical relationships existing among the different capital assets and macroeconomic variables of interest are incorporated. The mathematical model consists of a stochastic discrete model that estimates wealth and its components on an annual basis along the period 2003-2020. Estimations before 2013, are based on available data, while estimations after 2013 are the result of projections of possible scenarios incorporating random variable to simulate uncertainty. A detailed description of the assumptions considered in the model is presented in Appendix B.

Wealth, $W_t$, at time $t$ is given by adding up the values of produced capital, $C_t^P$, human capital, $C_t^H$, and natural capital, $C_t^N$, as follows

$$W_t = C_t^P + C_t^H + C_t^N, \quad \forall t = \{2003, 2004, \ldots, 2020\} \tag{4.1}$$

The value of $C_t^P$ is estimated using Perpetual Inventory Method (PIM) as described by Dey-Chowdhury (2008). Therefore, $C_t^P$ is given by

$$C_t^P = \sum_{a}^{A^P} \sum_{\tau=0}^{\infty} (1 - \tau\gamma_{t-\tau}^a) I_{t-\tau}^a, \quad \forall a \in A^P \tag{4.2}$$

where $I^a$ is the investment in a particular asset $a$, $\gamma^a$ is the depreciation rate of asset $a$ at a particular year, and $A^P$ is the set of produced assets.

In the case of $C_t^H$, the estimation of this component is done in an adaptation of the approach introduced by Fender (2012). This approach estimates the value of HC as the lifetime labour income of an individual at a given age and educational attainment level expressed as

$$C_t^H = \sum_{g=1}^{6}\sum_{d=1}^{6} Y_{g,d,t} N_{g,d,t}, \tag{4.3}$$

where $Y_{g,d,t}$ is the lifetime labour income of an individual in the age group $g$ (i.e. six age groups to cover the range 16-64, the working age in the UK) and educational attainment level $d$ (i.e. six categories: degree or equivalent, higher education, GCE A-level, GCSE grades A-C, other qualifications, no qualifications) and $N_{g,d,t}$ is the number of employed individuals in the specific age and education category. $Y_{g,d,t}$ is computed using the following expression

$$Y_{g,d,t} = E_{g,d,t} B_{g,d,t} + \left( \sum_{d=1}^{6} Y_{g+1,d,t} \Pi_{g,d,t} \right) (1 - h_{g,t}) \frac{1+\kappa}{1+\rho}, \tag{4.4}$$

where $E_{g,d,t}$ is the employment rate, $B_{g,d,t}$ is the annual labour income, $\Pi_{g,d,t}$ is the probability of upgrading to a higher educational attainment level, $h_{g,t}$ is the mortality rate, $\kappa$ is the productivity growth rate (2.0% p.a.) and $\rho$ is the discount rate (3.5% p.a.).

In regard to natural capital, the methodology used to measure the value of natural assets is based on the net present value (NPV) approach, as detailed by Khan et al. (2014). This approach uses projections of future asset prices to generate time series of future returns during the expected lifespan of the assets. The monetary value of natural capital is, therefore, calculated as

$$C_t^N = \sum_{a}^{A^N} NPV(K_t^a, \rho, \chi^a) = \sum_{a}^{A^N}\sum_{t}^{\chi^a} \frac{K_t^a}{(1+\rho)^t}, \qquad \forall a \in A^N \tag{4.5}$$

where $K_t^a$ is the resource rent for natural asset $a$, $\rho$ is the discount rate (3.5% p.a.), $\chi^a$ is the asset life for asset $a$ (i.e. 25-year for most assets) and $A^N$ represents the total set of natural assets included in the accounts. The stock of natural assets currently included in the UK's capital accounts considers the non-renewable assets of oil & gas reserves, coal reserves, agricultural land and mineral reserves (i.e. silver, limestone, chalk, sand & gravel, peat and lead); the renewable assets of timber resources, fishery and water supply; and the ecosystem services of outdoor recreation and greenhouse-gas (GHG) sequestration. The method employed to estimate the resource rent varies according to each natural asset. However, they all aim to isolate the value of the benefits produced by the asset itself.

The resource rent for minerals and coal is estimated as follows

$$K_t^a = P_t^a \cdot S_t^a \cdot \delta_t^a, \tag{4.6}$$

where $P_t^a$ and $S_t^a$ are the market price and production level of asset $a$ respectively, and $\delta_t^a$ is a resource rent ratio introduced to isolate the resource rent for each component. Market prices for mineral and coal are taken from data reported in their respective markets for those years for which data is available. Otherwise, they are modelled using Geometric Brownian motion (GBM) and Mean-Reverting (MR) stochastic processes as described in Chapter 3.

In the case of oil & gas, the resource rent for this asset is given by

$$K_t^a = (P_t^o \cdot S_t^o + P_t^g \cdot S_t^g) - (q_t^o + q_t^d + q_t^u), \tag{4.7}$$

where $P_t^o$ and $P_t^g$ are the price of oil and gas respectively, and $S_t^o$ and $S_t^g$ their level of production. The first term on the right side of Equation (4.7) represents the net income derived from oil & gas activities (i.e. commercialisation of these assets in their respective markets) and the second term represents the total cost associated with the asset production, which includes operating cost ($q_t^o$), decommissioning cost ($q_t^d$) and user cost of produced assets ($q_t^u$). Similar to the case of minerals and coal, the prices of oil and gas are taken from their respective market for those years where data is available, whereas for the period when data is unavailable they are modelled using the GBM process. In regard to the total cost of producing this asset, the model projects its value into the future following a growth rate that is inputted into the model as an assumption based on historical trends. The asset life for oil & gas is determined by the years to depletion of proven and probable reserves. which occurs when cumulatively projected production surpasses existing reserves.

For the assets agricultural land, water supply, and fishery the resource rents are computed by subtracting the total cost associated with a specific industrial classification from the output ($\theta_t^a$ of that industry, as follows

$$K_t^a = \theta_t^a - \underbrace{(\omega_t^a + \nu_t^a + \eta_t^a + \zeta_t^a + \phi_t^a)}_{\text{total cost}}, \tag{4.8}$$

where the second term on the right side of the equation represents the total cost associated with a particular industry to include the intermediate consumption ($\omega_t^a$), compensation of employees ($\nu_t^a$), difference between taxes and subsidies ($\eta_t^a$), fixed capital consumption ($\zeta_t^a$) and return to produced assets ($\phi_t^a$).

As for timber resources, the total stocked area of timberland at time $t$, $L_t^T$, is distributed across six different categories according to their age, namely: i) 0-20 ($i = 1$), 21-40 ($i = 2$), 41-60 ($i = 3$), 61-80 ($i = 4$), 81-100 ($i = 5$) and +100 ($i = 6$). A resource rent is estimated for each category. The estimation is based on the fraction of timber area associated with each age category, denoted by $l_{i,t}^T$, such that $\sum_{i=1}^6 l_{i,t}^T / L_t^T = 1$, which is given by

$$K_{i,t}^a = P_t^w \cdot l_{i,t}^T \cdot \varphi, \tag{4.9}$$

where $P_t^w$ is the stumpage price of wood at time $t$, and $\varphi$ is the volume of timber per area (assumed constant at 304 $\mathrm{m}^3$/ha) at harvesting age (50 years). As previously done for other commodity prices, $P_t^w$ is modelled using an MR process for years in which data is not yet available, otherwise it is taken from prices reported in the timber market. The asset life for each age category is calculated by subtracting the middle point of the age category from the harvesting age.

In outdoor recreation, the resource rent is calculated as the amount consumers are willing to pay to visit recreational places as reflected in the cost of travelling. Two main elements are considered in the travel cost, namely the transport fuel cost, $M_t$, and the visiting time. $M_t$ includes the average expenditure per person on petrol and diesel per visit. The visiting time, on the other side, is given by 75% of the average hourly wage, $Z_t$, multiplied by the average duration of the visit, $F_t$ (Fezzi et al., 2014). Therefore, the resource rent is computed as

$$K_t^a = (M_t + 0.75 Z_t F_t) \cdot v_t, \tag{4.10}$$

where $v_t$ is the annual number of visits to recreational sites, computed as the product between the average number of times a person visits the environment in a year and the total population of the UK. $M_t$ and $D_t$ are assumed to be described by normal distributions such that $M_t \sim N(\mu_M, \sigma_M)$ and $D_t \sim N(\mu_D, \sigma_D)$.

The resource rent for GHG sequestration is estimated by summing the net amount of gases captured or emitted by terrestrial ecosystems in the Land Use, Land Use Change and Forestry (LULUCF) sector. LULUCF groups are put into six different categories according to their use: forestland ($j = 1$), cropland ($j = 2$), grassland ($j = 3$), wetlands ($j = 4$), settlements ($j = 5$), and other ($j = 6$). Each land category has a corresponding area $L_t^j$, such that, $\sum_j L_t^j / L = 1$, where $L$ is the total area of the UK, assumed constant for the purpose of our analysis. The resource rent is computed by multiplying the net amount of gas sequestered from the atmosphere times the social price of carbon ($P_t^s$), as follows

$$K_t^a = \sum_{j=1}^{6} \Lambda_t^j \cdot P_t^s, \tag{4.11}$$

where $\Lambda_t^j$ is the net GHG emissions from land category $j$.

Finally, per capita values for wealth and each of its capital components are obtained dividing $W_t$, $C_t^P$, $C_t^H$ and $C_t^N$ by UK's total population, $X_t$, at time $t$. For the analysis of the period 2015-2020, it is of interest to compute the risk of declining per capital values of aggregate wealth and natural capital over time. The analytical model defines risk as the probability that changes in per capita wealth or natural capital between two points in time are negative. Therefore, the risk of declining per capita wealth is expressed as

$$R^W = \text{Prob}\left[\left(\frac{W_{t+\Delta t}}{X_{t+\Delta t}} - \frac{W_t}{X_t}\right) \leq 0\right], \tag{4.12}$$

similarly,

$$R^N = \text{Prob}\left[\left(\frac{C^N_{t+\Delta t}}{X_{t+\Delta t}} - \frac{C^N_t}{X_t}\right) \leq 0\right], \tag{4.13}$$

represents the probability of declining the value of per capita natural capital. Where $\Delta t$ is assumed to be always greater than zero.

In addition to the valuation methodologies for capital assets described above, the model incorporates a number of empirical relationships between capital assets and relevant macroeconomic variables. The value taken by capital assets at a certain point in time is affected by the condition of other capital assets. In the context of natural capital, for instance, the value taken by the ecosystem service of GHG sequestration depends on the value of timber resources, as they are both linked by the total area of forestland and their capacity to capture CO2 from the environment. Moreover, these two values may also depend on the values of produced capital or agricultural assets as they relate to changes in land use. Likewise, macro-economic variables such as average wages, employment and unemployment rates, play a significant role in determining values for human capital. These variables, in many cases, are influenced by the economic performance of a country as reflected in GDP changes. In order to account for these interdependencies, the model includes a number of relationships built on empirical data using regression models. The number of relationships represented in the model is limited by data availability and the complexity of the interactions found among capital assets. The most significant relationships considered in the model are described in Appendix C. However, the author acknowledges that more relationships can be incorporated in the model, provided that data is available.

### 4.2.2 Data sources

The data required to estimate UK wealth and its components have been obtained from a wide range of official sources, and are presented in detail in Appendix D. The value of different produced capital sub-components was extracted from the UK National Accounts and published in TheBlueBook (2014). Produced assets in the UK include the value of fixed assets, dwellings, other buildings and structures, machinery, equipment, ICT infrastructure, biological resources, intellectual property products and inventories.

In regard to human capital estimation, time series on historical labour income (i.e. annual and hourly wages) were extracted from the Annual Survey of Hours and Earnings (ASHE, 2014). Quarterly data on GDP changes and inflation rate, as well as, annual data on employment and unemployment rates have been drawn from ONS archives on *UK key economic time series data* (ONS, 2016b). Records on UK total population and population disaggregated by age groups were taken from the 2014-based National Population Projections reported by ONS. Data on mortality rates by age group have been obtained from the UK National Life Tables 1980-2012. Finally, we use data on educational attainment level by age group that we have extracted from EuroStat (2015).

In relation to natural capital, the required data for the estimation of mineral and coal, including UK's mineral exports in value and volumes, as well as, production levels for each considered mineral asset and coal was provided by the British Geological Survey *Mineral Year Book*. For oil & gas, we have gathered data on market prices, production, and level of reserves from the UK OilandGasAuthority (2016) and the Department of Energy and Climate Change (DECC, 2015). In regard to the valuation of the assets agriculture, fishery and water supply, the figures corresponding to the output of relevant industries (i.e. mining and quarrying, agriculture, water and fishery) together with information on operating cost, intermediate consumption, compensation, taxes and subsidies, and the cost of produced assets, were obtained from the Input-Output Supply and Use tables published by ONS. As for timber resources, data on prices of coniferous standing wood, forest stocked areas, and timber volumes have been extracted from the timber statistics and national inventory sections of the UK's Forestry Commission (UKFC, 2015). In order to compute the value of outdoor recreation, information about the number of people visiting the natural environment, the average duration of visits to recreational sites and the average expenditure per visit were collected from the Monitor of Engagement with the Natural Environment (MENE) reports (MENE, 2014). Finally, figures on GHG emissions and removals by the LULUCF sector, as well as, data on land areas for the different land categories used in the valuation of GHG sequestration, were obtained from the Centre for Ecology and Hydrology's report (Miles et al., 2014). Time series on the social price of carbon have been drawn from DEFRA's section on UK carbon evaluation (DEFRA, 2014).

## 4.3 Simulation results

We begin the analysis of UK's natural capital and wealth changes by examining the period 2003-2013, where estimations are based on the available data extracted from the sources previously described. Thereafter, values at 2013 are taken as a starting point so that we may analyse the projections of natural capital and wealth values for the period 2015-2020 under multiple scenarios. Finally, a sensitivity analysis is conducted to identify the most important parameters driving changes on natural capital value over the projected period. All monetary values in this analysis are provided in real £for 2014.

### 4.3.1 UK wealth composition between 2003 and 2013

Table 4.1 depicts the composition of UK's wealth and changes in per capita value of each of its components during the period 2003-2013. From the table, we can observe that, by 2013, the value of UK aggregated per capita wealth was £433,781. The largest contribution of UK wealth is the human capital component, whose value during 2013 accounted for £286,430 (66% of total wealth). Produced capital follows with a registered per capita value in 2013 of £122,512 (28% of wealth). Whereas the per capita value of natural capital, when considering the aggregates of non-renewable, renewable and ecosystem services, was estimated at £24,839 (6% of wealth) during the same year representing by far the lowest component of UK wealth. Although based on a partial estimation of the natural assets measured to date, the value of natural capital is still as little as 11-time lower than human capital and nearly five times lower than produced capital. Most of the value of UK's natural capital is found in ecosystem services, which accounted for a monetary estimation of £22,601 in 2013. This is followed by non-renewable natural capital with a value of £1,634, and renewable natural capital with the lowest value of £665. The wealth composition exhibited by the UK is to be expected, give that in most develop economies values of human and produced capital represent the dominant fraction of wealth, and natural capital generally has a low share. In developing economies, on the contrary, natural capital share can be as high as 37% of wealth (Barbier, 2014b). It is worth mentioning that over the period 2003-2013, the population in the UK grew at an almost constant annual rate of 0.7%, passing from 59.5 million in 2003 to 63.9 million in 2013. During the same period, GDP per capita in this country grew at an average annual rate of 0.5% with two specific periods of negative growth in 2008 and 2009. The analysis of changes in value for the UK's wealth and each of its capital components is described below.

### Aggregated wealth, human capital, and produced capital

Figure 4.1 shows the trajectory followed by the aggregated value of UK's per capita wealth between 2003 and 2013. During the first five years of this period, 2003-2008, aggregated wealth in the UK grew at an average annual rate of 2.03% increasing from £434,761 in 2003 to £480,068 in 2008. However, in the subsequent five years, between 2008 and 2013, UK's wealth declined at an average of -1.99% annually, falling to £433,781 in 2013. Thus, net changes in per capita wealth were positive during the first half of the period reaching a +10.4% increase, whereas a negative net change of -9.6% was registered for the second half. When we examine Figure 4.1, we can also observe that wealth in the UK was following an upward

Table 4.1: UK per capita wealth between 2003 and 2013 (in £, 2014)

| | 2003 | 2008 | 2013 | % Changes 2003-08 | % Changes 2008-13 |
|---|---|---|---|---|---|
| Produced Capital | 118,933 | 132,131 | 122,512 | +11.1% | -7.3% |
| Human Capital | 281,933 | 318,351 | 286,430 | +12.9% | -10.0% |
| Natural Capital | 33,895 | 29,587 | 24,839 | -12.7% | -16.0% |
| Minerals | 344 | 335 | 328 | -2.5% | -2.3% |
| Coal | 256 | 262 | 196 | +2.3% | -25.3% |
| Oil & Gas | 5,041 | 2,698 | 1,111 | -41.6% | -58.8% |
| *Non renewable* | *5,641* | *3,295* | *1,634* | *-41.6%* | *-50.4%* |
| Timber | 77 | 95 | 156 | +23.2% | +63.5% |
| Agriculture | 612 | 534 | 382 | -12.8% | -28.5% |
| Water supply | 103 | 44 | 46 | -56.9% | +3.7% |
| Fishery | 75 | 78 | 82 | +4.1% | +4.9% |
| *Renewable* | *867* | *751* | *665* | *-13.4%* | *-11.5%* |
| GHG sequestration | 93 | 139 | 207 | +49.1% | +48.8% |
| Outdoor recreation | 27,288 | 25,433 | 22,395 | -6.8% | -11.9% |
| *Ecosystem Ser.* | *27,381* | *25,572* | *22,601* | *-6.6%* | *-11.6%* |
| **Total Wealth** | **434,761** | **480,068** | **433,781** | **+10.4%** | **-9.6%** |

trajectory until 2006, its highest point, after which the trajectory took a downward trend that accelerated particularly from 2008.

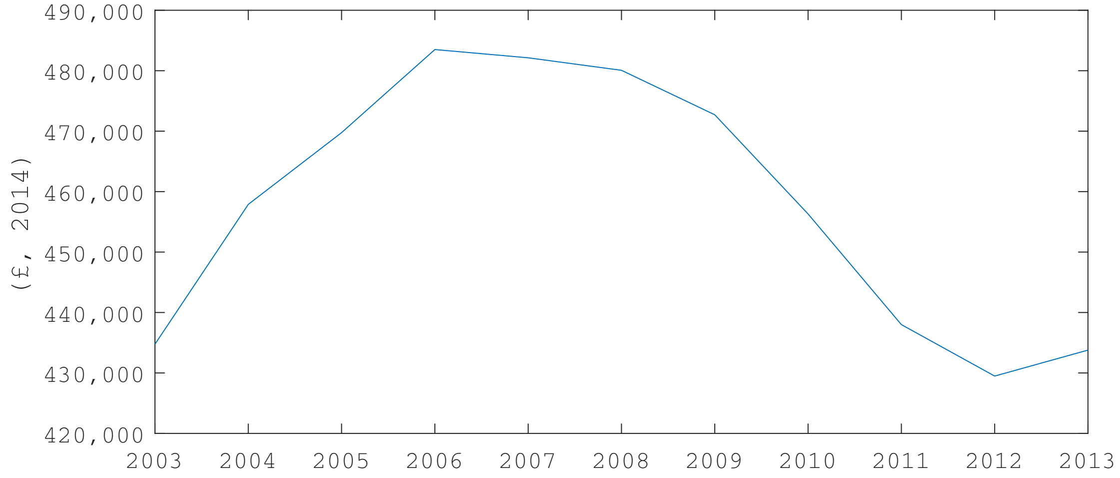


Figure 4.1: UK per capita wealth trajectory between 2003 and 2013 (in £, 2014)

The trajectory followed by UK wealth is largely driven by the values of human and produced capital, because they both represent the major contributors of wealth. Table 4.2 presents the correlation values registered between the UK aggregated

Table 4.2: Correlation matrix for UK per capita wealth, produced capital, human capital, and GDP value between 2003 and 2013

| | GDP | Wealth | Produced Capital | Human Capital |
|---|---|---|---|---|
| GDP | 1.00 | | | |
| Wealth | 0.57 | 1.00 | | |
| Prod. Cap. | 0.63 | 0.88 | 1.00 | |
| Human Cap. | 0.61 | 0.98 | 0.88 | 1.00 |

per capita wealth, human capital, produced capital, and GDP. The information in the table shows that the correlation between per capita GDP and aggregated wealth is 0.57, between GDP and human capital is 0.61, and between GDP and produced capital is 0.63. Moreover, the correlations between wealth and values of human and produced capital are 0.98 and 0.88 respectively. The significantly positive correlations found among these factors provide an indication of how wealth values are positively associated to human and produced capital, and at the same time, the value of these two are also positively associated to GDP. Therefore, the composition of UK wealth, highly composed by its human and produced capital, determines that changes in aggregated wealth value are largely driven by the economic performance of the country as reflected in its GDP growth. The 2008 financial crisis imposed a shock on the UK wealth trajectory. In the years prior to the crisis, which were characterised by a stable economic growth, wealth levels increased faster than the population, because the value of the UK's human and produced capital were also increasing. Nevertheless, in 2008 and thereafter, the financial crisis severely impacted on the values of human and produced capital and dragged down the value of total wealth to its lowest point at year 2012. These results are in line with the study on wealth conducted by UNEP&UNU-IHDP (2014).

The trajectories for the UK's per capita human and produced capital between 2003 and 2013 are presented in Figures 4.2 and 4.3, respectively. Human capital per capita in the UK experienced an average annual growth of 2.5% in the five years period between 2003 and 2008, increasing from £281,933 at the beginning of the period to £318,351 at the end. This significant growth, however, reverted in the following five years declining at an average rate of -2.1% annually to a value

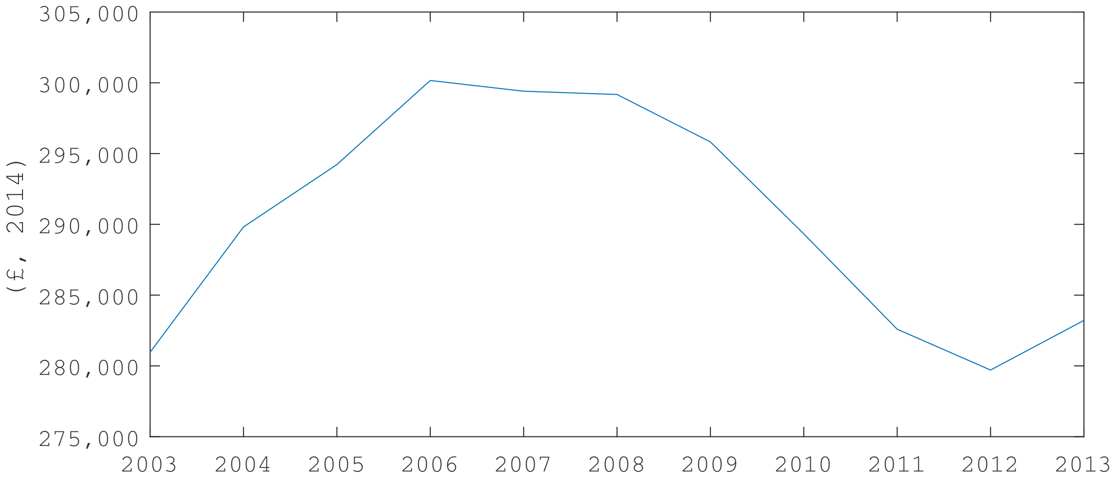


FIGURE 4.2: UK human capital per capita values between 2003 and 2013 (in £, 2014)

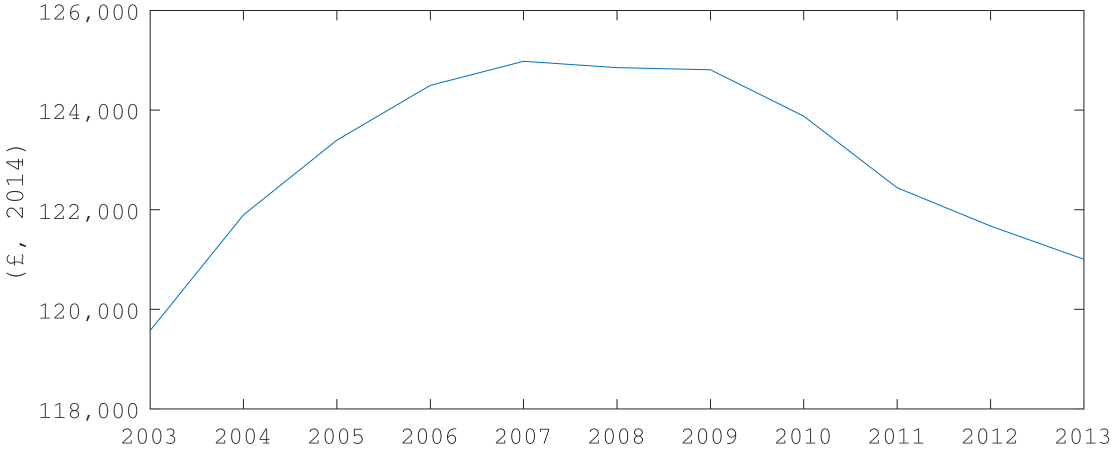


FIGURE 4.3: UK produced capital per capita values between 2003 and 2013 (in £, 2014)

of £286,430 in 2013. The downturn experienced during the financial crisis in 2008 affected the value of human capital stock as falling employment rates and shrunken real earnings. Similarly, the stock of produced capital was significantly affected by the crisis, manifesting as generalised reductions and cuts in infrastructure investments. As a result, the UK's produced capital passed from experiencing an average annual growth of 2.14% in the five years prior to the crisis, to a negative growth of -1.50% in 2008-2013.

### Natural capital

The analysis of the UK's natural capital value is broken down into the three different forms of natural capital (i.e. non-renewable, renewable, and ecosystem services). The decomposition of the analysis in different natural capita categories allow us to appreciate the changes in the values of all the natural capital components, which would otherwise have been masked if aggregate values were considered. Figures 4.4, 4.5 and 4.6 show the trajectories of the per capita values of non-renewable natural capital, renewable natural capital and ecosystem services between 2003 and 2013, respectively. Our first observation based on the figures is that the values of all different forms of natural capital in the UK, without exception, have followed downward trends across the evaluated period.

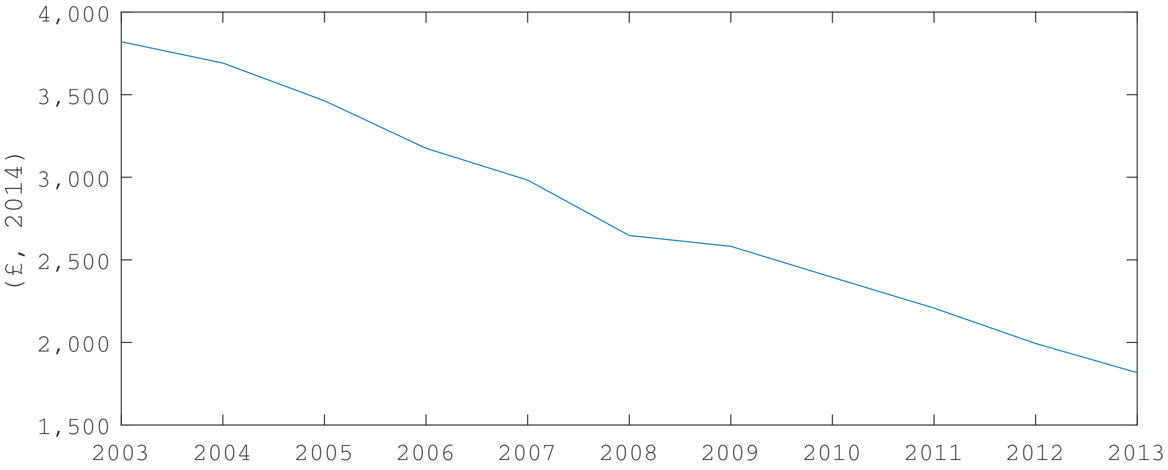


FIGURE 4.4: UK's non-renewable natural capital per capita value between 2003 and 2013 (in £, 2014)

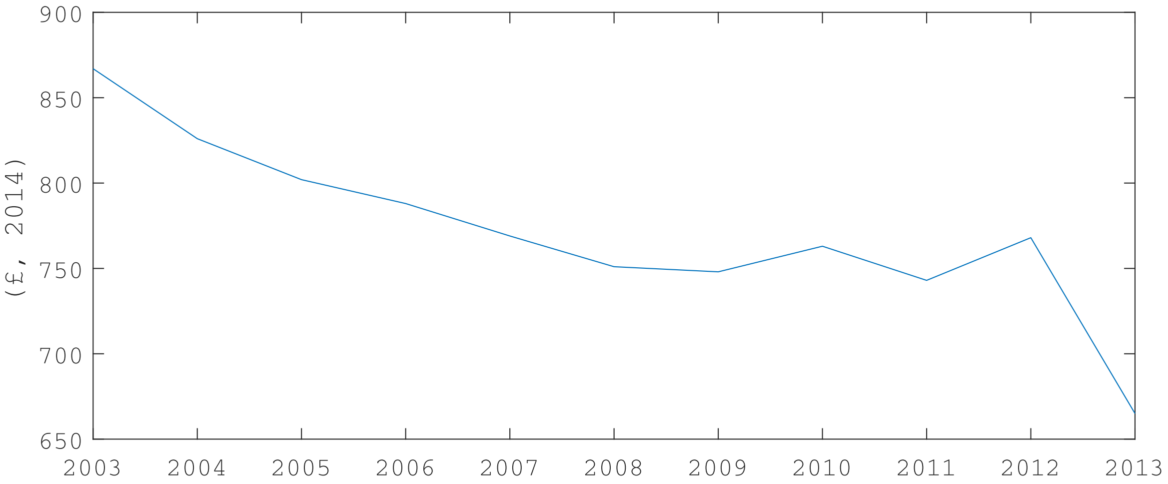


FIGURE 4.5: UK's renewable natural capital per capita value between 2003 and 2013 (in £, 2014)

The value of non-renewable natural capital decreased from £5,641 in 2003 to £1,634 in 2013, declining at an average annual rate of -11.5%. The major driver

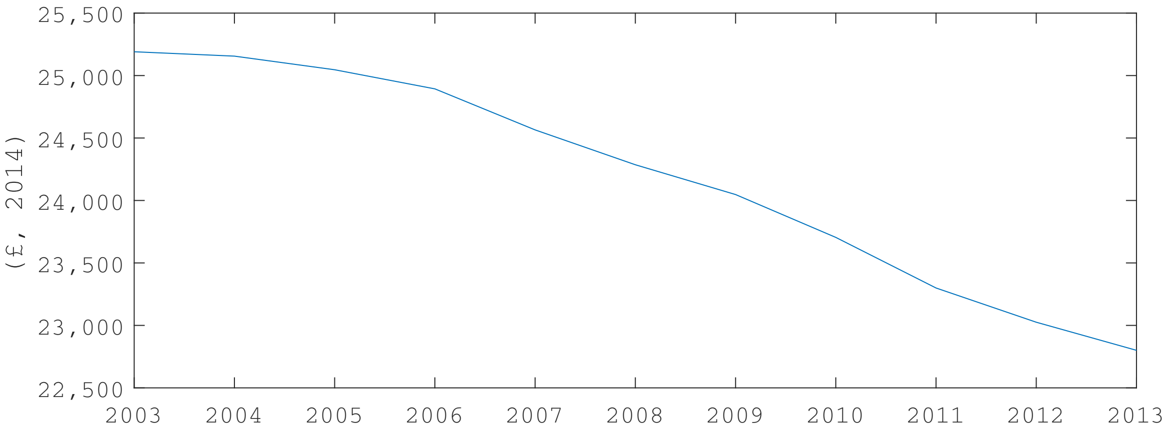


FIGURE 4.6: UK's ecosystem services per capita values between 2003 and 2013 (in £, 2014)

for this loss is a fall in the monetary value of the UK's oil & gas reserves. As shown in Figure 4.7, oil & gas showed a net change in value of -£3,930 (-78% value loss) between 2003 and 2013, being by far the largest among all non-renewable natural capital assets. UK's oil & gas reserves have been declining consistently over the past two decades, nearly halving from 2,286 MM tonnes in 1999 to just 1,164 MM tonnes in 2013. Oil & gas production has also decreased too, reducing from 137.1 MM tonnes in 1999 to 49.9MM tonnes in 2013 for oil, and from 37.5 to 15.9 billion therms over the same period for gas. In addition, the monetary values of mineral and coal reserves declined as well, registering a net change of -£16 (-4.7%) and -£60 (-23%), respectively, on their per capita value between 2003 and 2013. Similar to the case of oil & gas, the values of minerals and coal have largely been affected by a reduction in overall levels of productions during the examined period.

In the case of UK's renewable natural capital, its value per capita decreased from £867 in 2003 to £665 in 2013, at an average rate of -2.5% per year. The declining rate for renewable natural capital is over four times slower compared with that of non-renewable natural capital. The fall in renewable natural capital value was mainly due to the loss of per capita value of agriculture and water supply assets, which exhibited a negative net change of -£231 (-37.6%) and -£57 (-55.3%), respectively, between 2003 and 2017, as shown in Figure 4.8. In reality, the total non-per capita value of the agricultural natural asset has been increasing slightly over the examined period at an average annual rate of 0.5%, as the output from

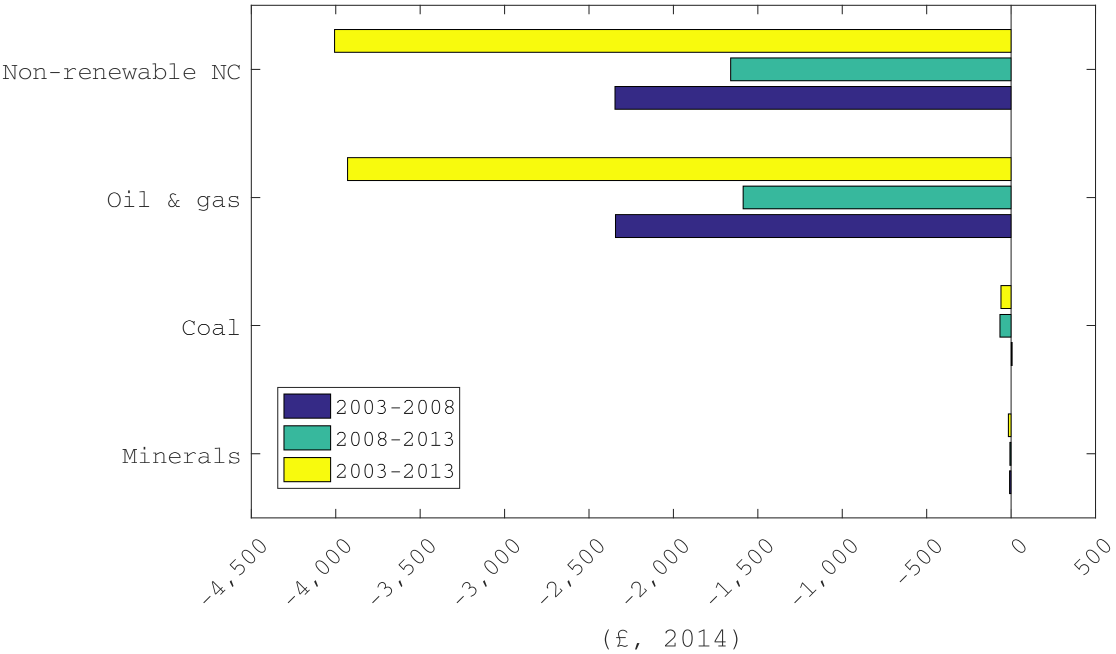


FIGURE 4.7: Changes in non-renewable per capita natural capital value, 2003-2013 (£, 2014)

the Agriculture industry in the UK has incremented as well. However, the rate of increase of the value of this particular asset has been slower than the rate of population growth (0.7%) over the same period, resulting in decreasing per capita values. On the other side in renewables, timber and fishery are the only natural capital assets in all categories to have registered a net positive change in value of £78 (+102.6%) and £7 (+9.3%) respectively. Nevertheless, the increase in per capita value of these assets was not sufficient to overcome the losses introduced by the other non-renewable assets.

Finally, the per capita value of ecosystem services also declined from £27,381 in 2003 to £22,601 in 2013. The average annual decline rate for ecosystem services was -1.9%, the slowest among all of the natural capital forms. The value decline, in this case, has been primarily driven by a significant loss in value of outdoor recreation, which registered a net change in value of -£4,780 (-17.5%) between 2003 and 2013. This is shown in Figure 4.9. Although the other ecosystem service of GHG sequestration registered a positive net change of £114 (+122%) over the same period, this increase in value was too small to compensate for the losses registered for outdoor recreation. The decline of the outdoor recreation value

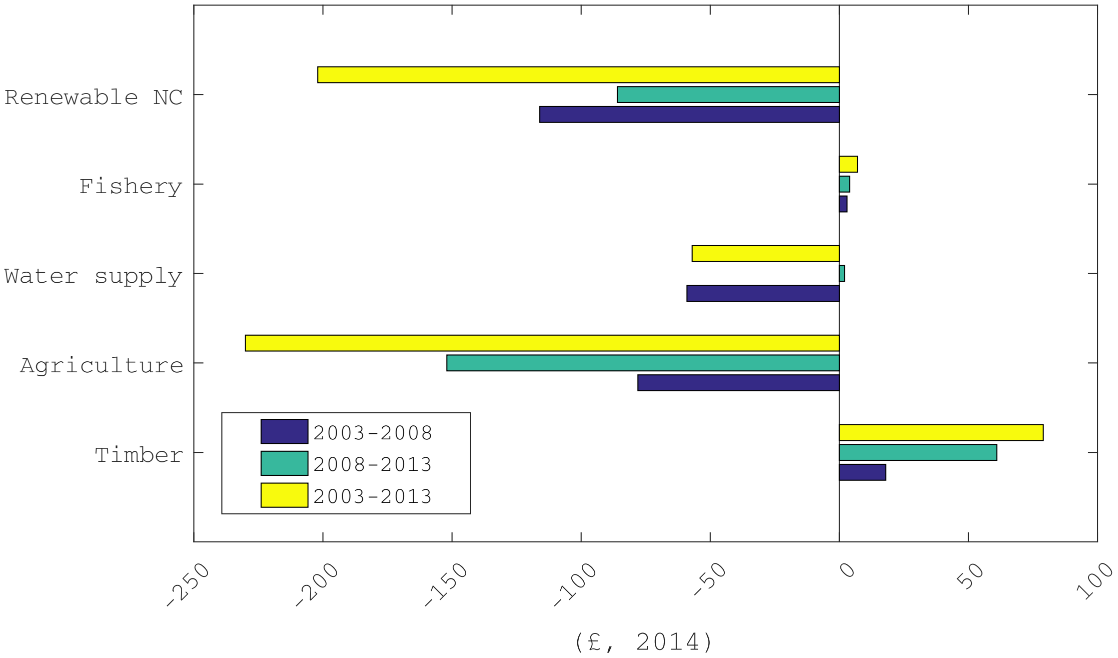


FIGURE 4.8: Changes in renewable per capita natural capital value, 2003-2013 (£, 2014)

is mainly associated with fluctuations in the total number of people visiting the natural environment in the UK during the last five years. Recreational visits to the environment were largely affected by the economic crisis and a reduction in GDP per capita as reported in the Outdoor Recreation Economy Report (ORE, 2017). On the contrary, the increasing value of GHG sequestration is linked to the increase of timberland resources that has resulted from an increasing afforestation rate.

TABLE 4.3: Correlation matrix for UK natural capital components and GDP per capita between 2003 and 2013

| | GDP | Non-renewable nat. cap. | Renewable nat. cap. | Ecosystem services |
|---|---|---|---|---|
| GDP | 1.00 | | | |
| Non-renewable nat. cap. | -0.24 | 1.00 | | |
| Renewable nat. cap. | -0.42 | 0.88 | 1.00 | |
| Ecosystem Serv. | -0.09 | 0.98 | 0.82 | 1.00 |

When investigating the association between economic performance (i.e. GDP changes) and the value of natural capital, we found that changes in natural capital value are less related to GDP changes when compared with produced or human capital. Table 4.3 summarises the correlation coefficients registered for the per

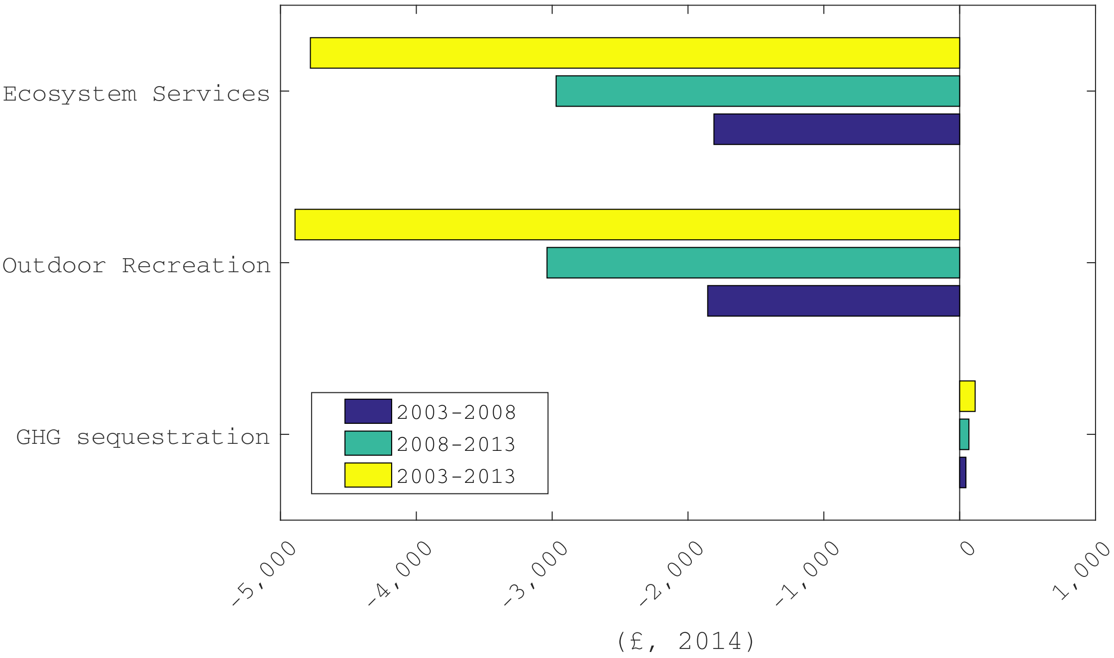


FIGURE 4.9: Changes in per capita ecosystem services natural capital value, 2003-2013 (£, 2014)

capita values of the different forms of natural capital and per capita GDP between 2003 and 2013. The coefficients in the table indicate that the correlation between GDP per capita and non-renewable natural capital is -0.24, with renewable natural capital at -0.42, and ecosystem services at -0.09. The negative coefficients indicate a negative association between GDP changes and changes in value for all forms of natural capital. Contrary to what was observed for human and produced capital, correlations are negative in sign and lower in magnitude, signifying that the changes in value for natural capital are less associated to changes in GDP per capita. The shock introduced by the financial crisis in 2008 had no significant effect on the trajectories of the natural capital components. In general, the decline in values of the different natural capital forms in the UK has not been driven by the specific event of the financial crisis, but rather by a progressive depletion of natural assets (with the exception of the value of outdoor recreation).

### 4.3.2 Scenario evaluation 2015-2020

Having examined the UK's wealth composition and natural capital value between 2003 and 2013, we are now able to revise our projections for the period 2015-2020. Although there is not rule of thumb to define the length of the projected period, five years were considered taking as reference other analyses found in the literature. Most works analysing changes in natural capital value, including Dasgupta (2014) and Ollivier and Giraud (2011), consider periods of five to ten years when it comes to tracking change in natural capital. A length of five years can be regarded as prudential when considering limits on data availability and the experimental condition of the existent methodologies to estimate natural capital value. Longer periods may result in more inaccuracy in our estimations, leading to less realistic projections.

In this section, we analyse three different scenarios built on projections and estimate for each scenario the risk of decline in the aggregated per capital value of natural capital and wealth. The value of natural capital in this part of the analysis has been considered at the aggregated level, where we combine the values of non-renewable and renewable natural capital and ecosystem services. Market price data for commodity assets, including mineral, coal, oil & gas, timber stumpage price, and social price of carbon is, however, partial or still non-existent for the whole period 2015-2020. Therefore, after 2013 possible price paths for these commodities have been generated randomly using Geometric Brownian Motion (GBM) and Mean-Reverting (MR) stochastic models calibrated with historical data (see Chapter 3 for a description of these stochastic processes). In this way, the model captures the uncertainty associated with future price fluctuations. As for the rest of the key variables involved in the computation of natural capital and wealth values, the model projects their values into the future by following specifically assumed growth rates that have been determined by the evaluated scenarios. Monte Carlo simulations are performed to conduct the risk analysis on the UK's wealth composition and its changes over time. The number of Monte Carlo simulations used is 5,000, defined after calibrating the model with a total of 6,000 simulations and after confirming that variations in the output variables are negligible. Figure 4.10 shows values for the risk of declining wealth and natural capital per capita (the model outputs) as a function of the number of Monte Carlo runs. From the figure, we can see that the output values in the model remain fairly constant after 2,000 simulations.

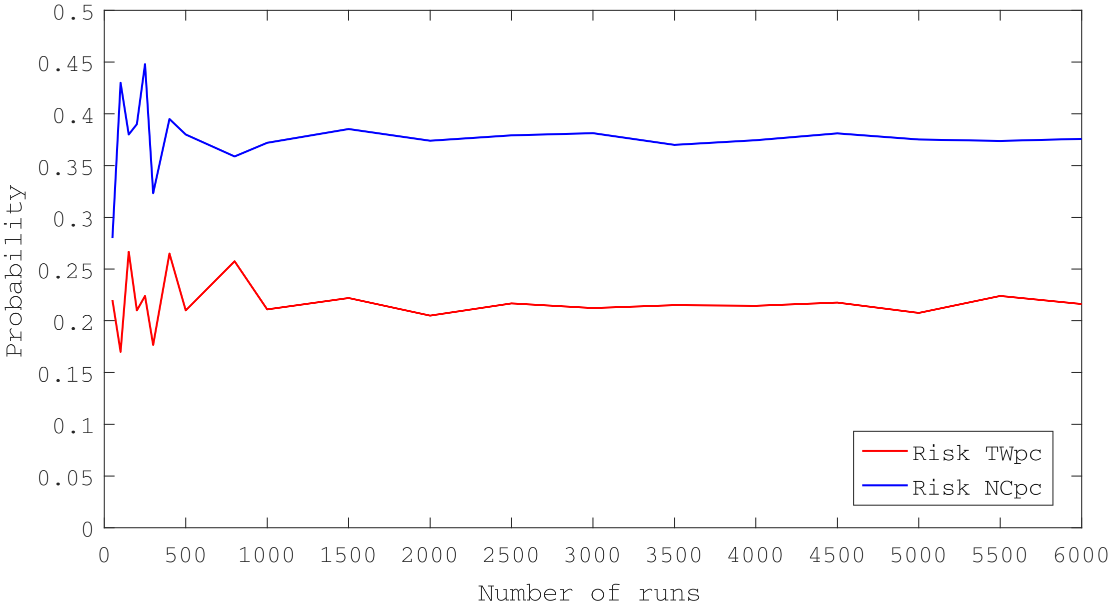


FIGURE 4.10: Output variables as a function of the number of Monte Carlo simulation runs.

The scenarios studied in the model are defined by the parameters presented in Table 4.4. Most parameters are given by annual growth rates of the most important variables used in the methodologies for calculating natural capital and wealth values and macroeconomic variables that shape the trend of natural capital value. This includes annual growth rates for GDP, population, mineral production, oil & gas production, and industrial outputs (e.g., agriculture, fishery and water supply). In addition, the annual growth rate for afforestation and settlement area are also considered, together with, the average number of time people visit recreational places in a year. These parameters have been identified by MEA (2005) as drivers of natural capital change as they are directly linked to the stream of benefits produced by natural assets. Changes in the value of those parameters directly impact the value registered by the accounts. A number of other relevant factors, such as commodity prices, discount rates, inflation rates, or natural assets

TABLE 4.4: Model parameters and scenarios for 2015-2020.

| Parameter | Values | | |
|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| GDP annual growth rate (%) | +2.0 | -0.15 | +3.0 |
| Population annual growth rate (%) | +0.7 | +0.76 | +0.6 |
| Mineral Production annual growth rate (%) | | | |
| Silver | +13.0 | +12.7 | +12.7 |
| Chalk | -7.0 | -13.0 | -2.3 |
| Salt | 0.0 | +2.8 | -2.5 |
| Sand & Gravel | -5.0 | -32.0 | -0.2 |
| Lead | 0.0 | 0.0 | +45.0 |
| Peat | -7.0 | -6.6 | +10.0 |
| Limestone | -3.0 | -7.8 | +0.8 |
| Coal | -5.0 | +0.2 | -10.6 |
| Oil & Gas production annual growth rate (%) | | | |
| Oil | -2.0 | -8.0 | -7.0 |
| Gas | -5.0 | -9.0 | -6.0 |
| Agriculture output annual growth rate (%) | +2.0 | +3.8 | +3.3 |
| Fishery output annual growth rate (%) | +5.0 | +4.5 | +4.7 |
| Water output growth rate (%) | +4.0 | +3.0 | +5.9 |
| Avg. No of visits to recre. sites per person in a year* | 55 | 55 | 55 |
| Aforestation annual rate (ha/year) | 12,000 | 4,200 | 8,600 |
| Settlement annual rate (ha/year) | 17,000 | 11,400 | 7,400 |

*Note: This value is assumed to be constant in the three scenarios due to the lack of historical data for the full period 1999-2013.

life time, could have also been included within the set of parameters for the scenario analysis. Nevertheless, the number of parameters selected were limited by the computational and time cost of conducting Montecarlo simulations and global sensitivity analysis in the model. A particular parameter of interest that worth studying carefully is the selection of discount rates. Discount rates can be interpreted as the expected rate of return on the environmental assets and its value can be chosen from either social or market discount rates depending on the purpose of the study. For the purpose of the our analysis, we have assumed a fixed discount rate of 3.5% following the recommendation provided by the UK Treasury on its Green Book for accounting and sustainability exercises (HMTreasury, 2003). However, the literature seems not to agree of which discount rate is best to apply for natural capital valuation. A comprehensive discussion on selecting discount rates for natural capital accounting is provided by Khan and Greene (2013).

Scenario 1 is based on the average annual growth experienced by each parameter during the 14-year period 1999-2013, and on the projections forecasted by specialists for the period 2015-2020. This scenario can be considered as ‘most likely’ and it represents the baseline scenario in the analysis. In this particular scenario, values for GDP and population annual growth are taken from the projections of the IMF[1] and ONS, respectively, for the period 2015-2020. The estimation of the number of visits per person is derived from the estimations reported in the *Monitor of Engagement with the Natural Environment* report during 2009-2014 (MENE, 2014). The afforestation rate and the settlement area growth rate are based on 2012 levels as reported in the *DECC 2050 Pathway Analysis* report, and used in their projections to 2050 (DECC, 2010).

Scenario 2 is built on the basis of the average growth rates registered by the model parameters over the 5-year period 2008-2013. This scenario can be considered as ‘pessimistic’, as it represents the conditions experienced in the five years after the financial crisis. Over this period, GDP grew at an average negative annual rate and population growth registered at the highest among all scenarios. Many minerals (i.e. chalk, sand and gravel, limestone), as well as oil & gas assets, experienced significantly less production growth compared to Scenario 1, and the outputs from fishery and water supply industries were also lower. Afforestation rates and settlement area annual growth rates also shrank, with respect to the 14-year historical average.

Scenario 3 recreates the conditions during the five years (2002-2007) prior to the crisis and can be considered as ‘rather optimistic’. In this scenario, average annual GDP growth was higher and population growth was lower, compared to Scenario 1. Most mineral production rates were significantly higher than the historical average and all the industries of interest experienced a faster growth. Despite afforestation and settlement area growth rates were still lower than the historical averages, their values were, nevertheless higher, compared to Scenario 2. In the cases of silver production annual growth and the number of visits to recreational places, the same values were assigned in all three scenarios. These values were obtained by taking the average over the period 2008-2013, the only period for

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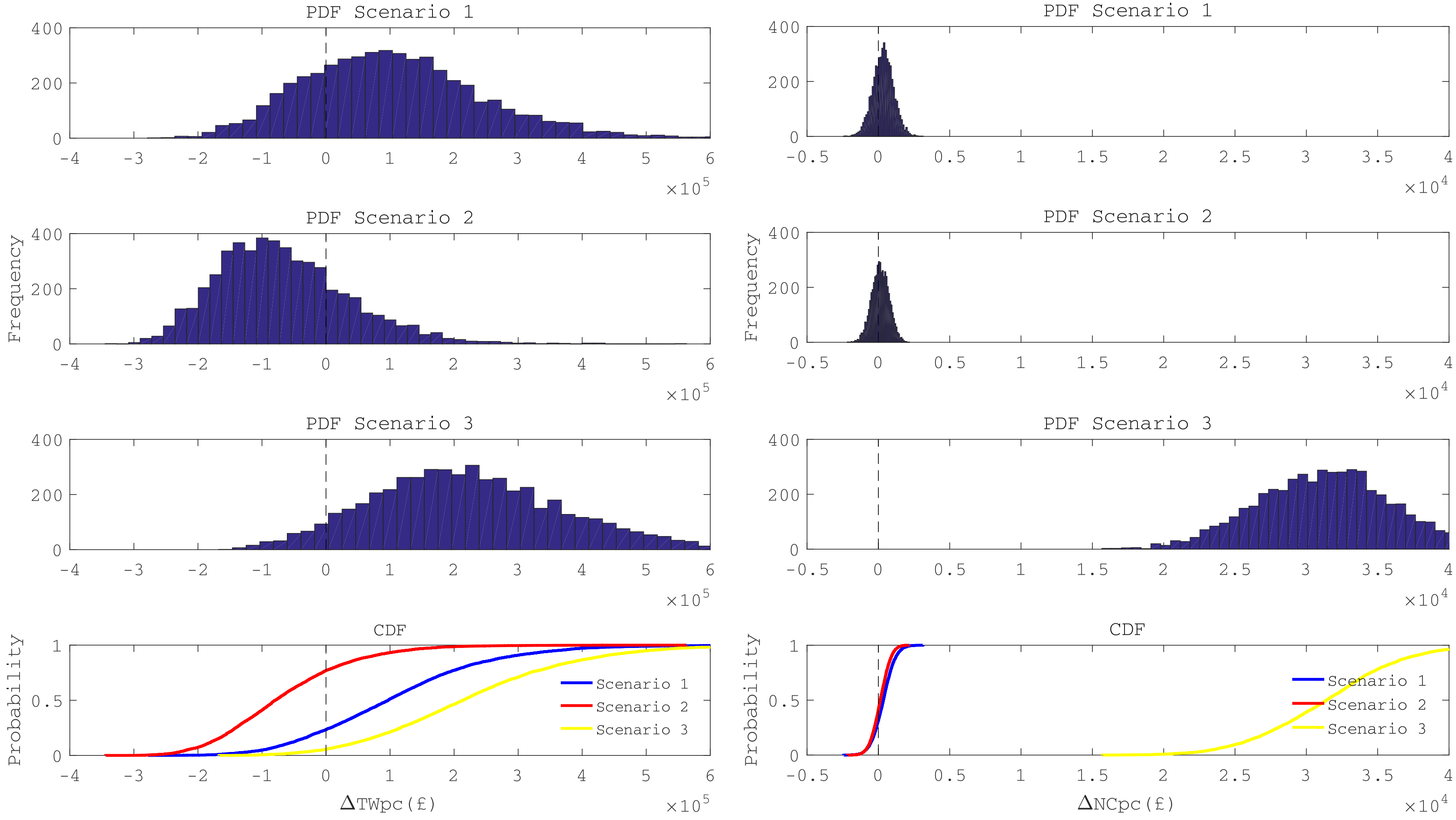
[1] Based on projections on UK GDP growth done before Brexit referendum

which data is available. A constant annual inflation rate of 1.5% is assumed in all three scenarios, based on the last 10 years average registered by the UK consumer price index (CPI).

Figure 4.11 shows for each scenario the probability distribution function (pdf) and the cumulative distribution function (cdf) empirically obtained for changes in per capita wealth and per capita natural capital. Also, Table 4.5 summarises the statistics obtained for changes in the value of per capita wealth and per capita natural capital. The figure and the table illustrate the risk of declining wealth and natural capital for each scenario. Results obtained for Scenario 1 indicate that the risk of declining per capita wealth is 0.2336, suggesting that, under this scenario, it is over 76% likely for per capita wealth values to experience a positive change between 2015 and 2020. The risk of declining aggregated per capita natural capital is 0.3144, 8% higher than the risk registered for wealth, leaving a 68% likelihood of maintaining the aggregated value of natural assets. In the case of Scenario 2, changes in per capita wealth averaged negative and the risk of declining wealth significantly increased to 0.7698, nearly 54% higher than the same risk in Scenario 1. The risk of declining per capita natural capital also augmented to 0.4118, about 10% more than the value registered in Scenario 1. Under the conditions imposed in Scenario 2, an almost certain net negative change in value of per capita wealth will result by the end of the period. On the contrary, in Scenario 3, the resulting risk of declining per capita wealth is 0.0564, 17.7% lower than Scenario 1. In Scenario 3, it is 94% likely that positive changes in per capita wealth will occur. Moreover, the third scenario, which is the most optimistic, is the only one reporting zero risk of diminishing the value of natural capital. When we look at the uncertainty of changes in the values of wealth and natural capital in Scenaros 2 and 3, we find that Scenario 2 exhibits the lowest degree of uncertainty (£103,691 for per capita wealth and £611 for per capita natural capital), while Scenario 3 presents the highest (£155,214 for per capita wealth and £4,800 for per capita natural capital). Scenario 1 lies somewhere in the middle situates in the middle (with £140,689 for changes in wealth and £720 for changes in natural capital). It is worth mentioning that the positive assessment results for the risk of declining natural capital value



(a) Changes in per capita wealth

(b) Changes in per capita aggregated natural capital

FIGURE 4.11: Uncertainty analysis of changes in per capita wealth and per capital natural capital for the tested scenarios between 2015 and 2020.

TABLE 4.5: Statistics for changes in per capita wealth and natural capital and the risk of declining their value for the period 2015-2020.

| | | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| Wealth | Mean | +106,392 | -66,832 | +225,372 |
| | Std. Dev. | 140,689 | 103,691 | 155,214 |
| | Risk | 0.2336 | 0.7698 | 0.0564 |
| Natural capital | Mean | +341 | +136 | +31,345 |
| | Std. Dev. | 720 | 611 | 4,800 |
| | Risk | 0.3144 | 0.4118 | 0.0000 |

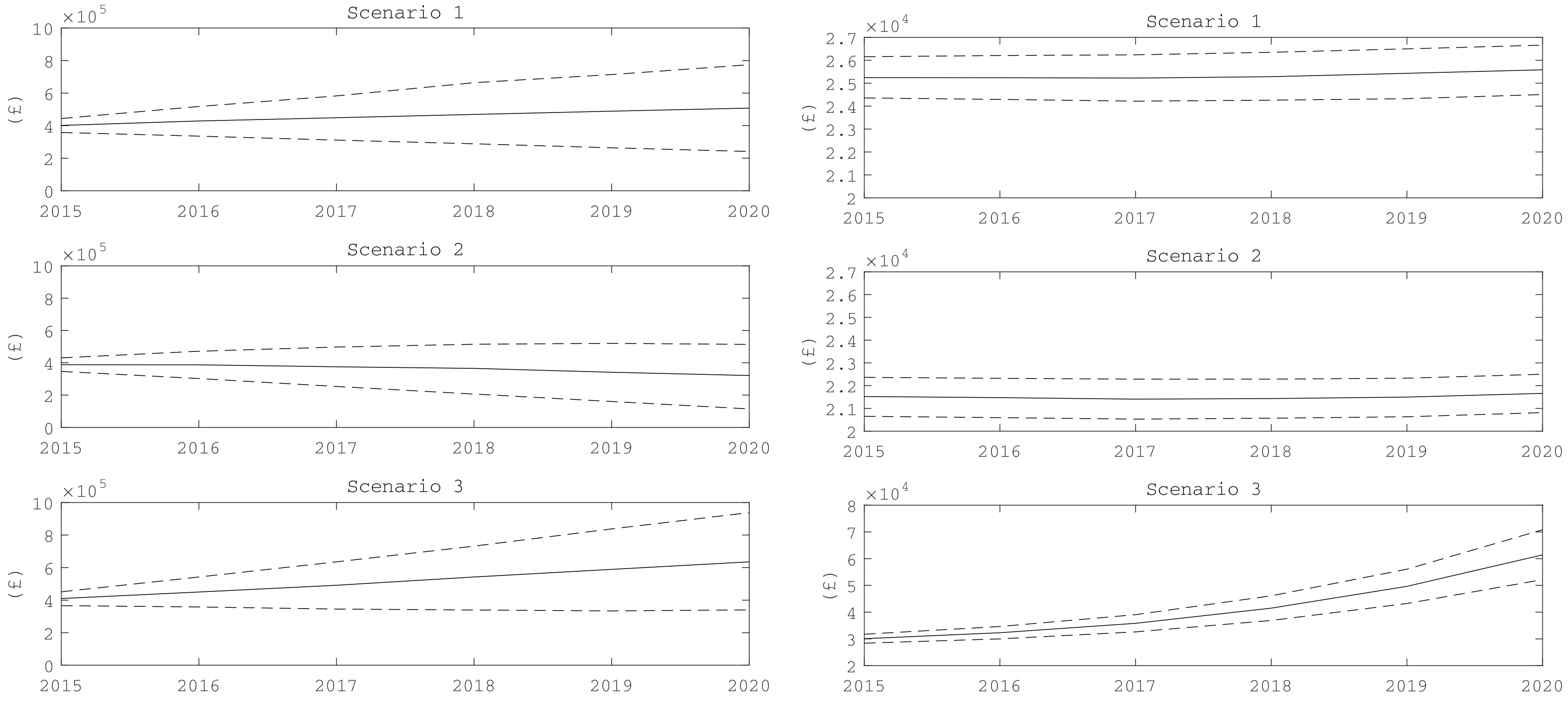
in Scenarios 1 and 3, are due to the influence of the value of ecosystem services. As the value of natural capital is considered at the aggregated level, the value of ecosystem services drives the trajectory of natural capital value. The conditions tested in Scenarios 1 and 2 favour an increase in valuation of ecosystem services, and in particular of outdoor recreation, and in doing so, significantly reducing the risk of declining overall natural capital. This condition, however, could mask a loss in the value of non-renewable and renewable natural capital over the examined period.

The projected trajectories for the values of per capita wealth and natural capital between 2015 and 2020, for the three examined scenarios, are shown in Figure 4.12. Continuous lines in the figure represent expected values, while dotted lines indicate the 95% confidence intervals. From the figure we can observe that, in the case of Scenario 1, the mean value of per capita wealth exhibits a clearly ascending trajectory, rising from £401,448 in 2015 to £507,840 in 2020. This represents an average growth rate of 4.0% per year. The mean value of per capita natural capital, is projected to grow from £25,243 in 2015 to £25,585 in 2020, at a slow rate of 0.2% growth per year. In Scenario 2, on the contrary, a slightly negative slope is registered for the expected trajectory of per capita wealth, decreasing from £387,997 in 2015 to £321,164 in 2020 showing an average annual growth of -3.1%. The trajectory for per capita natural capital remains fairly constant, going from £21,522 in 2015 to £21,659 in 2020. And yet, its value across the period is significantly lower (£3,836 in average) compared to the trajectory registered for Scenario 1. Finally, in the case of Scenario 3, we observe that the average trajectory for per capita wealth depicts an ascending trajectory, rising steadily from £409,908 in 2015 to approximately £635,280 in 2020, for an annual growth rate of 7.0%. Similarly, the expected value of per capita natural capital in this scenario exhibits nearly twice the increase, rapidly rising from £30,073 in 2015 to £61,418 in 2020, for an average annual growth of 12.0%. Similar to our observations for the risk assessment, the increasing trajectories projected for per capita natural capital in Scenarios 1 and 3 are driven by an increase in the value of ecosystem services. However, these trajectories may mask declining trajectories for non-renewable and renewable natural capital values.

### 4.3.3 Sensitivity analysis

In order to identify which model parameters are more influential over the risk of declining per capita wealth and natural capital between 2015 and 2020, we performed a sensitivity analysis. Global sensitivity indices as defined by Sobol (2001) are computed by following the methodology introduced by Saltelli (2002). Global sensitivity indices allow us to rank factors for complex nonlinear models without having to closely examine many scatter plots; and they also allow us to capture the combined effects of multiple factors. On the downside, global sensitivity analysis may be computational demanding when applied to our model given the large number of input variables found. In addition, the method faces limitations when representing dependency among input factors. For the purpose of the sensitivity analysis presented in this section, we assume the parameters defining our tested scenarios are, therefore, independent. Table 4.6 presents the sensitivity indices obtained for each model parameter and the ranges of variation considered in each case. Negative signs are due to numerical errors in the estimates of indices close to zero (i.e. unimportant factors).

Our analysis of the sensitive indices shows that GDP annual growth rate is the most influential parameter in the risk of declining per capita wealth, while the rest of the parameters are non-influential as their first-order and total indices are negligible. The fact that $1-\sum_i S_i = 0$ suggests that there are few interactions between the considered parameters. Therefore, GDP growth is clearly the highly dominant



(a) Total Wealth

(b) Natural capital

FIGURE 4.12: Estimated trajectories of per capita wealth and per capita natural capital for the period 2015-2020

Table 4.6: First-order and total-effect sensitivity indices obtained for the risk of declining per capita wealth and natural capital

| Parameter | Distribution | $\mathbb{R}_{\text{TWpc}}$ | | $\mathbb{R}_{\text{NCpc}}$ | | $\mathbb{R}_{\text{NCpc}}$ (ex. Eco. Serv.) | |
|---|---|---|---|---|---|---|---|
| | | $S_i$ | $S_{Ti}$ | $S_i$ | $S_{Ti}$ | $S_i$ | $S_{Ti}$ |
| GDP annual growth rate (%) | $\sim U(-1.0;+5.0)$ | **1.00** | **1.30** | **0.05** | **0.07** | -0.00 | -0.00 |
| Population annual growth rate (%) | $\sim U(+0.4;+0.8)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Mineral production annual growth rate (%) | | | | | | | |
| Silver | $\sim U(+7.0;+19.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Chalk | $\sim U(-15.0;+1.0)$ | -0.00 | 0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Salt | $\sim U(-6.0;+6.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | **0.01** | -0.00 |
| Sand&gravel | $\sim U(-20.0;-1.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Lead | $\sim U(-5.0;+5.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Peat | $\sim U(-13.0;0.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Limestone | $\sim U(-8.0;0.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Coal | $\sim U(-8.0;0.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | **0.02** | -0.00 |
| Oil & Gas production annual growth rate (%) | | | | | | | |
| Oil | $\sim U(-4.0;-0.1)$ | -0.00 | -0.00 | -0.00 | -0.00 | **0.13** | **0.03** |
| Gas | $\sim U(-10.0;-1.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | **0.02** |
| Agriculture output growth rate (%) | $\sim U(0.0;+4.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | **0.83** | **0.83** |
| Fishery output growth rate (%) | $\sim U(+1.0;+7.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | 0.01 |
| Water output growth rate (%) | $\sim U(+1.0;+5.0)$ | -0.00 | -0.00 | -0.00 | -0.00 | **0.08** | **0.06** |
| No. of visits | $\sim U(45;65)$ | -0.00 | -0.00 | **0.74** | **0.95** | - | - |
| Afforestation annual rate (ha/year) | $\sim U(4,000;20,000)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |
| Settlement area growth rate (ha/year) | $\sim U(1,000;20,000)$ | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 | -0.00 |

parameter in the risk, with no significant dependencies shown of the value taken by other parameters. This result, however, is not surprising. GDP growth directly influences the per capita values of human and produced capital that, taken together, account for over 94% of UK total wealth. The aggregated value of natural assets completes the remaining share, and accounts for less than 6% of total wealth, as shown in Table 4.1. The small share represented by aggregated natural capital makes it very difficult for marginal natural asset components to have a significant impact on the risk of declining total wealth. The risk, in this case, is fully driven by changes in human and produced capital, which are subjected to GDP fluctuations.

As for the risk of declining aggregated natural capital, the most influential parameters, in this case, are the average number of visits to recreational places and GDP annual growth. The total indices in Table 4.6 also suggest that a light interaction exists between these two parameters. The ecosystem service of outdoor recreation is by far the greatest component (in monetary terms) among all of the natural assets. Its value accounts for up to 90% of the overall natural capital measured. This disproportion with the remainder of the natural assets eliminates the significance of other assets components, in terms of influencing the risk of reducing per capita natural capital. In estimating the value of outdoor recreation, the average number of visits to recreational places represents the most important factor driving its value, and therefore, driving the risk of declining natural capital's value at aggregate level. In addition, the influence produced by GDP growth is due to its indirect effects on average hourly wages, which also affects the value of outdoor recreation, resulting in the interaction with the number of visits parameter. In principle, if GDP rises at a higher growth rate, it is more likely to result in higher average wages (and vice-versa). This context, in combination with the average number of visits, will define variations in outdoor recreation, and thus define variations in the risk of declining per capita natural capital. Population growth rate, within the considered range (0.4-0.8% p.a.), does not appear to be a determinant factor influencing either the risk of declining per capita wealth or per capita natural capital.

In order to investigate the influence of the rest of the other natural capital forms (i.e. non-renewable and renewable natural capital), we also performed the sensitivity analysis of the parameter over the risk of declining per capita natural capital when the value of ecosystem services is excluded from the accounts. This is shown in the last two columns on the right in Table 4.6. In this case, we find that for the remaining fraction of natural wealth, the rate at which the agriculture industry output grows and the rate at which oil production declines are the most sensitive parameters influencing risk. Between these two, the former is more relevant than the latter. Moreover, the former seems not to depend on interactions with other parameters while the sensitivity of the latter depends on the condition of other parameters. The values of oil & gas assets in the UK have been dropping steadily since first measured in 2002, and are expected to continue to drop below the value of agricultural land as reserves reach depletion at some point between 2015 and 2020. This finding indicates that the growth rate of the output of the agricultural industry will become more influential upon the risk than that of the oil production rate, as levels of oil&gas reserves deplete. Other sensitive parameters are the growth rate of the water supply industry output, the rate of declining coal production and the growth rate of salt production. Similarly, the rate at which the water supply industry grows is more influential on the risk than the rates of production of coal and salt. However, in this case, the sensitivity of the water industry growth does depend on the value taken by other parameters, in particular, those for oil & gas production rates.

## 4.4 Discussion

Natural capital accounting is becoming a fundamental part of the UK's national wealth accounts. The information provided by natural capital accounting systems is important for tracking the value of natural resources over time and identifying the major drivers of change in those values. Understanding the extent to which those drivers can affect the risk of declining natural capital and wealth value is also relevant. In this chapter, we have presented a description of the UK's wealth composition and changes in value between 2003 and 2013, with a special focus on the study of its natural capital. We also introduced a stochastic model in order to estimate the risk of experiencing negative changes in per capita wealth and per capita natural capital under different scenarios projected over the period 2015-2020. Our emphasis was the study of the condition of UK natural capital assets grouped into renewable, non-renewables and ecosystem services, and to analyse the most important factors affecting the value of these assets.

Results from this analysis showed that the wealth composition of the UK by 2013 was primarily given by its human (65%) and produced capital (28%), while the share of natural capital, when aggregated together, represented only a minimal fraction (6%). This wealth composition is consistent with the proportions of wealth share estimated for the UK in the Inclusive Wealth Report (UNEP&UNU-IHDP, 2014). The large contribution of human and produced capital entails that changes in wealth value are greatly subjected to the economic performance of the country as reflected in its GDP changes. The analysis here found that GDP per capita is significantly and positively associated with the per capita values of human and produced capital due to the influence of the economy on factors such as employment rates, average earning and investment levels in infrastructure. Since these two capital forms, when considered together, hold more than 94% of total wealth, any changes in their value drive changes in the aggregated value of wealth. Therefore, economic shocks introduced in the form of financial crisis, e.g., the 2008 financial crisis, can reverse trends followed by wealth values. The great influence that GDP changes have on wealth trajectories was confirmed in the sensitivity analysis conducted for the projected period 2015-2020, where it GDP appeared to be the most dominant factor influencing the risk of declining wealth per capita without any dependency on other factors.

With regard to the UK's natural capital, results showed that the large majority of the natural capital value in the country is found in the group of ecosystem services, followed by non-renewable natural capital, and renewable natural capital. For all of the natural capital forms (i.e., non-renewable and renewable natural capital, and ecosystem services), without exception, the aggregate per capita value decreased between 2003 and 2013. Yet, the rate of decline was faster in particular for non-renewable natural capital. On the contrary, the value of ecosystem services experienced the slowest decline rate. The only natural assets that experienced positive net changes in value are the non-renewable asset of timber resources and the ecosystem service of GHG sequestration. Unlike human and produce capital, changes in the value of the different natural capital forms are less associated with GDP variations. Negative and smaller correlation coefficients were found between GDP and natural capital values, indicating that financial shock events are less likely to affect natural capital trajectories as compared with human or produced capital. At the aggregated level, the loss of natural capital value has been more significantly driven by a progressive depletion or degradation of natural assets, but not by the specific effects of the 2008 financial crisis. For instance, the loss of outdoor recreation and non-renewable natural capital, the two major components of overall natural capital value, were mainly driven by a reduction in the number of people visiting recreational sites and depleting oil & gas reserves, respectively. The value of renewable natural capital was observed to decline as a whole over the period 2003-2013 driven primarily by a slow positive or negative growth of water and agriculture industries. Although it may be argued that the financial crisis may have influenced industrial outputs (see e.g., Campello et al. (2010)), a drastic GDP drop was not among the most significant drivers of change for aggregated natural capital, during the period 2003-2013, due to the low share hold by renewable and the low correlation existing between changes in GDP and changes in the industry outputs.

In relation to the rapid decline of non-renewable natural capital, the particular situation for the UK is that it is currently too late to revert its declining trend as oil and gas reserves in the country are close to reach full depletion. The declining rate may actually accelerate in coming years, provided that no significant new oil or gas fields are discovered. In general, the value of non-renewable natural assets are prone to decline in the long run as assets are extracted or consumed. Nevertheless, approaches can be developed to maintain the value of this assets over time. For instance, as will be seen in Chapter 6, investment instruments in the form of funds can be implemented to transform the value of non-renewable natural capital into a financial capital form that can be preserved for the future. This approach could be used in the UK, for example to maintain the value of shale gas and oil if these resources are exploited in the future.

The sensitivity analysis conducted for natural capital value projections over the period 2015-2020 also confirmed that GDP growth is not the most determinant factor influencing the risk of declining aggregate natural capital values, as it was for aggregated wealth. Future trajectories of natural capital value, when considering all of the natural capital forms aggregated, are mainly driven by the value of ecosystem services and outdoor recreation in particular. The relevant parameter, in this case, is the number of people visiting recreational sites. If this number increases in the coming years, we can expect to see an increase in the aggregated value of natural capital per capita as projected in some of the scenarios examined. Nevertheless, an apparent overall increase of natural capital value due to such circumstances may mask declining trends for renewable and non-renewable natural capital forms. At the disaggregated level, and when ecosystem services were excluded from the analysis, results indicated that factors from non-renewable natural capital including oil & gas production, as well as, coal production were determinant drivers of natural capital value change over the period 2003-2013. However, results from the sensitivity analysis conducted on future projections found that as oil & gas reserves deplete and coal production slow over the next years, factors from non-renewable natural capital such as agriculture and water supply industry outputs will overtake in relevance to influence the risk of lowering the value of natural capital between 2015 and 2020. With the increasing relevance of renewable natural capital forms in coming years, GDP growth may become a more relevant factor driving natural capital trends in the future. However, the extend to which GDP may be a relevant driver of renewable natural capital trajectories will depend on its ability to influence the output of the water and the agriculture industries. This finding highlights an indication that, in the strategy adopted in the coming years for recovering the value of natural capital in the UK, great importance will need to be given to maintaining the value of non-renewable natural capital forms. Particular focus should be paid in identifying the drivers that influence the performance of the agriculture and water industries in this country.

The model used to estimate the values of UK wealth and natural capital is subjected to a number of limitations. First, the model is based on the approaches adopted by UK authorities to measure and account for the value of human, produced, and natural capital. Therefore, the model presented in this work involves a large number of assumptions and limitations associated with each individual methodology. In addition, the condition and value of capital assets, and in particular those of natural capital assets, depend on the condition of other capital assets. Each natural capital asset is not an independent unit whose value is unrelated to the value of other capital components, but rather they are the result of a complex network of relationships. However, it is noteworthy that the number of empirical relationships included in the model is limited due to lack of data availability. Moreover, the analysis here conducted is based on a partial estimation of UK natural capital, which include only a subset of the natural capital that authorities in this country have thus far been able to quantify. Several other elements of nature, such as the value of biodiversity, natural aesthetic or ecosystems, have been neglected also due to insufficient empirical data or lack of valuation mechanisms. Other parameters affecting the risk of declining natural capital or wealth, such as commodity price fluctuations, changes in the inflation rate, natural assets discount rates, average duration of visits to recreational sites, can also be investigated further. The analysis presented in this chapter, however, constitutes a first attempt to study the major factors influencing the risk of declining per capita natural capital, based on the available data and information while this research was being conducted.

# 5

# Performance of investments in natural assets

INvestments in natural capital, in the form of green investments, are gaining increasing attention among governments and private investors seeking to deliver green economies and support the recovery of natural capital. However, despite growing interest in green investments, institutional investors' direct allocations in green assets remain low (Della-Croce et al., 2011). According to Scholtens (2011), some of the main barriers preventing institutional investors from dedicating major investments into green or natural assets include lack of performance information, credible standards, little transparency, and low financial incentives. Whereas the incentives for investors to dedicate allocations in green assets can range widely from ethical considerations, image and reputation, response to legal and regulatory constraints, or ultimately the search for risk mitigation and higher financial returns. Nevertheless, green investments have traditionally been perceived by many investors as relatively poor performers (Lewis, 2001). If, however, institutional investors are to consider major green investments, it is fundamental that we determine whether the financial performance of green assets is verifiably advantageous.

The present chapter examines the performance of green investments that benefits the value of natural capital. Although there is no standard definition of green investments, for the purposes of the analysis in this chapter, we use this term to refer to allocations in low carbon and climate resilient initiatives, clean technologies, renewable energy, or natural assets that can be considered beneficial to recover the value of natural capital. In this sense, we group green investments into two broad categories: non-real green assets (or indirect investments in natural assets) and real green assets (or direct investments in natural assets). Indirect investments in natural assets refer to the acquisition of intangible non-physical assets, such as shares publicly traded in listed markets from companies whose underlying businesses and profits derived from operations aimed at improving natural capital. Non-real green assets includes companies developing alternative energy technologies, timberland, agriculture, and green bonds. On the other hand, direct investments in natural capital, encompass the acquisition and management of real physical natural assets, represented for instance, by timberland and farmland properties. The aim of this chapter is to investigate, from a private investor point of view, which form of private green investments may result more attractive and convenient based on their associated financial benefits and risks.

Private investments correspond to capital investments done mainly by institutional investors such as pension funds, hedge funds, or mutual funds, as well as wealthy individuals. Traditionally, large institutional investors have not held major investments in natural capital assets, and it is only in recent years that this asset class is becoming more prevalent in institutional portfolios. Andonov et al. (2012) show that during the decades 1990-2010, about 80% of major investment funds held investments in traditional assets such as real estate, equities, or bonds; while less than 1% of these funds held any investments in natural assets by 2000. Nevertheless, this percentage increased to 32% by the end of their sample in 2010. Moreover, the percentage of allocations institutional investors devote to these assets remains minor too. While most investors load their portfolios with 60-80% in equities and bonds or 0-6% in real estate, allocations in natural assets are typically $< 1\%$. One motivation of our work is to show that investing in natural capital assets can be attractive for investors; and thus, that they can push greater allocations into this asset class.

In this chapter we investigate the following aspects of performance of indirect and direct investments in natural capital assets: (i) their risk-return characteristic, (ii) their down-side risk, (iii) their correlation with traditional assets such as public equities, government bonds, real estate, and not so traditional ones such as infrastructure assets, (iv) their diversification benefits resulting from adding them into a portfolio composed of equities, bonds, real estate and infrastructure, (v) their ability to hedge inflation, and (vi) their exposure to shocks in the stock markets liquidity. Our analysis is conducted over the period 2000-2016. Although the length and frequency of the data involved differ for direct and indirect natural asset investments due to limitations in the data availability for each type of investment. We also provide a discussion on the lack of liquidity and high cost of trading associated with natural asset investments.

Results show that private investor seeking to invest in natural capital should hold direct investments in real natural capital assets, rather than indirect investments in non-real ones. The diversification benefits, higher expected returns, lower volatilities, and a positive valuation of alphas and betas exhibited by real natural assets contrast with the lower expected returns, higher volatility, lower alphas and betas performance, and poor diversification potential of non-real ones. In addition, we illustrate how green natural assets, in general, can provide hedging against inflation. Despite the significant benefits of direct investment in real natural capital assets, we also show that the critical aspects of lack of liquidity and high trading cost may still limit institutional and individual investors with shorter investment horizons from investing in natural assets. Thus, demonstrating that such investments demand investors with a longer horizon and greater capital to be able to reach their financial benefits. Later in the next chapter, we study a newly emerging investment mechanism that can be used not only to manage non-renewable natural capital but also to prompt major investments into real natural capital assets supporting the preservation of overall natural wealth in the long-run.

## 5.1 Literature review on green investments

The study of the relationship between green investments and portfolio performance has been broadly addressed in the literature over the past two decades.

Diltz (1995), for instance, examines returns of twenty-eight stock portfolios over the period January 1989-December 1991 to determine the impact of ethical investments on portfolio performance. Findings reveal that environmental performance can enhance portfolio performance. Cohen et al. (1997) study the performance of high polluter and low polluter portfolios, finding that green investments neither improve or lessen portfolio performance. Konar and Cohen [2001] look at the relationship between firms green reputation and valuation in the market place, revealing that good environmental performance is positively correlated with the intangible asset value of a firm. Derwall et al. (2005) examine the performance of portfolios constructed based on eco-friendly scores between 1995 and 2003 and find that stock portfolios with high 'green scores outperform those with lower scores. On the contrary, Olsson (2007) who also study the performance of stock portfolios built with different degrees of environmental risk, reports that no significant association is found between green investments and returns. In a more recent study, Eichholtz et al. (2012) find no significant relationship between greening an investment portfolio and improving overall returns when examining the performance of US REITs. The authors, however, find that portfolios with a higher fraction of green investments display lower market betas. Nevertheless, Chan and Walter (2014) report that positive and statistically significant excess returns are exhibited by green stock investments when compared with non-green benchmarks after evaluating the return of 748 green stock listed in US markets. In contrast, Silva and Cortez (2016) study the performance of US and European green funds finding that green funds tend to underperform their benchmarks, particularly during non-crisis periods. Finally, in a very recent work Miroshnychenko et al. (2017) examine the relationship between green investment adoption and financial performance of listed companies. Their results indicate that adopting green strategies tend to produce negative impacts on the financial performance of companies.

A review of the green investment literature reveals a lack of consensus when assessing the benefits of investing in green assets for financial portfolios. The inconclusive evidence on the relationship between green investments and financial performance has often discouraged investors from taking green approaches to investing. In this regard, this thesis contributes to the literature in providing guidelines on what type of green investments investor should focus on to enhance their financial performance and define beneficial green approaches. The innovation in the analysis presented in this chapter is to assess the financial performance of a set of specific green instruments, grouped into real and non-real, and quantitatively measure the effect of having these instruments included in traditional investment portfolios. Our findings provide a clear indication on that real green assets, in particular, may represent a credible alternative to adopting green investments among institutional investors.

## 5.2 Data description

In this section, we provide a description of the data and their sources considered to evaluate investments in natural capital and compare their performance with investments in traditional assets. In order to represent investments in natural capital, a group of financial indexes listing companies traded in international markets were use to proxi the performance of these investments over time. The considered indexes were selected to represent environmental beneficial investments that can be linked to the natural capital categories introduced in the previous chapter. Investments in natural assets are distinguished between two types: indirect investments in green assets, which we refer to as non-real green assets in the rest of our analysis; and direct investments in natural assets referred as real green assets. This distinction results from each form of investment presenting different characteristics and performance profile. The first type of investments, that is in non-real green assets, consider investments in publicly traded timberland, farmland, green bonds, and renewable infrastructure, and they involve share acquisition in companies whose businesses develop around these assets. The second type, real green asset investments, consider direct allocations in private timberland and farmland properties in which the investor directly owns the physical assets. Finally, among traditional assets, we consider global public equities, government bonds, real estate, and infrastructure. For each investment, we use return data obtained from financial indexes that are broadly accepted to represent the performance of a particular asset class.

The data time series for the evaluation of non-real green assets consist on monthly returns extending over the 8-year period from November 2008 to November 2016; while the data for real green assets are given by quarterly returns over the 16-year period from March 2000 to March 2016. The choice of the evaluation period in each case was defined based on data availability while trying to consider as many data sample as possible. Therefore, the differences in the data series are due to variations in the time period and frequency for which data was available for each of the examined asset classes. In the case of non-real green assets, for instance, data on returns were available from 2008. Hence, only returns after this year were considered. Moreover, monthly observations were preferred in this case in order to increase the number of observation points. As for real green assets, the only return data available is reported in quarterly basis. Thereafter, quarterly samples were preferred in this case. Typical investment horizons for real natural assets (e.g., timber and farmland) range from 10 to 15 years (Phillips, 2016; Grene, 2014). Therefore, in order to cover this length, a time series of 16 years has been used in our analysis. Despite these differences in data availability, our main analysis is all conducted over the time span 2000-2016. Below we provide a detailed description of the data for each asset class. It worth mentioning that the performance of returns observed over the considered period does not provide guarantee of similar performance over other periods of time. Therefore, the results derived from our analysis will be limited to the considered time span. In order to extend the generalization of the results here obtained, it is recommended to conduct similar analysis in the future when new return data is produced.

### 5.2.1 Non-real green assets

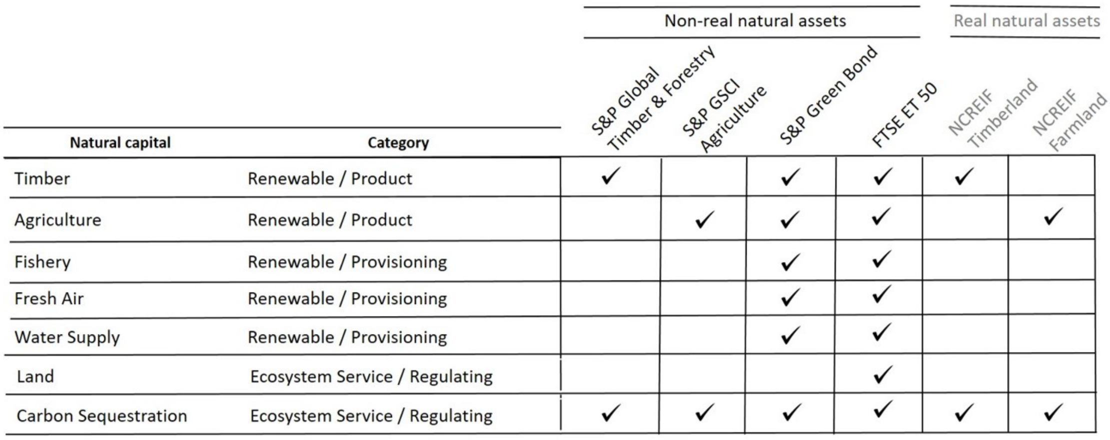
We consider four types of non-real green assets to represent indirect investments in natural capital, namely: public timberland, public farmland, green bonds, and renewable infrastructure. These assets represent publicly traded equity investments to which any investor can access.

In the case of non-real timberland, the index used to capture its performance is the S&P Global Timber & Forestry Index, for which monthly time series are taken from the S&P Dow Jones Indices website (SPIndices, 2016). This index reflexes the performance of the 25 global largest publicly traded companies engaged in the ownership, management, and supply chain of forest and timber products and operations. This includes forest product companies, timber REIT's, paper products companies, or paper packaging companies listed in developed stock markets around the world. Companies listed in this index are responsible for the management of forest resources and their upstream supply chain. The index only considers stocks traded in developed market exchanges where strict regulations and certifications are in place to secure a sustainable management of the timber resources. Therefore, this index has been linked to the renewable natural capital category timberland as introduced in Chapter 4. The index can be also associated to the ecosystem service of GHG sequestration, as forest are directly related to their capacity of capturing CO2 from the environment.

As for non-real farmland, the index used is the S&P GSCI Agriculture Index which reflexes the performance of publicly available investments in global agricultural commodity markets. This index is built considering contracts and average reference prices for the commodities of wheat, corn, soybeans, coffee, sugar, cocoa, and cotton (SPGlobal, 2016). Companies listed in this index are responsible for owning and managing agricultural farms and products including their production and upstream supply chain. Therefore, the index has been associated with the natural capital category Farmland introduced the previous chapter. In addition, since farm processes involve a significant amount of carbon emissions, the index can be also linked to the ecosystem service of GHG sequestration.

Regarding green bonds, the index used for these investments is the S&P Green Bond Index. This index is designed to track the global green bond market that trades those bonds whose proceeds are used to finance environmentally friendly projects. Bonds included in the index are issued by multilateral, governments and corporations from a pull of over 1,570 constituents that must be flagged as ‘green’ by the Climate Bond Initiative (CBI), and possess a maturity no shorter than a month. Green bonds are issued to finance environmental friendly projects that can vary a lot in nature, being the most prominent related to renewable energy, energy efficiency, low carbon transport, sustainable water systems, reduced pollution, and sustainable agriculture and forestry projects (Olsen-Rong et al., 2015). Given the wide diversity of the projects, green bonds can, therefore, be associated to the benefit of multiple forms of natural capital including renewable timber, agriculture, water supply or fishery, an ecosystems services such as carbon sequestration, clean air provisioning, and land use efficiency.

Finally, investments in renewable infrastructure are proxied using the FTSE ET50 Index that measures the performance of the 50 largest companies globally whose core business is in the development and deployment of environmental technologies and infrastructure. This includes renewable and alternative energy, energy efficiency, water technology and infrastructure, waste management, pollution control, environmental support services, and food provisioning (FTSEIndex, 2016). Similar to the case of green bonds, this index covers a broad range of green assets. Thus, deriving in benefits to multiple forms of natural capital and ecosystems services, such as clean air, carbon sequestration, sustainable water management, agriculture provisioning, and forest products. Figure summarizes the association of each index with the natural capital categories presented in Chapter 4.



| | | Non-real natural assets | | | | Real natural assets | |
|---|---|---|---|---|---|---|---|
| **Natural capital** | **Category** | S&P Global Timber & Forestry | S&P GSCI Agriculture | S&P Green Bond | FTSE ET 50 | NCREIF Timberland | NCREIF Farmland |
| Timber | Renewable / Product | ✓ | | ✓ | ✓ | ✓ | |
| Agriculture | Renewable / Product | | ✓ | ✓ | ✓ | | ✓ |
| Fishery | Renewable / Provisioning | | | ✓ | ✓ | | |
| Fresh Air | Renewable / Provisioning | | | ✓ | ✓ | | |
| Water Supply | Renewable / Provisioning | | | ✓ | ✓ | | |
| Land | Ecosystem Service / Regulating | | | | ✓ | | |
| Carbon Sequestration | Ecosystem Service / Regulating | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

FIGURE 5.1: Relationship between indexes and natural capital categories

### 5.2.2 Real green assets

Direct investments in real green assets consider private investments in timberland and farmland. Other investments such as unlisted green infrastructure, could have been considered too. However, when it comes to available data for real green assets, there are little choices. No data for unlisted green infrastructure was available, and there are only two relevant indexes available for private timberland and farmland: The Timberland Performance Index and the National Council of Real Estate Investment Fiduciaries (NCREIF) Timberland and Farmland Property Index. From these, we have chosen the latest to represent private investments in timberland and farmland, since they are the most widely adopted in the literature and they are widely accepted as a proxy for these investments. The NCREIF Timberland Index measure the investment performance of a large pool of private timber properties acquired in four different areas in the US. Only timberland properties that are at least 80% directly owned (i.e. no more than 20% leased) are included, and the properties must be managed in a fiduciary manner for the owners who may be tax-exempt institutions or taxable investors. Timber properties are usually managed by Timber Investment Management Organizations (TIMO's) on behalf of investors. TIMO's require to gain a certification of sustainable forest management in order to offer their properties in the market. Therefore, this index has been associated with the natural capital category Timberland and GHG sequestration as shown in Figure 5.1.

Similarly, the NCREIF Farmland Index captures the performance of a large pool of individual farmland properties traded in the US private market across twelve different regions. The agricultural properties include permanent, row, and vegetable croplands. Likewise, farmland properties are managed by Investment Trusts on behalf of investors and they require sustainability certificates granted by international organizations in order to trade their products in the market. Thus, a sustainable management of the properties is assumed and the index has been linked to the benefit of the natural capital category farmland. Quarterly returns on the timberland and farmland indexes are published by the NCREIF based on the appraisal of income and return appreciation on the timber and farmland properties managed by TIMO's. Thus, for these indexes, we consider quarterly time series over the 16-year period March 2000 - March 2016.

### 5.2.3 Traditional assets: equities, bonds, real estate, and infrastructure

Traditional assets in our analysis are represented by publicly traded global equities, government bonds, real estate, and infrastructure. In the case of equities, we consider the specific equity markets in the US, Europe, and Japan, whose performance are reflected in the S&P 500, the Stoxx Euro 600, and the Nikkei 225 indexes respectively. For each of these indexes, both monthly and quarterly price time series were collected over the period starting in March 2000 and ending in March 2016, extracted from Thomson Reuters database. Regarding investments in government bonds, we consider bonds issued by the governments of the US, Germany, and Japan whose performance are captured by the S&P US Treasury Bonds, S&P Germany Sovereign Bond, and the S&P Japanese Government Bond index, respectively. Likewise, for the bond indexes, we collect monthly and quarterly return data from March 2000 to March 2016 from Thomson Reuters database. Real estate investments consider the real estate markets in the US, UK, and Europe (ex. the UK) for which the Thomson Reuters US, UK, and Euro Real Estate Index are used as a proxy, respectively. Infrastructure investments include investments in telecommunication, transport, energy and utility infrastructure. The indexes used in these cases are the Thomson Reuters Global Telecommunications, Transport, Energy, and Utility index, which capture the performance of investments in companies shares specialized in telecommunications, transport, energy, and utility industry, respectively. Finally, our proxy used for a risk-free asset is the US Treasury bills.

## 5.3 Investment performance

### 5.3.1 Performance of non-real green assets

#### Average returns, volatility, Sharpe ratio and diversification potential

Table 5.1 presents the basic descriptive statistics of the investment performance for non-real green assets during the period December 2008 - November 2016. Over this eight-year period, the annualized mean return across asset classes varies from 0.53% for agriculture to 11.75% for US real estate, as captured by the S&P GSCI agriculture index and the Thompson Reuter US real estate index respectively. Using monthly returns, the most volatile asset class is European real estate with a monthly volatility of 6.46%, while the least volatile assets are government bonds, and in particular the Japanese government bond with a monthly volatility of 0.41%. Next, we compute the monthly Sharpe ratio (i.e. the ratio of the mean monthly return divided by the monthly volatility). The Sharpe ratio is found to range from -82.72 for Japanese government bonds to 9.16 for the S&P 500 Index. The maximum draw down that measures the maximum cumulative loss from a peak to a trough of an investment ranges from 1.72% for Japanese bonds to 69.83% for agriculture.

TABLE 5.1: Performance of historical returns for non-real assets, December 2008 - November 2016

| | Monthly return (%) | Annualized return (%) | Volatility of monthly returns (%) | Sharpe Ratio | Max. Draw down (%) |
|---|---|---|---|---|---|
| *Equity* | | | | | |
| S&P 500 | 0.88 | 10.58 | 4.05 | 9.16 | 20.60 |
| STOXX Euro 600 | 0.49 | 5.93 | 4.04 | -0.41 | 23.63 |
| Nikkei 225 | 0.67 | 8.08 | 5.57 | 2.93 | 27.88 |
| *Gov. Bonds* | | | | | |
| US Treasury | 0.20 | 2.44 | 0.92 | -33.33 | 3.82 |
| Germany Gov. | 0.30 | 3.62 | 0.99 | -21.13 | 4.40 |
| Japan Gov. | 0.17 | 2.05 | 0.41 | -82.72 | 1.72 |
| *Infrastructure* | | | | | |
| Telecom. | 0.22 | 2.66 | 3.68 | -7.86 | 16.85 |
| Transport | 0.76 | 9.17 | 4.93 | 5.14 | 23.16 |
| Energy | 0.06 | 0.68 | 5.75 | -7.89 | 63.26 |
| Utilities | 0.06 | 0.72 | 3.61 | -12.47 | 18.43 |
| *Real Estate* | | | | | |
| US | 0.98 | 11.75 | 6.13 | 7.65 | 36.04 |
| UK | 0.45 | 5.45 | 6.02 | -0.93 | 38.10 |
| EU | 0.63 | 7.58 | 6.46 | 1.88 | 34.86 |
| *Green Assets* | | | | | |
| Timber | 0.55 | 6.56 | 6.35 | 0.57 | 38.56 |
| Agriculture | 0.04 | 0.53 | 6.84 | -6.81 | 69.83 |
| Green Bonds | 0.27 | 3.29 | 2.64 | -8.96 | 14.17 |
| Renew. Energy | 0.27 | 3.21 | 5.99 | -4.06 | 48.10 |

When comparing the basic statistics among asset classes, it is found that non-real green assets, in general, tend to be among the assets exhibiting some of the lowest mean returns (only outperforming most of the listed infrastructure) and higher volatility. Agriculture, in particular, underperforms most asset classes presenting a low annual mean return of 0.53% and a relatively high volatility of 6.84%. In the case of green bonds, this asset class registers a relatively low average monthly return of 0.27%, with a moderate volatility of 2.64%. While renewable energy exhibits a similarly low average monthly return of 0.27%, with a larger volatility of 5.99%. In consequence, these three non-real green assets register negative Sharpe ratios of -6.81, -8.96, and -4.06 respectively. Among non-real green assets, timberland is the one presenting the largest mean monthly return with 0.55%; yet this asset class also registers the highest monthly volatility with 6.35% which provides it with a low positive Sharpe ratio of 0.57. In contrast, government bonds instruments stand the assets with the lowest volatility, ranging from 0.41% for Japanese government bonds to 0.99% for the Germany government bonds. These assets, at the same time, show some of the lowest average returns, varying from 0.17% in the case of Japanese bonds to 0.30% for German government bonds. Bonds instruments traditionally represent the bottom asset class for risky investors, since they tend to offer low volatility but limited returns too. Therefore, they are perceived as a secure alternative with low financial benefits. Regarding infrastructure assets, finding are mixed. While transport infrastructure excels as one of the best performing assets with a mean monthly return of 0.76% and a volatility of just 4.93%, assets such as telecommunication, energy and utilities infrastructure perform poorly with average monthly returns of 0.22%, 0.06% and 0.06%, and standard deviations of 3.68%, 5.75% and 3.61% respectively. Other assets with excelling performance include the S&P 500 with an average return of 0.88% per month and volatility of 4.05%, and the US real estate registering an average return of 0.98% with a volatility of 6.13%.

Figure 5.2 shows the cumulative investment performance of £1 investment at the beginning of the examined period (i.e. December 2008) all the way through the end of the period in November 2016. From the figure, we can see that values at the end of the period range from £0.83 for non-real agriculture to £2.15 for S&P 500 index. The ending value for the £1 investment in other non-real green assets is £1.39 for timberland, £1.25 for green bonds, and £1.09 for renewable energy. In comparison, the ending value for US, EU, and UK real estate are £2.13, £1.29, and £1.50 respectively; for telecommunication, transport, energy, and utility infrastructure are £1.16, £1.85, £0.90 and £0.99 respectively; and for the US, Germany and Japan government bonds are £1.21, £1.33, and £1.18 respectively. The figure also shows the downside risk exhibited by the different assets. Significant losses are observed in particular in the last months of 2008 (i.e. during the 2008 financial crisis) and during the second half of 2011 (i.e. the stock markets fall registered as a consequence of the European sovereign debt crisis). With the exception of government bonds, the rest of the asset classes registered a significant drop. However, some of the most severe falls were registers among the green assets including agriculture (69.8%), renewable energy (48.1%) and timber (38.6%) as evidenced in the last column in Table 5.1.

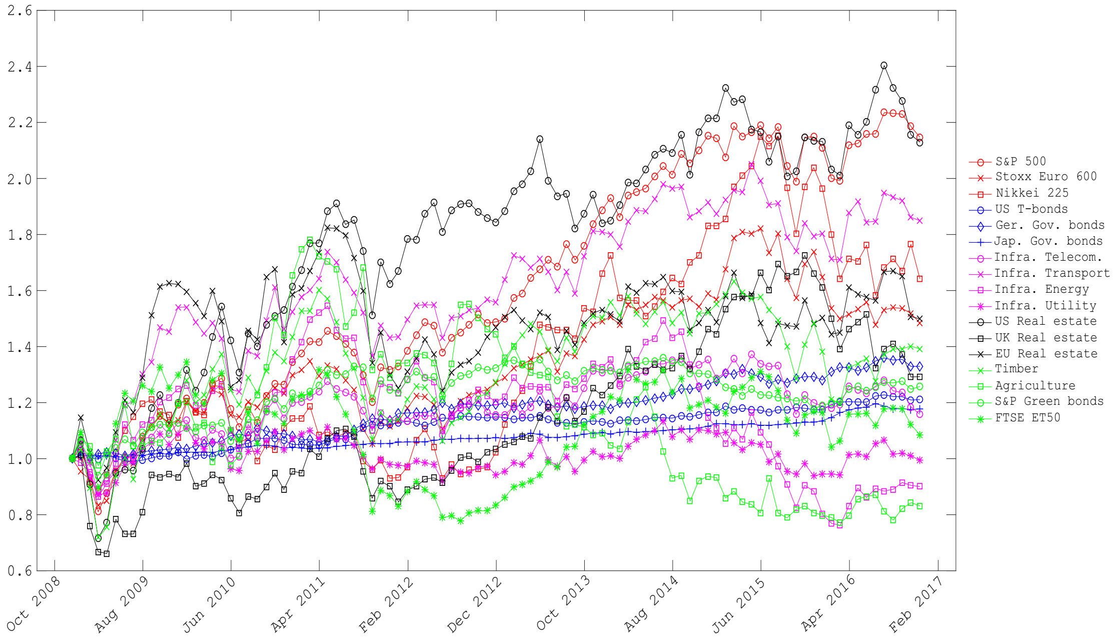


FIGURE 5.2: Cumulative investment performance of an initial £1 investment, 2008-2016)

Table 5.2 reports the correlation of the monthly returns for non-real green assets and the rest of traditional assets between November 2008 and November 2016. All non-real green assets present high positive correlation with the majority of equity indexes, infrastructure, and real estate. The exception is found in the correlation with government bonds, which is low positive to negative in all the cases. However, these lower correlations seem to be more a property of the bonds instruments since they also present a low positive to negative correlation with the rest of the asset classes. Among the non-real green assets, agriculture stands the one exhibiting the lowest correlations, presenting a correlation of 1% with the Nikkei 225 (compared with 58% for timber, 31% for green bonds, and 55% for renewable energy), 18% with UK real estate (compared with 66% for timber, 49% for green bonds, and 57% for renewable energy), and 20% with the Stoxx Euro 600 (compared with 81% for timber, 43% for green bonds, and 70% for renewable energy). Nevertheless, non-real agriculture still registers significantly higher correlations with the remaining assets examined. The high levels of correlation found among non-real green assets suggest that the diversification potential of these assets is not very strong, resulting less attractive for potential investors.

TABLE 5.2: Correlation of monthly returns, 2008-2016

| | S&P 500 | Stoxx Euro 600 | Nikkei 225 | US T-bonds | Ger. Gov. Bonds | Jap. Gov. Bonds | Infra. Telecom. | Infra. Transport | Infra. Energy | Infra. Utilities | US Real estate | UK Real estate | EU Real estate | Timber | Agriculture | Green bonds | Renew. Energy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S&P 500 | 1.00 | | | | | | | | | | | | | | | | |
| Stoxx Euro 600 | 0.80 | 1.00 | | | | | | | | | | | | | | | |
| Nikkei 225 | 0.63 | 0.65 | 1.00 | | | | | | | | | | | | | | |
| US T-bonds | -0.20 | -0.30 | -0.37 | 1.00 | | | | | | | | | | | | | |
| Ger. Gov. Bonds | -0.33 | -0.22 | -0.34 | 0.70 | 1.00 | | | | | | | | | | | | |
| Jap. Gov. Bonds | -0.12 | -0.26 | -0.33 | 0.50 | 0.43 | 1.00 | | | | | | | | | | | |
| Infra. Telecom. | 0.79 | 0.62 | 0.48 | 0.05 | -0.19 | 0.15 | 1.00 | | | | | | | | | | |
| Infra. Transport | 0.81 | 0.68 | 0.47 | -0.02 | -0.25 | 0.01 | 0.85 | 1.00 | | | | | | | | | |
| Infra. Energy | 0.79 | 0.65 | 0.43 | -0.31 | -0.43 | -0.14 | 0.70 | 0.75 | 1.00 | | | | | | | | |
| Infra. Utilities | 0.73 | 0.57 | 0.41 | 0.08 | -0.13 | 0.23 | 0.82 | 0.81 | 0.64 | 1.00 | | | | | | | |
| US Real estate | 0.79 | 0.67 | 0.45 | 0.06 | -0.03 | 0.07 | 0.65 | 0.70 | 0.54 | 0.72 | 1.00 | | | | | | |
| UK Real estate | 0.67 | 0.70 | 0.49 | -0.05 | -0.13 | -0.12 | 0.55 | 0.61 | 0.39 | 0.52 | 0.73 | 1.00 | | | | | |
| EU Real estate | 0.71 | 0.63 | 0.39 | 0.01 | -0.19 | 0.07 | 0.75 | 0.85 | 0.62 | 0.71 | 0.68 | 0.67 | 1.00 | | | | |
| Timber | 0.85 | 0.81 | 0.58 | -0.21 | -0.32 | -0.13 | 0.67 | 0.77 | 0.71 | 0.66 | 0.79 | 0.66 | 0.67 | 1.00 | | | |
| Agriculture | 0.36 | 0.20 | 0.01 | 0.01 | -0.24 | 0.08 | 0.38 | 0.42 | 0.46 | 0.34 | 0.32 | 0.18 | 0.41 | 0.36 | 1.00 | | |
| Green bonds | 0.69 | 0.43 | 0.31 | 0.16 | -0.18 | 0.14 | 0.75 | 0.78 | 0.69 | 0.69 | 0.63 | 0.49 | 0.78 | 0.60 | 0.55 | 1.00 | |
| Renew. Energy | 0.83 | 0.70 | 0.55 | -0.28 | -0.40 | -0.10 | 0.69 | 0.80 | 0.75 | 0.64 | 0.68 | 0.57 | 0.73 | 0.84 | 0.37 | 0.66 | 1.00 |

### Alphas and betas of non-real green assets relative to equities, bonds, and infrastructure

Alphas and betas are estimated by regressing the monthly excess returns in a particular non-real green asset on the monthly excess returns on public equities, government bonds, infrastructure, and real estate assets. Excess returns are computed by subtracting the actual return register by an asset class on the monthly return of a risk-free asset (i.e. US treasury bills). Alphas and betas allow comparing the returns of the respective non-real green asset to the returns of a benchmark asset, and they are commonly used by investors to support their investment decisions. The alpha is the regression coefficient in the regression constant. A positive alpha means that the examined asset class outperforms the benchmark asset, suggesting that an investor would be able to improve the performance of his investments by including this asset in a portfolio. The beta, on the other side, is the regression coefficient in the regression slope. A beta close to one means that the examined asset move the same as the benchmark asset, while a beta lower than one indicates that the examined asset presents a lower volatility compared to the benchmark. A beta greater than one, therefore, suggests that an investor would expect to register a higher volatility if the asset is included in his portfolio. Therefore, attractive assets for an investor will present high positive alphas and betas below one.

Tables 5.3 and 5.4, respectively, present the regression results for alpha and beta values on the non-real green assets considered. We find that the non-real green assets present negative alphas with the majority of the benchmark assets consisting of public equities, government bonds, infrastructure, and real estate. As the p-values in parentheses indicate, green bonds have negative alphas with S&P 500 (-4.8% p.a., $= 12 \times -0.004$), transport infrastructure (-3.6% p.a.), and US real estate (-4.8% p.a.) that are statistically significant at 5% or 10%. Likewise, renewable energy infrastructure presents a statistically significant negative alpha with the S&P 500 at 5%. For the rest of the assets, no statistical significance was found, suggesting that it is inconclusive to tell whether non-real green assets underperform the benchmarks. Yet, the tendency in most cases is to take negative alphas. When looking at the beta values in Table 5.4, we observe on the other hand that the majority of the beta estimates are statistically significant at 1% or 5%. The majority of non-real green assets have beta values below 1 relative to the benchmarks, suggesting that in most cases these assets present lower volatility than the corresponding benchmark. Timberland and renewable infrastructure, however, exhibit betas greater than one when compared to the S&P 500 (1.303 and

1.216 respectively), the Stoxx Euro 600 (1.216 and 1.012 respectively), telecommunication infrastructure (1.13 and 1.12 respectively), and utilities infrastructure (1.13 and 1.05 respectively). In these particular cases, timberland and renewable infrastructure assets present greater volatility than the corresponding benchmarks.

TABLE 5.3: Alpha estimates for non-real green assets, 2008-2016

| | Timber | Agriculture | Green Bonds | Renewable Infra. |
|---|---|---|---|---|
| S&P 500 | -0.004 | -0.007 | -0.004** | -0.007** |
| | (0.202) | (0.297) | (0.039) | (0.046) |
| Stoxx Euro 600 | 0.001 | -0.005 | -0.002 | -0.002 |
| | (0.886) | (0.506) | (0.338) | (0.609) |
| Nikkei 225 | -0.001 | -0.005 | -0.003 | -0.003 |
| | (0.896) | (0.506) | (0.303) | (0.513) |
| US T-Bonds | -0.003 | -0.004 | -0.001 | -0.006 |
| | (0.676) | (0.552) | (0.713) | (0.357) |
| Ger. Sov. Bonds | -0.002 | -0.007 | -0.003 | -0.005 |
| | (0.701) | (0.336) | (0.315) | (0.362) |
| Jap. Gov. Bonds | -0.002 | -0.003 | -0.001 | -0.003 |
| | (0.817) | (0.712) | (0.841) | (0.694) |
| Infra. Telecom | 0.004 | -0.003 | -0.001 | 0.001 |
| | (0.458) | (0.686) | (0.645) | (0.859) |
| Infra. Transport | -0.002 | -0.006 | -0.003** | -0.005 |
| | (0.611) | (0.344) | (0.048) | (0.189) |
| Infra. Energy | 0.004 | -0.002 | -0.001 | 0.001 |
| | (0.406) | (0.727) | (0.633) | (0.786) |
| Infra. Utilities | 0.005 | -0.002 | 0.000 | 0.002 |
| | (0.276) | (0.785) | (0.960) | (0.631) |
| US Real Estate | -0.003 | -0.006 | -0.004* | -0.006 |
| | (0.396) | (0.351) | (0.088) | (0.225) |
| UK Real Estate | 0.001 | -0.005 | -0.002 | -0.002 |
| | (0.879) | (0.513) | (0.338) | (0.677) |
| EU Real Estate | 0.000 | -0.005 | -0.003 | -0.003 |
| | (0.929) | (0.423) | (0.113) | (0.440) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

TABLE 5.4: Beta estimates for non-real green assets, 2008-2016

| | Timber | Agriculture | Green Bonds | Renewable Infra. |
|---|---|---|---|---|
| S&P 500 | 1.303*** | 0.607*** | 0.451*** | 1.216*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Stoxx Euro 600 | 1.216*** | 0.334** | 0.287*** | 1.012*** |
| | (0.000) | (0.048) | (0.000) | (0.000) |
| Nikkei 225 | 0.648*** | 0.026 | 0.160*** | 0.585*** |
| | (0.000) | (0.837) | (0.001) | (0.000) |
| US T-Bonds | -1.024* | 0.098 | 0.439* | -1.101** |
| | (0.078) | (0.877) | (0.069) | (0.045) |
| Ger. Sov. Bonds | -1.354** | -1.024* | -0.189 | -1.467*** |
| | (0.011) | (0.077) | (0.399) | (0.003) |
| Jap. Gov. Bonds | -0.592 | 0.535 | 0.524 | -0.068 |
| | (0.481) | (0.556) | (0.131) | (0.933) |
| Infra. Telecom | 1.130*** | 0.695*** | 0.536*** | 1.117*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Infra. Transport | 0.986*** | 0.574*** | 0.415*** | 0.977*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Infra. Energy | 0.775*** | 0.541*** | 0.312*** | 0.783*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Infra. Utilities | 1.130*** | 0.629*** | 0.504*** | 1.052*** |
| | (0.000) | (0.001) | (0.000) | (0.000) |
| US Real Estate | 0.811*** | 0.349*** | 0.270*** | 0.666*** |
| | (0.000) | (0.002) | (0.000) | (0.000) |
| UK Real Estate | 0.682*** | 0.211* | 0.218*** | 0.565*** |
| | (0.000) | (0.066) | (0.000) | (0.000) |
| EU Real Estate | 0.657*** | 0.432*** | 0.315*** | 0.682*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

The results from the alphas and betas analysis in overall indicate to an investor that including non-real green assets into an investment portfolio is unlikely to bring any benefits to the portfolio. On the contrary, a negative effect is likely to be expected since alphas do not show any evidence of out-performance and betas shows statistically significant evidence of higher risk in some cases. Therefore, an investor would be unlikely to favour investments in non-real green assets.

### Inflation and non-real green assets

A potential feature investors look in assets is their capability to provide a hedge against the risk of increasing inflation. This is particularly relevant for pension funds providing defined investment plans with inflation protection, as evidenced by Andonov et al. (2012). In our analysis, we measure inflation considering the US Consumer Price Index (CPI). The US CPI has been considered since most of the assets in our analysis are currently traded in US dollars. Figure 5.3 shows the monthly changes in the US CPI registered between 2008 and 2016. Over the full period, the average change in the CPI was 0.13% per month, and the standard deviation was 0.33%. Periods in our sample with relatively high increases of inflation include June 2009, March 2011, and February 2013.

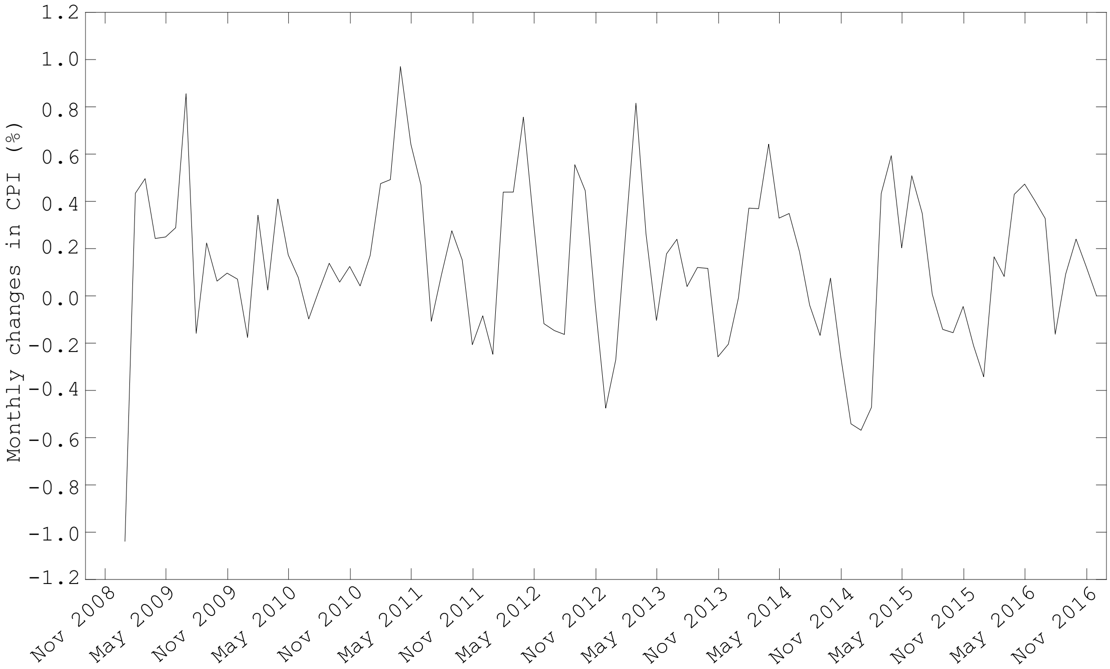


FIGURE 5.3: Monthly changes in US CPI, 2008-2016.

For each non-real natural asset considered in this analysis, we measure the ability to hedge changes in inflation over the time period November 2008-November 2016. Following Erb and Harvey (2006) and Cremers (2013), we assume that changes in CPI provide a reasonable proxy for expected, unexpected, and actual inflation.

Sometimes financial markets respond to news about inflation (i.e. expected inflation) which comes out with some delay. In other cases, financial markets may be able to anticipate up to certain point future news about inflation. In order to consider all these possibilities, we perform the regression of the assets monthly returns on current changes in inflation, in addition to the one-, two-, and three-month lags of changes in inflation, as well as on the one- and two-month future changes in inflation.

The regression results are presented in Table 5.5. A positive coefficient on future, current, or lagged changes in CPI can be interpreted as evidence of inflation hedging, while a negative coefficient suggests that the investment performance tends to worsen when inflation increases. The results in the table indicate that non-real green asset are able to provide hedging against changes in CPI, and in particular on future changes. Positive coefficients that are both economically and statistically significant at 5% and 10% are found for the assets agriculture, green bonds, and renewable energy when related to CPI changes 1M in the future. In addition, green bonds and renewable energy are also positive related to 1M CPI changes in the past and 2M CPI changes in the future respectively. The coefficients on current changes in CPI are rather negative for all green assets, but statistically insignificant at the same time. The economic magnitude of the coefficients appears to be significant too. For instance, the coefficient on the 1M future CPI change for green bonds equals 2.23, with an associated p-value of 0.01. As a result, an increase in CPI of 1% in any particular month can be associated to anticipatory returns of 2.23% in the previous month and can be further associated with lagged positive returns of 1.50% in the following month. Notoriously, timberland stands the only non-real green asset that does not register any association that is statistically significant.

### Effects of including non-real green assets in an investment portfolio

We have so far examined the features of non-real green assets by studying their historical time series in stand alone and comparing them with the historical prices of other asset classes. We now aim to assess the impact of including the non-real

TABLE 5.5: Investment performance of non-real greet assets and changes in CPI

| | 2M Future CPI change | 1M Future CPI change | CPI change | 1M Lagged CPI change | 2M Lagged CPI change | 3M Lagged CPI change |
|---|---|---|---|---|---|---|
| S&P 500 | 0.658 | 2.416* | -0.017 | 1.644 | 1.281 | -1.865 |
| | (0.634) | (0.076) | (0.989) | (0.198) | (0.304) | (0.113) |
| Stoxx Euro 600 | 1.621 | 2.510* | -0.599 | -0.437 | 0.458 | -1.866 |
| | (0.240) | (0.065) | (0.637) | (0.731) | (0.718) | (0.127) |
| Nikkei 225 | 0.819 | 2.160 | -1.379 | 0.515 | 0.670 | -2.695 |
| | (0.664) | (0.247) | (0.431) | (0.770) | (0.699) | (0.117) |
| US T-bonds | -0.074 | -0.633** | -0.629** | 0.398 | 0.205 | 0.021 |
| | (0.813) | (0.041) | (0.028) | (0.149) | (0.436) | (0.937) |
| Ger. Gov. Bonds | -0.141 | -0.588* | -0.447 | 0.041 | -0.189 | -0.111 |
| | (0.669) | (0.077) | (0.148) | (0.894) | (0.544) | (0.723) |
| Jap. Gov. Bonds | -0.069 | -0.255* | -0.154 | 0.123 | -0.134 | -0.120 |
| | (0.621) | (0.066) | (0.231) | (0.323) | (0.280) | (0.335) |
| Infra. Telecom. | 0.909 | 2.170* | -1.012 | 2.285** | 0.499 | -0.857 |
| | (0.467) | (0.079) | (0.381) | (0.044) | (0.647) | (0.427) |
| Infra. Transport | 2.532 | 3.659** | -0.494 | 2.036 | 0.628 | -1.491 |
| | (0.131) | (0.027) | (0.750) | (0.188) | (0.677) | (0.318) |
| Infra. Energy | 3.888** | 7.473*** | 2.172 | 1.828 | 0.300 | -1.257 |
| | (0.047) | (0.000) | (0.228) | (0.314) | (0.870) | (0.487) |
| Infra. Utilities | 0.715 | 1.719 | -0.926 | 1.830 | 1.516 | -0.826 |
| | (0.563) | (0.159) | (0.414) | (0.103) | (0.173) | (0.432) |
| US Real Estate | 2.983 | 2.480 | -1.542 | 2.637 | 4.086** | -1.173 |
| | (0.152) | (0.232) | (0.423) | (0.170) | (0.027) | (0.499) |
| UK Real Estate | 1.327 | 1.187 | -2.259 | 2.907 | 4.278** | -0.646 |
| | (0.518) | (0.561) | (0.231) | (0.125) | (0.011) | (0.701) |
| EU Real Estate | 2.177 | 5.123** | -2.334 | 0.918 | 2.806 | -1.098 |
| | (0.320) | (0.018) | (0.250) | (0.645) | (0.153) | (0.574) |
| Timberland | 3.393 | 3.347 | -1.964 | 1.030 | 0.682 | -2.341 |
| | (0.117) | (0.119) | (0.324) | (0.608) | (0.729) | (0.207) |
| Agriculture | 1.983 | 5.735** | -1.248 | -0.872 | -2.230 | -0.167 |
| | (0.398) | (0.012) | (0.562) | (0.686) | (0.301) | (0.939) |
| Green bonds | 1.164 | 2.234** | -0.781 | 1.496* | 1.048 | -0.436 |
| | (0.195) | (0.011) | (0.346) | (0.064) | (0.185) | (0.573) |
| Renewable Infra. | 3.412* | 5.859*** | -0.555 | 0.570 | -0.038 | -1.828 |
| | (0.093) | (0.003) | (0.768) | (0.761) | (0.984) | (0.319) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

green assets into a financial portfolio. For this purpose, we built a generic portfolio compounded by equity, bonds, infrastructure and real estate assets, to which we include non-real green assets and test its performance over the period November 2010 - November 2016. The portfolio uses Markowitz Mean-Variance optimization (see Chapter 3, Section 3.3) to determine the optimal weight allocation such that maximises the Sharpe ratio of the portfolio. To avoid null weights being allocated to the assets, we impose a constraint of 1% and 20% to the minimum and maximum weight respectively that can be assigned to a particular asset. The out-of-sample technique is used to reconstruct the investment process over the period of interest.

Figure 5.4 presents the performance of the cumulative investments obtained for a portfolio including non-real green assets and compare it with a portfolio excluding them. The figure shows how £1 invested at the beginning the period lead to a value of £1.14 at the end when investing it in a portfolio excluding non-real green assets. On the other hand, this value leads to only £1.03 when the portfolio includes a set of non-real green assets. The trajectories of the cumulative investment in both cases register a significant fall during the last months of 2011; however, the fall is significantly deeper in the portfolio containing non-real green assets followed by a slower recovery. Furthermore, Figure 5.5 compares the overall monthly returns obtained by the portfolio when green assets are included and excluded, and Table 5.6 reports the main return statistics. When comparing the returns of the overall portfolio, it is found that a portfolio with non-real green assets registers an average monthly return of 0.12% (i.e. 1.39% p.a.), compared with a 0.25% (i.e. 2.98% p.a.) obtained for the portfolio excluding non-real green assets. The volatility of monthly returns is also greater for the portfolio with green assets, registering 3.8% in contrast with the 3.6% obtained for the portfolio without this asset class. The Sharpe ratio for a portfolio with a green component is -23.27%, while for the portfolio without the green component is -21.10%, suggesting that the former portfolio underperforms the latter.

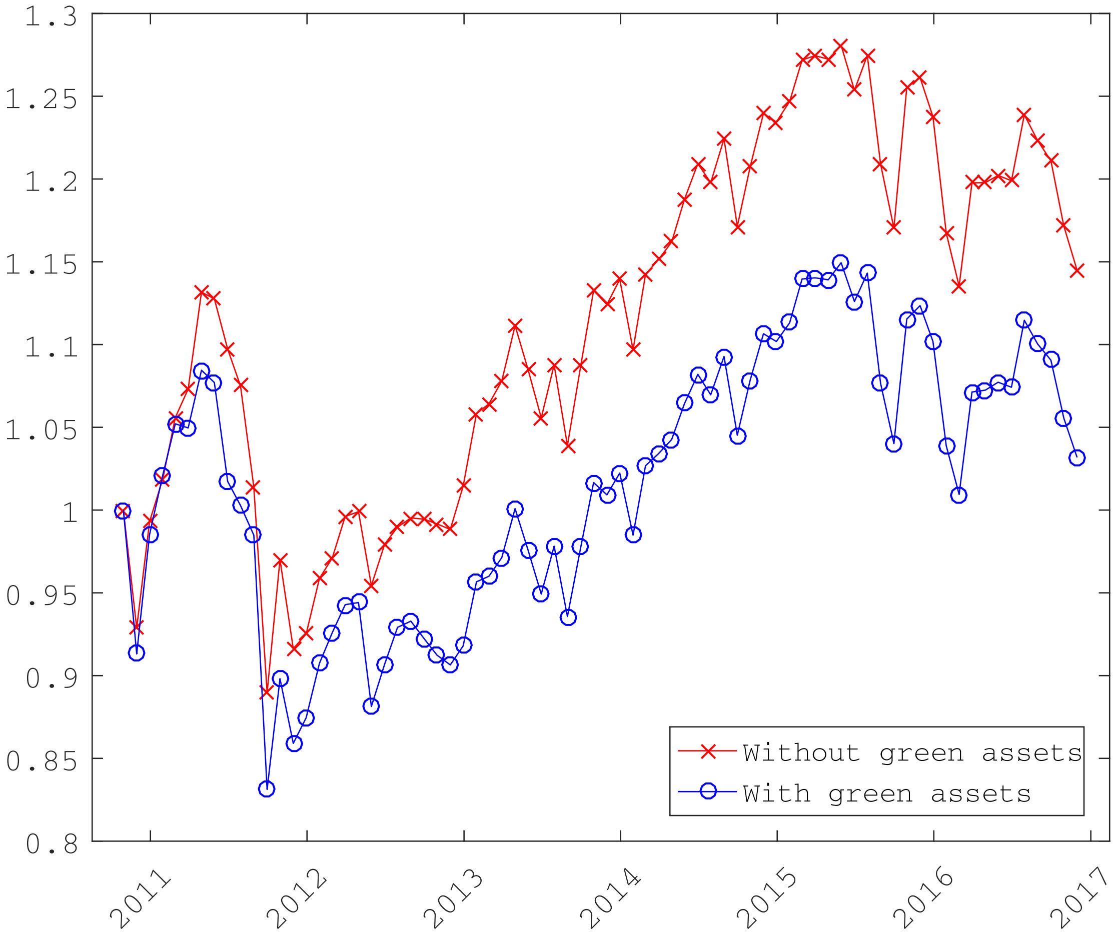


FIGURE 5.4: Cumulative investment performance for a portfolio including and excluding non-real green assets, 2010-2016

FIGURE 5.5: Monthly overall returns of an investment portfolio with and without non-real greet assets, 2010-2016

TABLE 5.6: Performance of a portfolio with non-real green assets

| | With Green Assets | Without Green Assets |
|---|---|---|
| Mean M-return | 0.12% | 0.25% |
| Annualized mean return | 1.39% | 2.98% |
| Volatility of M-returns | 3.80% | 3.56% |
| Sharpe Ratio of M-returns | -23.27% | -21.10% |
| Max. Drawdown | 25.04% | 23.01% |

The optimal weights allocated to each asset in the compared portfolios are presented in Figure 5.6. Allocations from November 2010 to October 2012 tend to give more importance to real estate, infrastructure, and non-real green assets; while allocations in equities and government bonds remain minimal. This time frame coincides with the months following the 2008 financial crisis that saw a period exceptionally bad for equity markets worldwide. However, from the end of 2012, when most equity markets started to recover, the allocation pattern changes to favour equities, infrastructure, and real estate, while minimizing the allocations on green assets for the remaining of the period. From the figure it can be seen that very little preference is given to non-real green assets in general; and only during those special periods when equities do particularly bad, they receive some significant allocations.

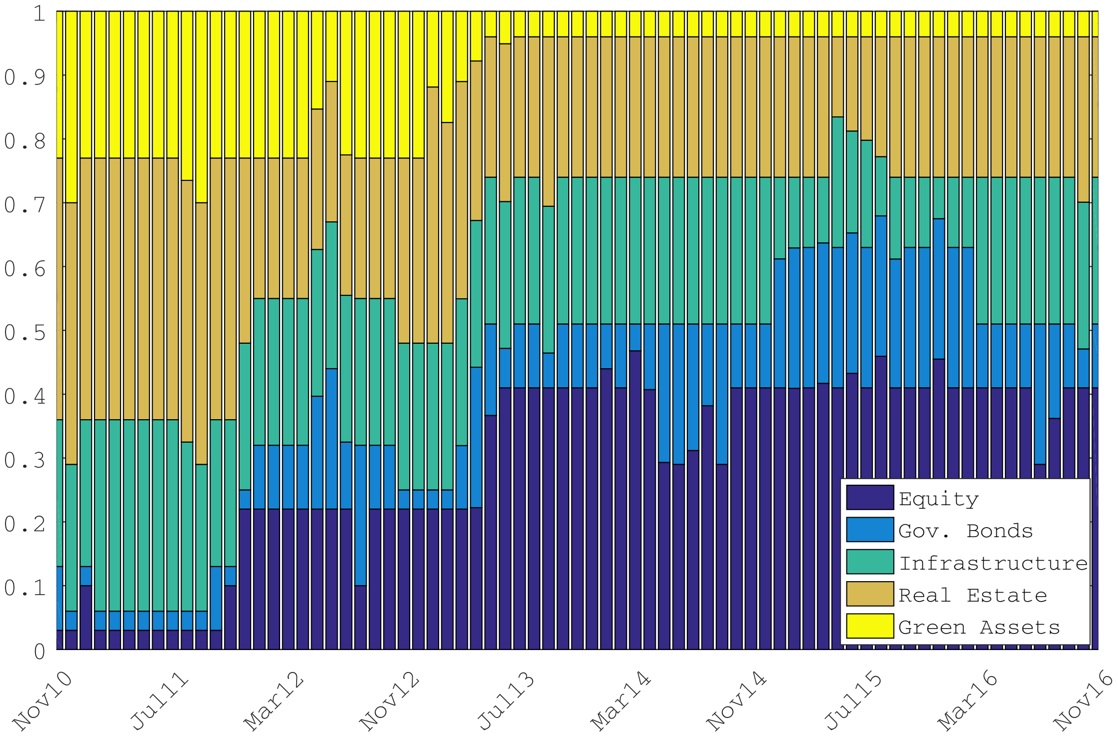


FIGURE 5.6: Optimal weight allocations in a portfolio containing equities, government bonds, infrastructure, real estate, and non-real green assets, 2010-2016.

In order to introduce robustness in our performance analysis, we also estimate the efficient frontier for the portfolio excluding non-real green assets and compare it when these assets are added in the portfolio. Figure 5.7 illustrates the efficient frontier generated by both portfolios with the 72 monthly returns from November 2010 to November 2016. In the figure, the star on the frontier line indicates the portfolio that maximises the Sharpe ratio. The figure shows that when non-real green assets are included among the investments, the frontier line shifts inwards, indicating that for a given level of expected return the volatility of the overall portfolio increases. This shows that portfolios containing non-real green assets underperform those excluding them. For instance, the portfolio that maximises the Sharpe ratio when green assets are excluded achieves an expected monthly return of 0.8% with a monthly volatility of 4.01%. While in the case when non-real green assets are included, this portfolio registers an inferior monthly average return of 0.75% and a greater monthly volatility of 4.19%.

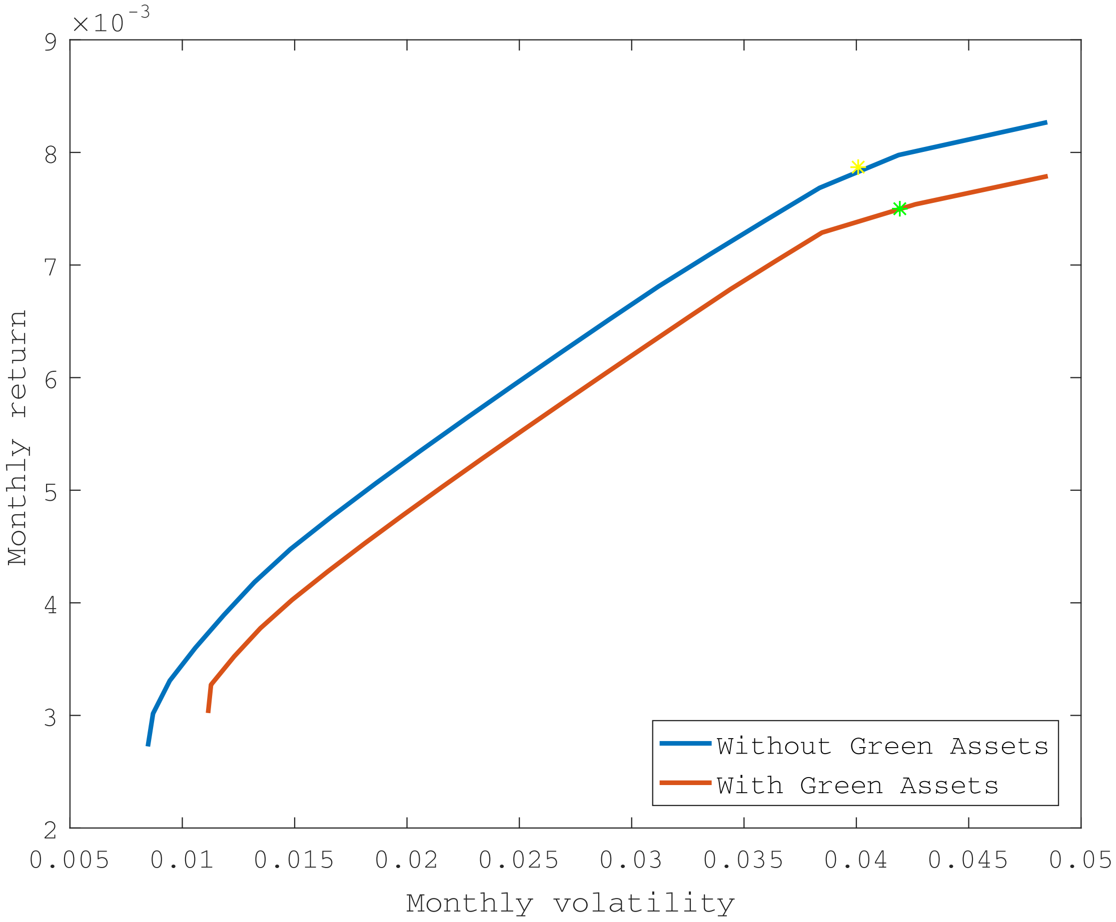


FIGURE 5.7: Average monthly return and volatility for portfolios combining non-real green assets with traditional assets, 2010-2016.

### Liquidity risk and non-real green assets

An important consideration when studying an asset's features is the liquidity of the asset. Liquidity refers to the degree of difficulty or cost to trade (i.e. buy or sell) an asset in a particular market. In periods of low liquidity, trading becomes more difficult and costly taking a longer time to buy or sell assets. On the contrary, in liquid markets assets can be traded quicker without significantly affecting their price. Direct investments in natural assets tend to be more illiquid when compared to traditional asset classes such as equities and bonds, both of which are among the most liquid assets traded in financial markets. This characteristic introduces a risk which is manifested most precisely during the long period in which the invested money is held in a particular illiquid investment. Therefore, the illiquidity of natural assets represents a concern for investors that may limit capital allocation into these asset class. The extent to which an investor may invest in natural assets depends on the value of assets under management, the investment horizon of the investor, and the level of risk an investor is willing to take. An investor allocating money in more illiquid assets would typically require higher expected returns to compensate the additional risk introduced.

In our analysis of liquidity, we investigate if non-real green assets tend to perform better or worse at times when liquidity in the stocks markets is low. If asset performance worsens at the time when liquidity is low, this would indicate that it is more costly for an investor to exit these investments during a crisis event, increasing its risk of the asset. On the contrary, if an asset performs better when liquidity is low, this would indicate that an investor would be less likely to exit the investment, reducing the risk of the asset. In measuring market liquidity, we follow the approach introduced by Lubos and Stambaugh (2003) to generate a liquidity index that captures temporary price changes due to the volume of trading. For a group of common shares indexed by $k$, the liquidity index, $\theta^2_{k,t}$, is estimated using time-series ordinary least squares (OLS) in a regression over the equation

$$r^{xs}_{k,d,t} = \theta^0_{k,t} + \theta^1_{k,t} \cdot r_{k,d-1,t} + \theta^2_{k,t} \cdot \mathrm{sign}(r^{xs}_{k,d-1,t}) \cdot vol_{k,d-1,t} + \varepsilon_{k,d,t}, \tag{5.1}$$

where $r_{k,d,t}$ is the return on the stock of company $k$ on day $d$ of month $t$. If we define $r^{mkt}_{d,t}$ as the market return where stocks are traded, the excess return $r^{xs}_{k,d,t} = r_{k,d,t} - r^{mkt}_{d,t}$ is given by the difference between the return on stock $k$ and the market return. We use the NYSE composite index and the NASDAQ composite index as proxy for the market returns associated to the NYSE and NASDAQ markets respectively. The value of shares traded is denoted by $vol_{k,d,t}$, measured in billion dollars. Specifically, we construct the market liquidity index taking the equally weighted average of the liquidity measures of individual stocks in the New York Stock Exchange (NYSE) and the NASDAQ stock market using daily data between January 2010 and September 2016. The NYSE and NASDAQ are composed by over 3,000 companies each. For our index construction, however, we have selected the 50 largest companies based on their market capitalization for which full time series price data is available over the period of interest. Table 5.7 lists the companies traded in the NYSE and NASDAQ considered in our index and presents their respective market capitalization as reported in the second quarter of 2016.

TABLE 5.7: Fifty largest companies traded in the NYSE and NASDAQ according to their market capitalization

| | NYSE | | NASDAQ | |
|---|---|---|---|---|
| No | Company | Market Cap. (US$ billion) | Company | Market Cap. (US$ billion) |
| 1 | Exxon Mobil Corp. | 369.1 | Apple Inc. | 607.6 |
| 2 | J P Morgan Chase & Co. | 305.9 | Microsoft Corp. | 481.8 |
| 3 | Johnson & Johnson | 305.4 | Amazon.com, Inc. | 365.2 |
| 4 | Wells Fargo & Co. | 287.0 | Intel Corp. | 169.5 |
| 5 | General Electric Co. | 281.1 | Comcast Corp. | 166.2 |
| 6 | AT&T Inc. | 248.0 | Cisco Systems, Inc. | 150.9 |
| 7 | Bank of America Corp. | 233.3 | Amgen Inc. | 106.7 |
| 8 | Procter & Gamble Co. | 225.8 | QUALCOMM Inc. | 101.2 |
| 9 | China Mobile (Hong Kong) Ltd. | 222.2 | Walgreens Boots Alliance, Inc. | 93.6 |
| 10 | Chevron Corp. | 218.6 | Celgene Corp. | 88.0 |
| 11 | Wal-Mart Stores, Inc. | 215.4 | Starbucks Corp. | 85.5 |
| 12 | Verizon Communications Inc. | 209.9 | The Priceline Group Inc. | 76.9 |
| 13 | Toyota Motor Corp Ltd Ord | 205.3 | Texas Instruments Inc. | 72.0 |
| 14 | Pfizer, Inc. | 192.4 | Costco Wholesale Corp. | 69.8 |
| 15 | Coca-Cola Co. | 181.1 | Adobe Systems Inc. | 51.9 |
| 16 | Citigroup Inc. | 171.1 | Twenty-First Century Fox, Inc. | 51.8 |
| 17 | HSBC Holdings plc | 169.0 | NVIDIA Corp. | 49.5 |
| 18 | Merck & Company, Inc. | 168.8 | Express Scripts Holding Co. | 44.7 |
| 19 | Walt Disney Co. | 166.9 | Automatic Data Processing, Inc. | 44.3 |
| 20 | Oracle Corp. | 166.4 | Yahoo! Inc. | 39.8 |
| 21 | Home Depot, Inc. | 162.5 | Applied Materials, Inc. | 35.0 |
| 22 | International Business Machines Corp. | 158.3 | CSX Corp. | 34.9 |
| 23 | Taiwan Semiconductor Manufac. Ltd. | 156.2 | Cognizant Technology Solutions Corp. | 33.9 |
| 24 | UnitedHealth Group Inc. | 152.4 | eBay Inc. | 33.5 |
| 25 | Pepsico, Inc. | 148.5 | Marriott International | 32.6 |
| 26 | Altria Group | 129.2 | Intuit Inc. | 30.0 |
| 27 | Unilever NV | 121.1 | Alexion Pharmaceuticals, Inc. | 29.6 |
| 28 | Schlumberger N.V. | 118.0 | DISH Network Corp. | 27.4 |
| 29 | BP p.l.c. | 113.5 | Activision Blizzard, Inc | 27.3 |
| 30 | 3M Company | 107.4 | Ross Stores, Inc. | 26.8 |
| 31 | United Parcel Service, Inc. | 104.4 | O'Reilly Automotive, Inc. | 26.1 |
| 32 | SAP SE | 103.7 | Electronic Arts Inc. | 23.8 |
| 33 | BHP Billiton Limited | 102.4 | PACCAR Inc. | 23.7 |
| 34 | Royal Bank Of Canada | 101.8 | TD Ameritrade Holding Corp. | 22.8 |
| 35 | Medtronic plc | 100.7 | Fiserv, Inc. | 22.7 |
| 36 | McDonald's Corp. | 100.7 | Analog Devices, Inc. | 22.5 |
| 37 | Boeing Co. | 96.6 | Sirius XM Holdings Inc. | 21.9 |
| 38 | Goldman Sachs Group, Inc. | 96.2 | Paychex, Inc. | 21.8 |
| 39 | Novo Nordisk AS | 93.7 | Micron Technology, Inc. | 21.4 |
| 40 | Toronto Dominion Bank | 92.7 | Dollar Tree, Inc. | 20.7 |
| 41 | GlaxoSmithKline PLC | 92.1 | Huntington Bancshares Inc. | 20.3 |
| 42 | Rio Tinto Plc | 91.5 | Fifth Third Bancorp | 20.3 |
| 43 | United Technologies Corp. | 90.4 | Northern Trust Corp. | 20.2 |
| 44 | Honeywell International Inc. | 88.6 | Mylan N.V. | 19.5 |
| 45 | U.S. Bancorp | 88.5 | Western Digital Corp. | 19.3 |
| 46 | Union Pacific Corp. | 86.5 | Incyte Corp. | 19.0 |
| 47 | Nike, Inc. | 86.1 | T. Rowe Price Group, Inc. | 18.6 |
| 48 | CVS Health Corp. | 85.5 | Autodesk, Inc. | 18.1 |
| 49 | Morgan Stanley | 81.9 | Lam Research Corp. | 16.9 |
| 50 | Nippon Telegraph and Telephone Corp. | 80.8 | Cerner Corp. | 16.4 |

Figure 5.8 illustrates the systematic stock market liquidity index developed using Equation (5.1) for the stocks traded in the NYSE and NASDAQ. As the figure shows, the time period from early 2000 to the end of 2003 is characterized by large changes in liquidity with several episodes of liquidity deterioration shown in the drastic negative drops of the index. This episode of large changes in liquidity

with significant drops may be associated with tech-bubble experienced between 1995 and 2000, which saw a drastic fall in the stock prices of NASDAQ, after having experienced a period of exceptionally rapid growth in prices resulting from a growing internet industry. After that period of drastic changes, the index started to stabilize experiencing less severe liquidity changes, in particular after 2009, when the index significantly flattens suggesting lower levels of liquidity and more smooth variations. The reason for this significant reduction in the index variation is attributed to a drastic fall in the trading volume of shares in stock markets that followed the 2008 financial crisis (PwC, 2015).

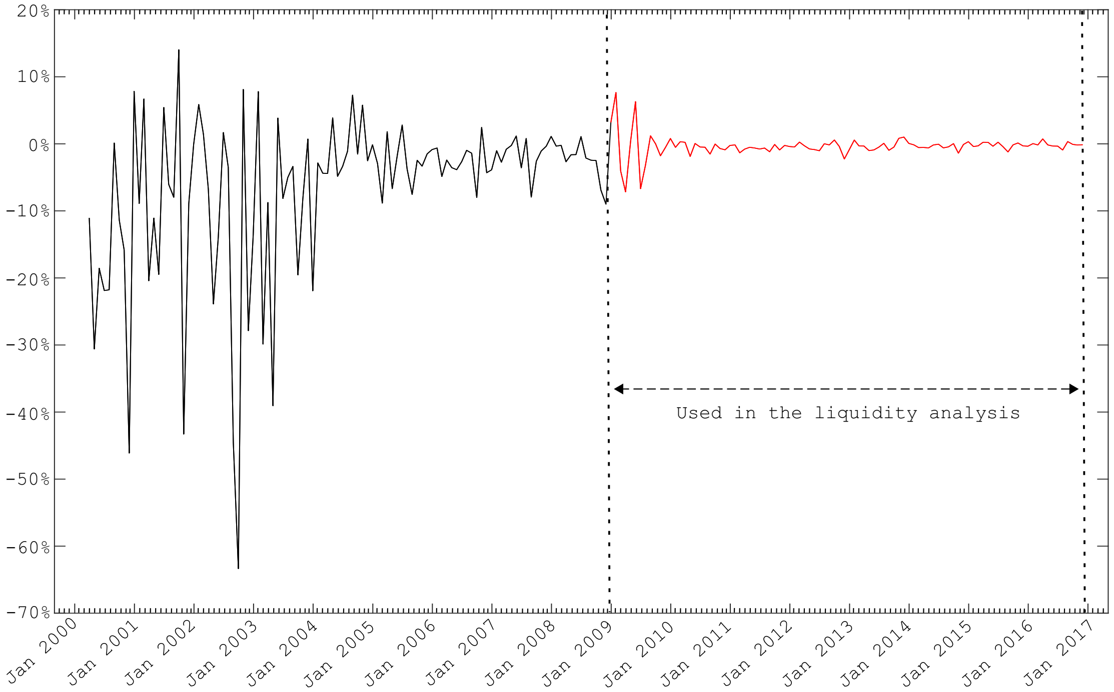


FIGURE 5.8: Monthly changes in the liquidity index in the aggregate stock markets of NYSE and NASDAQ, 2000-2016

Table 5.8 presents the results of regressing the monthly returns of the non-real green assets considered in our analysis on changes in the liquidity index and its one-month lag. The results show that none of the non-real green assets have a positive or negative association that is statistically significant with the stock market liquidity index developed. However, when examining the association with its one-month lag the performance of investments in non-real timberland, agriculture, green bonds, and renewable infrastructure have negative and statistically significant coefficients on the liquidity index, suggesting that these investments do slightly better with a certain delay when the liquidity in stock markets deteriorates. For instance, the coefficient on the one-month lag liquidity index for non-real timberland equals -1.984 (with a p-value of 0.00), such that a decrease in liquidity of 1% would be associated with a monthly return (1-month later) that is 1.98% higher. This indicates that non-real green assets can ease the exposure to the stock markets liquidity risk, or at least there is no evidence that these assets can increase liquidity risk.

TABLE 5.8: Aggregate stock market liquidity and non-real green assets, 2008-2016.

| | Liquidity Index | 1M Lagged Liquidity Index |
|---|---|---|
| S&P 500 | -0.076 | -0.993*** |
| | (0.764) | (0.000) |
| Stoxx Euro 600 | 0.180 | -0.901*** |
| | (0.476) | (0.000) |
| Nikkei 225 | -0.118 | -0.480 |
| | (0.735) | (0.168) |
| US T-bonds | -0.145** | -0.070 |
| | (0.010) | (0.205) |
| Ger. Gov. Bonds | -0.092 | 0.002 |
| | (0.134) | (0.971) |
| Jap. Gov. Bonds | 0.002 | 0.029 |
| | (0.942) | (0.248) |
| Infra. Telecom. | -0.132 | -0.576** |
| | (0.565) | (0.010) |
| Infra. Transport | -0.083 | -0.918*** |
| | (0.787) | (0.002) |
| Infra. Energy | 0.476 | -0.721** |
| | (0.184) | (0.044) |
| Infra. Utilities | 0.247 | -0.603*** |
| | (0.274) | (0.006) |
| US Real Estate | -0.119 | -1.881*** |
| | (0.756) | (0.000) |
| UK Real Estate | -0.687** | -1.612*** |
| | (0.066) | (0.000) |
| EU Real Estate | 0.319 | -1.245*** |
| | (0.431) | (0.001) |
| Timberland | 0.251 | -1.984*** |
| | (0.527) | (0.000) |
| Agriculture | 0.463 | -0.802* |
| | (0.279) | (0.059) |
| Green bonds | -0.158 | -0.604*** |
| | (0.340) | (0.000) |
| Renewable Infra. | 0.412 | -1.060*** |
| | (0.270) | (0.004) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

### 5.3.2 Performance of real green assets

#### Average returns, volatility, Sharpe ratio and diversification potential

The descriptive statistics for the performance of real green assets between June 2000 and March 2015 are presented in Table 5.9. From the table, it can be observed that the real green assets, represented by the NCREIF Timberland and Farmland indexes, significantly outperform the rest of the asset classes in terms of average return, volatility, Sharpe ratio, and cumulative losses. The average quarterly return for real timber and farmland equal 1.65% and 3.36% respectively, while equities represented by the S&P 500, the Stoxx Euro 600 and the Japanese Nikkei 225 exhibits mean returns ranging from 0.50% to -0.30%, US government bonds registers 1.31%, infrastructures assets varies between -0.79% and 1.41%, and real estate assets between 1.03% and 1.61%. The volatility of quarterly returns for real timberland and farmland are 4.22% and 5.06% respectively, compared with a range of 8.42-10.93% for equity assets, 1.69% for bonds, 8.72-10.98% for infrastructure assets, and 11.56-12.25% for real estate ones. The relatively higher expected returns of real green assets and their lower volatility also provide them with some of the highest Sharpe ratios, obtaining 29.54% in the case of timberland and 58.41% for farmland. These values are only comparable with the Sharpe ratio of 53.4% obtained for US bonds, while the ratio values for other asset classes are significantly lower. Similarly, in terms of cumulative losses as captured by the maximum drawdown, real green assets register among the lowest figures obtaining only 19.99% for timberland and 10.79% for farmland, compared to a range of 64.9-80.5% registered by equities, 58.16-108.61% by infrastructure assets, and 5.11-10.38% by real estate.

TABLE 5.9: Performance of historical quarterly returns for real green assets, June 2000 - March 2016

| | Quarterly return (%) | Annualized return (%) | Volatility of Q-returns (%) | Sharpe Ratio | Max. Draw down (%) |
|---|---|---|---|---|---|
| Equity | | | | | |
| S&P500 | 0.50 | 1.99 | 8.42 | 1.05 | 64.90 |
| STOXX Europe 600 | -0.24 | -0.97 | 9.48 | -6.87 | 80.25 |
| Nikkei 225 | -0.30 | -1.21 | 10.93 | -6.50 | 80.50 |
| Gov. Bonds | | | | | |
| US bonds | 1.31 | 5.24 | 1.69 | 53.37 | 2.47 |
| Infrastructure | | | | | |
| Telecom. | -0.79 | -3.17 | 9.57 | -12.55 | 108.61 |
| Transport | 1.41 | 5.65 | 8.72 | 11.53 | 72.00 |
| Energy | 0.57 | 2.26 | 10.98 | 1.43 | 69.81 |
| Utilities | 0.82 | 3.28 | 7.09 | 5.82 | 58.16 |
| Real estate | | | | | |
| US | 1.61 | 6.44 | 11.56 | 10.38 | 114.89 |
| UK | 1.03 | 4.14 | 12.25 | 5.11 | 149.46 |
| EU | 1.13 | 4.53 | 12.23 | 5.92 | 114.63 |
| Green assets | | | | | |
| NCREIF Timberland | 1.65 | 6.62 | 4.22 | 29.54 | 19.99 |
| NCREIF Farmland | 3.36 | 13.45 | 5.06 | 58.41 | 10.79 |

Figure 5.9 presents the cumulative investment performance of £1 investment in real green assets and compare it with the performance of the rest of the asset classes over the period June 2000 - March 2016. The highest ending values at the end

of the period are obtained for investments in farmland and timberland with £7.7 and £2.7 respectively. These values are followed by US bonds (£2.3), transport infrastructure (£1.9), US real estate (£1.6), utility infrastructure (£1.4), EU real estate (£1.3), and the S&P 500 (£1.1) which was the best-performing equity index. In terms of the downside risk exhibited by each asset, it can be observed that all real estate assets, infrastructure assets, and equity assets experienced significant losses between late 2007 and mid-2009, as a consequence of the 2008 financial crisis. Nevertheless, during the same period real green assets continued growing without experiencing drastic losses indicating that these assets presented a greater resilience against the effect of the crisis.

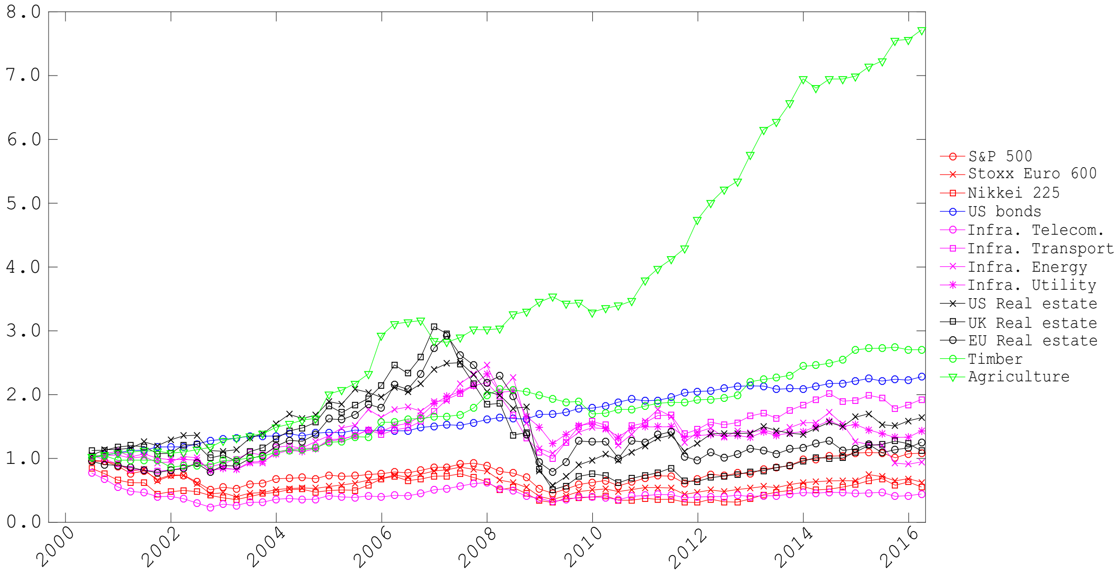


FIGURE 5.9: Cumulative investment performance of an initial £investment in real green assets, June 2000 - March 2016.

The diversification potential of real green assets is also found to be significant. Table 5.10 shows the correlation of the quarterly returns obtained for real green assets and the rest of the asset classes between June 2000 and March 2016. Real green assets present a low positive to negative correlation with all asset classes including equities, bonds, infrastructure and real estate assets. In the particular case of real timberland, the correlation with equities ranges from 0.08 to 0.13, while the correlation with bonds is just 0.02, the correlation stands between 0.05 and 0.19 with infrastructure assets, and between 0.03 and 0.17 with real estate. In the case of real farmland, correlations range between 0.07 and 0.20 for equities,

-0.16 for bonds, -0.06 to 0.11 for infrastructure, and between -0.06 and 0.07 for real estate. These values are among the lowest of all the values in the table, only outperformed by the US bonds which exhibit negative correlation with most of the assets. The low correlation that real green assets present with other traditional asset classes provide them with an important diversification potential that may be attractive for investors.

TABLE 5.10: Correlation of quarterly returns, June 2000- March 2016

| | S&P 500 | Stoxx Euro 600 | Nikkei 225 | US Bonds | Infra. Telecom. | Infra. Transport | Infra. Energy | Infra. Utilities | US Real Estate | UK Real Estate | EU Real Estate | Timberland | Agriculture |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S&P 500 | 1.00 | | | | | | | | | | | | |
| Stoxx Euro 600 | 0.91 | 1.00 | | | | | | | | | | | |
| Nikkei 225 | 0.71 | 0.75 | 1.00 | | | | | | | | | | |
| US Bonds | -0.42 | -0.38 | -0.53 | 1.00 | | | | | | | | | |
| Infra. Telecom. | 0.79 | 0.72 | 0.53 | -0.20 | 1.00 | | | | | | | | |
| Infra. Transport | 0.71 | 0.66 | 0.48 | -0.03 | 0.66 | 1.00 | | | | | | | |
| Infra. Energy | 0.72 | 0.71 | 0.51 | -0.28 | 0.64 | 0.74 | 1.00 | | | | | | |
| Infra. Utilities | 0.72 | 0.68 | 0.45 | -0.01 | 0.72 | 0.76 | 0.78 | 1.00 | | | | | |
| US Real Estate | 0.76 | 0.70 | 0.46 | -0.11 | 0.43 | 0.66 | 0.54 | 0.63 | 1.00 | | | | |
| UK Real Estate | 0.65 | 0.65 | 0.47 | -0.15 | 0.41 | 0.57 | 0.39 | 0.54 | 0.81 | 1.00 | | | |
| EU Real Estate | 0.65 | 0.64 | 0.45 | 0.00 | 0.59 | 0.83 | 0.61 | 0.70 | 0.73 | 0.75 | 1.00 | | |
| Timberland | 0.10 | 0.08 | 0.13 | 0.02 | 0.19 | 0.08 | 0.05 | 0.16 | 0.03 | 0.17 | 0.09 | 1.00 | |
| Agriculture | 0.10 | 0.07 | 0.20 | -0.16 | 0.11 | -0.06 | 0.07 | 0.04 | -0.06 | 0.07 | 0.00 | 0.57 | 1.00 |

### Alphas and betas for real green assets relative to equities, bonds, and infrastructure

When examining the alpha and beta values for real green assets we find that the results confirm that these particular assets outperform the traditional assets of equities, bonds, infrastructure, and real estate in terms of both expected returns and volatility levels. Table 5.11 shows the regression results for alpha values on the real green assets of timberland and farmland, while Table 5.12 presents the beta values. The figures in this table reveal that in both cases real green assets present positive alphas with all the other asset classes compared. Moreover, the positive coefficients are statistically significant at 1% and 5% in all cases. For example, the NCREIF Timber returns have a positive alpha of 4.8% p.a. (i.e., 4.8%= 4 × 0.012%) with the S&P 500, transport, energy, and utility infrastructure, and all real estates, that are statistically significant at 5%. NCREIF Farmland returns also produce a positive alpha of 11.6-12.0% p.a. with all the assets compared, that are statistically significant at 1%. From Table 5.12 it can be also seen that the regression coefficient for beta values computed for NCREIF timber and agriculture returns are less than one for all the assets considered as benchmarks. In this case, however, the large majority of the positive coefficient are statistically not significant, with the exception of timber and telecommunication infrastructure, and farmland and Japanese stocks, which are both statistically significant at 10%.

Table 5.11: Alpha estimates for real green assets, 2000-2016

| | NCREIF Timber | NCREIF Agriculture |
|---|---|---|
| S&P 500 | 0.012**<br>(0.023) | 0.029***<br>(0.000) |
| STOXX EUR 600 | 0.013**<br>(0.020) | 0.030***<br>(0.000) |
| Nikkei 225 | 0.013**<br>(0.018) | 0.030***<br>(0.000) |
| US Bonds | 0.012*<br>(0.052) | 0.033***<br>(0.000) |
| Infr. Telecom | 0.014**<br>(0.012) | 0.030***<br>(0.000) |
| Infr. Transport | 0.012**<br>(0.029) | 0.030***<br>(0.000) |
| Infr. Energy | 0.012**<br>(0.024) | 0.029***<br>(0.000) |
| Infr. Utilities | 0.012**<br>(0.026) | 0.029***<br>(0.000) |
| US Real Estate | 0.012**<br>(0.026) | 0.030***<br>(0.000) |
| UK Real Estate | 0.012**<br>(0.026) | 0.029***<br>(0.000) |
| EU Real Estate | 0.012**<br>(0.026) | 0.029***<br>(0.000) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

The analysis of alphas and betas for real green assets indicates to an investor that these assets may certainly provide higher expected returns when compared to the

Table 5.12: Beta estimates for real green assets, 2000-2016

| | NCREIF Timber | NCREIF Agriculture |
|---|---|---|
| S&P 500 | 0.060<br>(0.340) | 0.074<br>(0.333) |
| STOXX EUR 600 | 0.040<br>(0.473) | 0.048<br>(0.483) |
| Nikkei 225 | 0.060<br>(0.216) | 0.103*<br>(0.078) |
| US Bonds | 0.042<br>(0.896) | -0.418<br>(0.282) |
| Infr. Telecom | 0.094*<br>(0.087) | 0.070<br>(0.295) |
| Infr. Transport | 0.041<br>(0.499) | -0.028<br>(0.706) |
| Infr. Energy | 0.017<br>(0.734) | 0.031<br>(0.602) |
| Infr. Utilities | 0.088<br>(0.249) | 0.026<br>(0.778) |
| US Real Estate | 0.012<br>(0.794) | -0.022<br>(0.696) |
| UK Real Estate | 0.061<br>(0.161) | 0.030<br>(0.573) |
| EU Real Estate | 0.033<br>(0.453) | 0.004<br>(0.939) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

traditional assets of equity, bonds, infrastructure or real estate as represented in our selected benchmarks. The positive and statistically significant alphas mean that the examined real assets are able to outperform all the benchmark assets, suggesting that investment performance could be improved if these assets are included in a portfolio. On the other side, the lack of statistical significance in most of the beta values denies the possibility of concluding that these assets present lower volatilities than the benchmarks. Nevertheless, it also implies that there is no evidence that the real green assets will introduce a significantly higher risk into an investment portfolio. Thus, from an investor point of view, the analysis of alphas and betas would still suggest that he can be favoured by investing in these assets.

### Inflation and real green assets

Similarly, as we did for non-real green assets we measure the ability of real green assets to hedge inflation using quarterly returns over the period June 2000-March 2016. Although we use the same methodology, in this case, we measure inflation considering quarterly changes in the US CPI instead of monthly changes. Following the same argument of how financial markets may respond to inflation, we perform the regression of the assets quarterly returns on current changes in inflation, and also on one-, two-, and three-quarter lags of changes in inflation, as well as, the one- and two-quarter future changes.

Table 5.13 presents the results for the regression coefficients of the assets quarterly returns and changes in the CPI index. As stated before, a positive coefficient on future, current, or lagged changes in CPI can be interpreted as evidence of inflation hedging, while a negative coefficient indicates that an asset performance worsens at the time that inflation increases. The results in the table illustrate that from the real green assets, NCREIF timberland returns positively relates with 1Q future changes in CPI. The value of the coefficient is 1.16 and its associated p-value is 0.03, suggesting that the coefficient is both economically (i.e. 1% increase in the 1Q future inflation rate, would expect a returned increase of 1.16%) and statistically significant at 5%. In the case of NCREIF agriculture, no association that is statistically significant is found with either future, current or lagged CPI changes. These results suggest that the real green asset of timberland has the ability to provide hedging, particularly against unanticipated inflation which support the findings also reported by Rubens and Webb (1995), Healey et al. (2005), and Binkley et al. (2006).

TABLE 5.13: Investment performance of real green assets and changes in CPI

| | 2Q Future CPI change | 1Q Future CPI change | CPI change | 1Q Lagged CPI change | 2Q Lagged CPI change | 3Q Lagged CPI change |
|---|---|---|---|---|---|---|
| S&P 500 | -0.685 | 1.263 | 0.831 | 0.162 | -1.610 | -0.585 |
| | (0.526) | (0.239) | (0.436) | (0.880) | (0.138) | (0.594) |
| Stoxx Euro 600 | -0.556 | 1.751 | 0.739 | -0.376 | -1.552 | -0.688 |
| | (0.647) | (0.143) | (0.538) | (0.756) | (0.205) | (0.580) |
| Nikkei 225 | -1.284 | 1.138 | 1.405 | -0.831 | -2.306* | 0.118 |
| | (0.353) | (0.410) | (0.309) | (0.546) | (0.094) | (0.933) |
| US Bonds | 0.405* | 0.138 | -0.432** | 0.161 | 0.357* | -0.465** |
| | (0.056) | (0.522) | (0.040) | (0.455) | (0.098) | (0.028) |
| Infra. Telecom. | 0.079 | 2.171* | -0.588 | 0.068 | -0.464 | -0.378 |
| | (0.949) | (0.071) | (0.628) | (0.954) | (0.693) | (0.744) |
| Infra. Transport | 0.715 | 2.330** | 1.167 | -0.706 | -2.525** | -1.302 |
| | (0.524) | (0.033) | (0.289) | (0.526) | (0.022) | (0.249) |
| Infra. Energy | -1.144 | 3.348** | 3.793*** | -0.692 | -2.475* | -0.323 |
| | (0.417) | (0.014) | (0.005) | (0.621) | (0.079) | (0.823) |
| Infra. Utilities | -0.004 | 2.007** | 0.694 | 0.652 | -0.844 | -0.745 |
| | (0.997) | (0.023) | (0.439) | (0.471) | (0.356) | (0.421) |
| US Real Estate | -1.256 | 0.744 | 3.176** | 1.505 | -2.953** | -2.554* |
| | (0.398) | (0.614) | (0.027) | (0.306) | (0.045) | (0.089) |
| UK Real Estate | 0.428 | 1.111 | 0.523 | 2.226 | -1.367 | -2.742* |
| | (0.785) | (0.475) | (0.736) | (0.149) | (0.387) | (0.084) |
| EU Real Estate | 0.333 | 3.513** | 1.954 | -1.076 | -1.789 | -2.919* |
| | (0.832) | (0.021) | (0.205) | (0.490) | (0.257) | (0.066) |
| Timberland | 0.607 | 1.161** | -0.393 | 0.805 | -0.019 | 0.647 |
| | (0.259) | (0.028) | (0.462) | (0.132) | (0.973) | (0.227) |
| Agriculture | -0.031 | 1.029 | -0.472 | 0.678 | 0.455 | 0.836 |
| | (0.963) | (0.107) | (0.460) | (0.292) | (0.488) | (0.207) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

### Effects of including real green assets in an investment portfolio

In order to assess the impact of including real green assets in an investment portfolio, we build a portfolio compounded by equities, bonds, infrastructure, and real estate, and evaluate its performance over the period extending from June 2004 to March 2016 on a quarterly basis. Equities investments involve the US market represented by the S&P 500, the European market proxied by the Stoxx Euro 600, and the Japanese market as reflected in the Nikkei 225. As for bonds, we limit these investments to the US bond market including both government and corporate bonds as reported by the Barclays Capital Aggregate Bond Index. Investments in infrastructure include the global markets of telecommunication, transport, energy, and utility infrastructure. And real estate investment involves the US, UK, and EU real estate markets. Following a similar procedure as we did for non-real green assets, the constructed portfolio uses Markowitz Mean-Variance optimization to determine the optimal weights allocated to each asset in each time interval such that maximizes the Sharpe ratio of the portfolio. We keep the same constraints of 1% and 20% to the minimum and maximum weight respectively to avoid null allocations. Likewise, the out-of-sample technique is employed to reconstruct the investment process over the examined period, but this time performed on quarterly basis.

Figure 5.10 shows the performance of the cumulative investment obtained for a portfolio including in this case real green assets, and compare it with a portfolio that does not include them. It can be observed from the figure that an initial investment of £1 in a portfolio with real green assets leads to a value of £1.71 (i.e. a net growth of 71%) at the end of the period, while in a portfolio without real green assets this lead to just £1.12 (i.e. a net growth of just 12%). Despite both trajectories experiencing a drastic fall in their growth between March 2008 and March 2009, it is observed that the fall experienced by the trajectory of the portfolio excluding real green assets is significantly deeper and it does not recover at the same rate as the portfolio including real green assets. The performance of the quarterly returns obtained for both portfolios are illustrated in Figure 5.11, and their main statistics are summarized in Table 5.14. The comparison of the overall portfolio returns shows that a portfolio containing real green assets exhibits an average quarterly return of 1.22% (i.e. 4.88% p.a.), contrasted with only 0.55% (i.e. 2.2% p.a.) for a portfolio without real green assets. Moreover, the volatility of quarterly return in the first case is 4.30%, nearly 3.5% lower than the volatility register in the second case. The Sharpe ratio in the green portfolio rises up to 23.2%, more than five times that one register for the traditional portfolio. And the cumulative losses, as registered by the maximum drawdown, is 34.1% for a portfolio with real green assets compared with 73.2% for the portfolio without them.

When examining the weights allocated to each asset class along the studied period, we find that allocations in real green assets are greatly favoured during the whole period. This is shown in Figure 5.12. From the figure it can be seen how weights on real green assets account for as much as 60% of the portfolio during most of the period, indicating that these asset classes are preferred over traditional

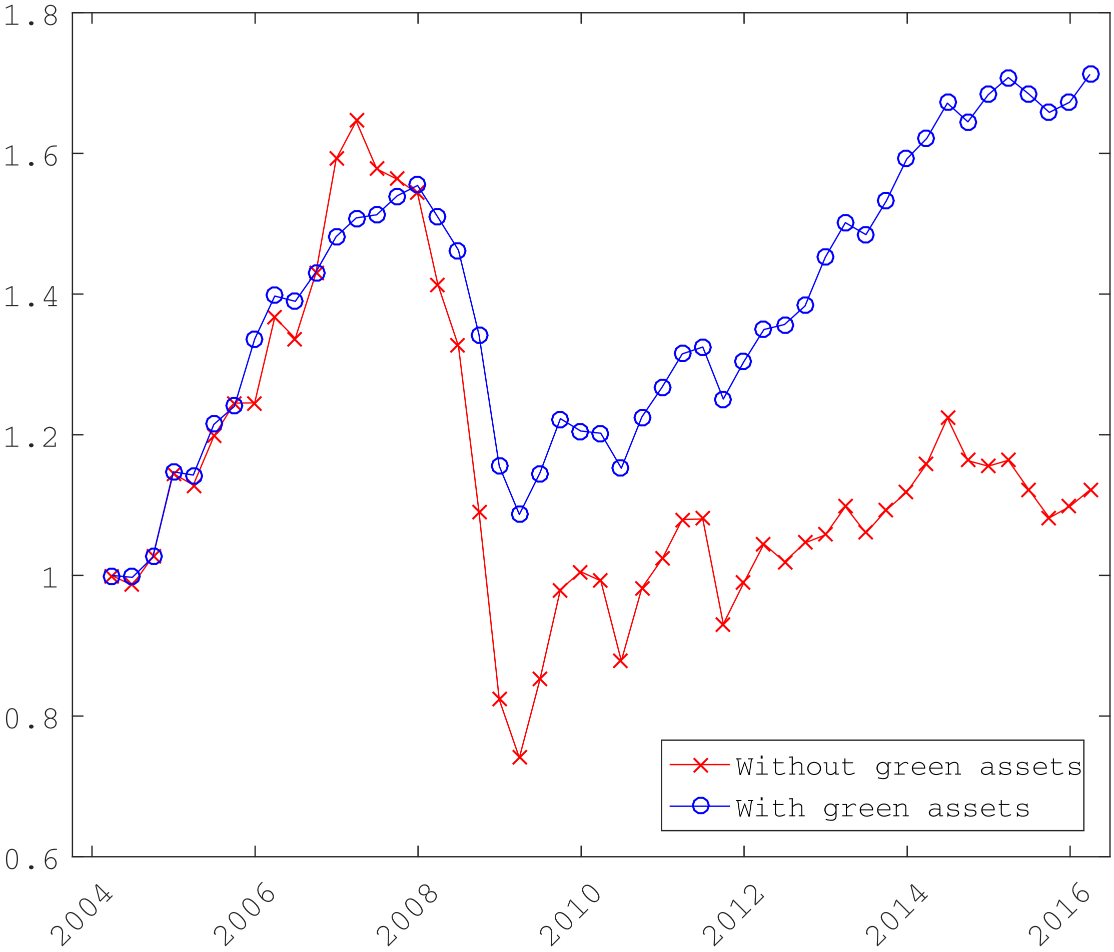


FIGURE 5.10: Cumulative investment performance for a portfolio including and excluding real green assets, 2004-2016

TABLE 5.14: Statistics on the quarterly returns of a portfolio with real green assets

| | With Green Assets | Without Green Assets |
|---|---|---|
| Mean Q-return | 1.22% | 0.55% |
| Annualized mean return | 4.88% | 2.19% |
| Volatility of Q-returns | 4.30% | 7.75% |
| Sharpe Ratio of Q-returns | 23.23% | 4.22% |
| Max. Drawdown | 34.1% | 73.2% |

equities, bonds or real estate even during periods of crisis. Infrastructure assets also receive a significant share of allocation. Yet weights, in this case, are variable being smaller at the beginning of the period and increasing after the end of 2008. Equities represent the asset class receiving the shortest weights averaging around just 3% during the whole period.

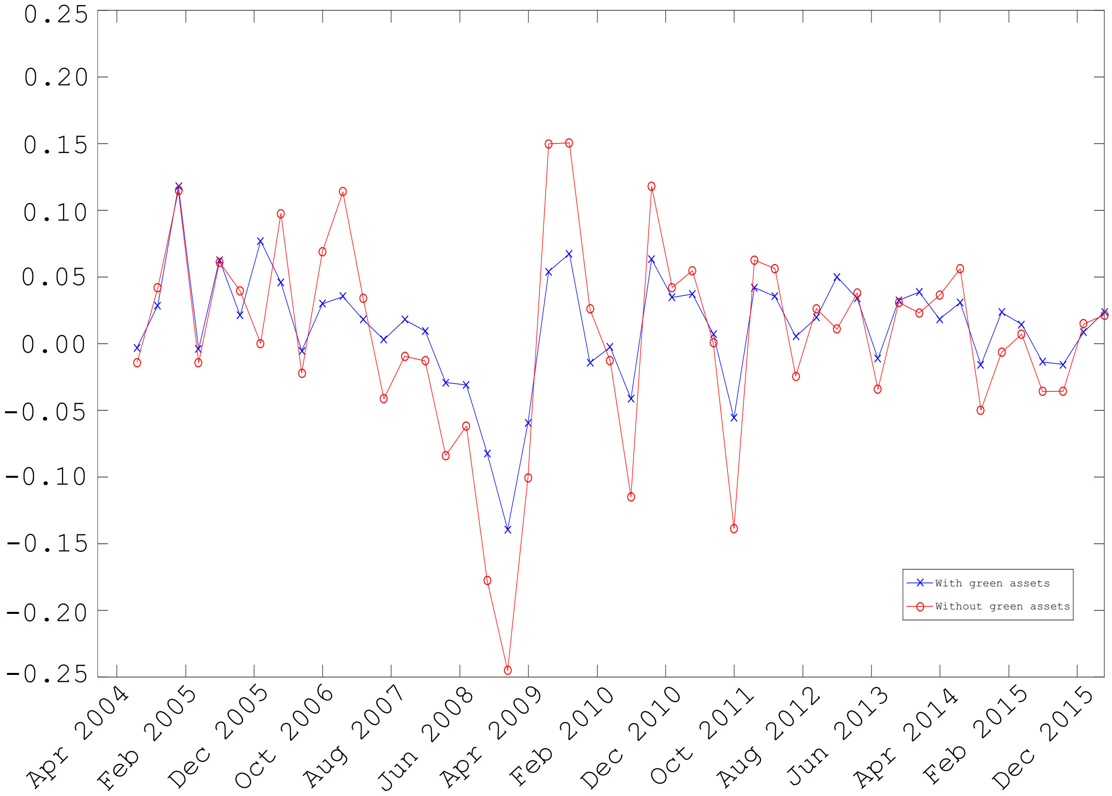


FIGURE 5.11: Quarterly returns of portfolio

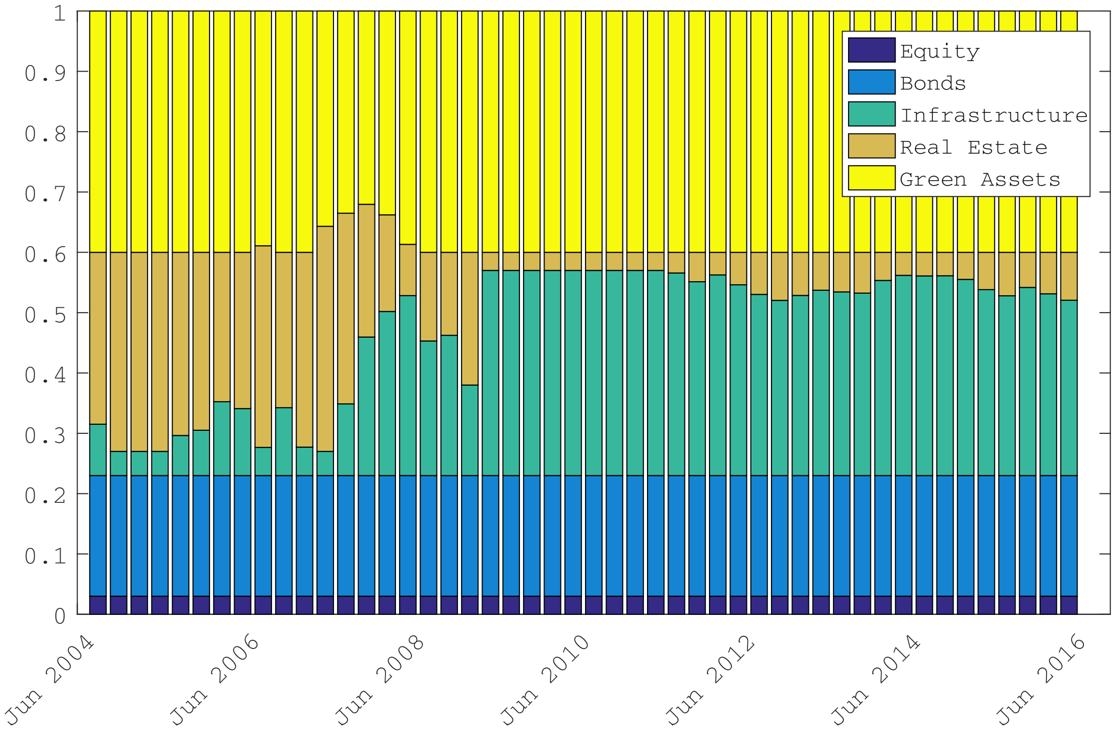


FIGURE 5.12: Optimal weight allocations in a portfolio containing equities, bonds, infrastructure, real estate, and real green assets, 2004-2016

Finally, Figure 5.13 presents the efficient frontier generated with the quarterly returns of the compared portfolios, where the star on the frontier lines indicates the portfolio that maximizes the Sharpe ratio. The figure shows that when real green assets are included in the portfolio, the frontier line shifts outward to the top left corner of the plot. This indicates that portfolios containing real green assets would expect higher average quarterly returns and lower volatilities when compared with those that do not include them. When taking the cases of the portfolios that maximize the Sharpe ratio, it is found that when real green assets are included the portfolio achieve an expected quarterly return of nearly 1.6% with an associated volatility of 4.6%. However, when real green assesses are absent the expected return diminish to 1.1% and the volatility increases to 7.5%.

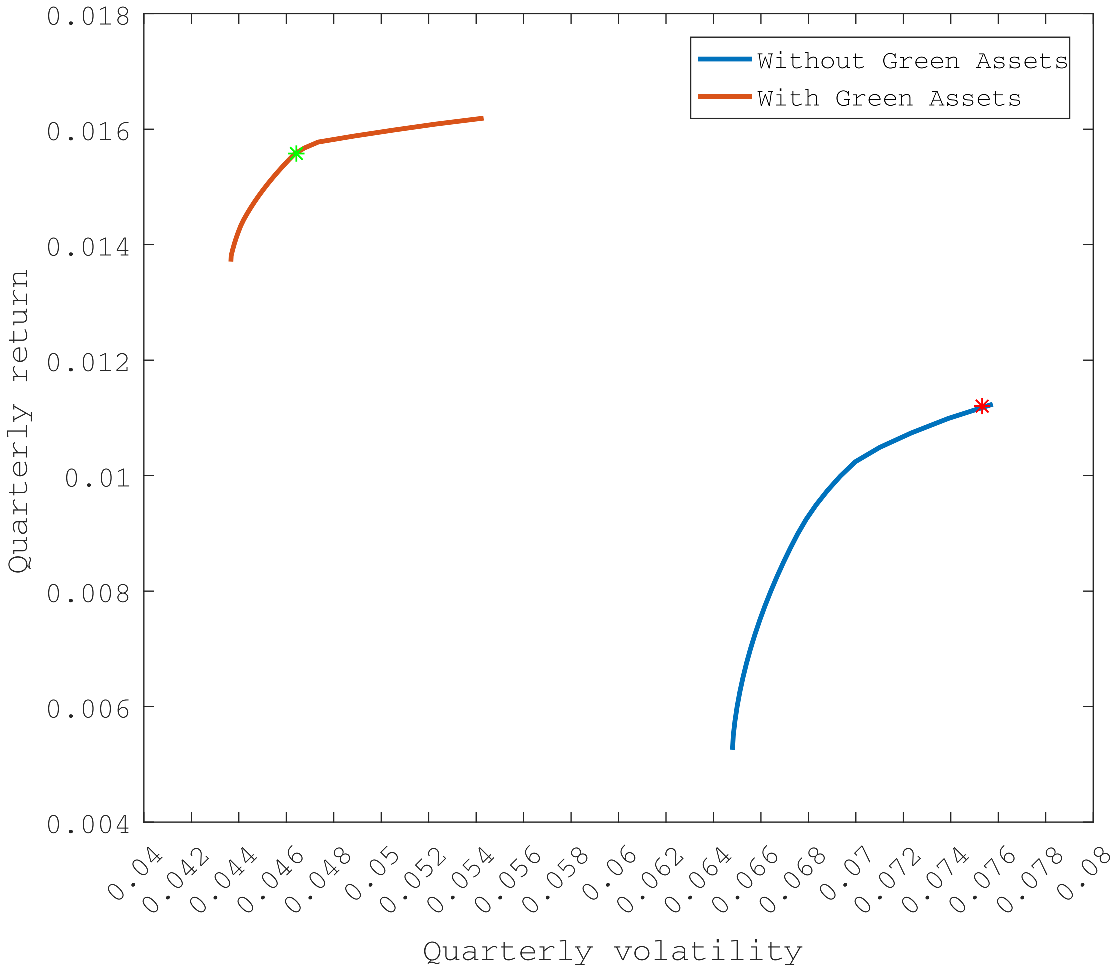


FIGURE 5.13: Average quarterly return and volatility for portfolios combining real green assets with traditional assets, 2004-2016

### Liquidity risk for real green assets

To study the association between real green assets and liquidity, we take the quarterly changes between June 2000 and March 2016 in the liquidity index (see Figure 5.8) constructed and regress them with the quarter returns exposed by the examined real green assets. Table 5.15 presents the results obtained on the regression coefficients on current changes in the liquidity index and its one-quarter lag. The results in the table indicate that direct investments in real timberland and farmland properties do not have a positive and statistically significant association with stock market liquidity as captured by our index. Moreover, real timberland actually presents a negative association of -0.102 with one-quarter lagged liquidity changes that is statistically significant at 10%, suggesting that this investment does slightly better when liquidity in stock markets decreases. Therefore, despite the common notion that real assets tend to be much more illiquid adding extra risk for investors, we find no evidence that the real green assets of timberland and farmland may actually increase the exposure to stock markets liquidity risk.

TABLE 5.15: Aggregate stock market liquidity and real green assets, 2000-2016

| | Liquidity Index | 1Q Lagged Liquidity Index |
|---|---|---|
| S&P 500 | 0.125 | -0.154 |
| | (0.251) | (0.162) |
| Stoxx Euro 600 | 0.185 | -0.116 |
| | (0.130) | (0.350) |
| Nikkei 225 | 0.053 | 0.043 |
| | (0.712) | (0.761) |
| US Bonds | -0.021 | -0.017 |
| | (0.338) | (0.454) |
| Infra. Telecom. | 0.157 | -0.275** |
| | (0.204) | (0.020) |
| Infra. Transport | 0.022 | -0.141 |
| | (0.843) | (0.216) |
| Infra. Energy | 0.089 | -0.216 |
| | (0.532) | (0.132) |
| Infra. Utilities | 0.123 | -0.219** |
| | (0.178) | (0.016) |
| US Real Estate | 0.072 | -0.141 |
| | (0.635) | (0.351) |
| UK Real Estate | 0.023 | -0.167 |
| | (0.886) | (0.295) |
| EU Real Estate | 0.054 | -0.236 |
| | (0.737) | (0.139) |
| Timberland | -0.032 | -0.102* |
| | (0.558) | (0.064) |
| Agriculture | -0.006 | -0.065 |
| | (0.931) | (0.324) |

Note. The p-values are given in parentheses. ***, **, and * indicate that the coefficient's p-value is below 1%, 5% and 10% respectively.

## 5.4 Discussion

In this chapter, we have examined the performance of private investments in natural green assets considering allocations in non-real green assets (i.e. non-real timberland, farmland, green bonds, and renewable infrastructure) and direct investments in real green assets (real timberland and farmland). Using monthly return data for non-real assets available over the period November 2008 - November 2016, and quarterly returns for real green assets, we investigate which form of green asset investments provide significant financial benefits for investors. Thus, resulting in a more attractive option relative to the benefits provided by traditional asset classes such as equities, bonds, real estate, and other non-traditional assets such as infrastructure.

When comparing the performance of natural green assets with other traditional asset classes, it was found that real natural assets tend to outperform global equities, bonds, and even real estate in all the metrics considered. This was the case, at least, for the period examined (2000-2016) which cover most of the time span for which returns on natural capital have been reported in global markets. Generalizing the obtained results to other periods will require conducting a similar study in the future when more return data is generated for the assets evaluated. The period considered in our analysis was characterized for the occurrence of a global financial crisis in 2008, a significant event that stressed financial markets and pushed down global equity prices. This particularity allowed to observe that investments in real natural assets do particularly well when equities and bonds perform poorly. It will be of interest to assess the performance of real green assets in future scenarios of crisis to confirm if similar results are observed.

The results obtained in this chapter also reveal that investing in green natural assets can have very different consequences for a private investor depending on the type of investment. While investments in non-real natural assets may show a significant downside, direct investments in real natural assets offer tangible benefits. The evidence from our analysis indicates that non-real green assets tend to present lower expected returns and higher volatilities compared with those of equities, bonds, real estate, and infrastructure. Moreover, non-real green assets offer very little diversification potential, present negative alphas, and betas lower than one leading to the deterioration of the overall performance of a portfolio. On the positive side of these assets, we find that they still may provide some hedging against unanticipated inflation and they do not exhibit evidence of introducing significant risk when stock markets experience liquidity shocks.

On the contrary, the evidence in our analysis supports the idea that direct investments in real natural assets can result in significant financial benefits for investors. Real green assets provide expected returns and volatilities that are significantly higher and lower, respectively, when compared with traditional asset classes. The alpha values for real green assets are highly positive in the majority of the cases, while beta values remain lower than one; moreover, the assets also exhibit a significant diversification potential. Additionally, our findings confirm that real timberland is able to provide hedging against unexpected inflation, and together with real farmland it does not show evidence of increasing the risk exposure to stock markets liquidity risk.

A particular investor desiring to invest in natural capital assets should do so by investing directly in real green assets, rather than non-real assets if financial benefits are to be expected. The main challenge for investments in real natural assets yet remains associated to the liquidity concern and the long holding period. Despite our results showing no evidence increasing risk in periods of low stock markets liquidity, real natural assets remain in practice more difficult to trade than bonds or equities. Even more, to access the benefits of real green assets including higher returns and lower volatility, an investor would typically be required to hold the assets for 10-15 years. Therefore, real green assets require investors that possess long investment horizons and large capital amounts. Most typical investors, including hedge funds, private individuals, or mutual funds normally have short investment horizons; and thus, are unable to have significant shares of their portfolio invested in this asset class.

A recently emerging new type of investment funds, the Sovereign Wealth Funds (SWFs), nevertheless have exhibited the appropriate characteristics, including very large size, long-term investment goal, and access to a greater liquidity risk exposure, required to increase allocations in real natural assets. This particular type of funds has the potential to become a novel investment mechanism for natural capital. SWFs are not only able to invest significant fractions of their portfolio in real green assets, which mainly refers to renewable natural capital, but they also have the capability of managing the wealth derived from non-renewable natural capital. This provides SWFs with the potential to be adapted as natural capital funds and support sustainability strategies. In the next chapter, we examine SWFs as mechanisms to manage and invest in natural capital, and we also demonstrate how this type of funds can reach the benefits of investing in real green assets.

# 6

# Sovereign Wealth Funds and Natural Capital Investments

Sovereign Wealth Funds (SWFs) have emerged as a new important class of global investors given the tremendous growth experienced in recent years (Butt et al., 2008; Beck and Fidora, 2008). An SWF is a government-owned investment vehicle with high foreign asset exposure and long-time horizon that serve multiple financial objectives (i.e. stabilization, saving, preserving investments or pensions) (IWG, 2008). By early 2016, there were over 70 SWFs distributed in more than 40 countries managing assets valued over US$ 7.1 trillion. According to the SWFI (2016) most SWFs are located in oil-exporting countries funded by the revenues realized from the liquidation of commodity assets (e.g. petroleum, gas, and minerals). These revenues are normally invested in highly diversified global portfolios aiming to maximize returns and preserve the wealth of the owning country. The distinctive characteristics of SWFs including their large size, type of ownership, the absence of standard liabilities and low liquidity constraints, provide them with a long-term investment capability no found in other institutional investors such as pension schemes (Stiglitz, 2012).

The characteristics of SWFs make them particularly suitable to preserve the value of different forms of natural capital. On one side, when used as saving mechanisms, SWFs can receive revenues realized from the liquidation of non-renewable natural resources (i.e. oil, gas, minerals) converting the value of this type of natural capital into a financial capital form that can be reinvested in a more diversified portfolio to preserve its wealth for the future. On the other side, as investment vehicles with a long horizon, SWFs can allocate part of their portfolio to directly invest in renewable natural capital and contribute to recovering their value. This idea is illustrated in Figure 6.1. Given their large size, SWFs have the ability to invest for much longer time horizon compared with other financial instruments, which convert them in suitable investors for natural capital assets. Despite their attributes, SWFs are not exempt of limitations and challenges. The main concerns associated to SWFs regard possible economic distortion, since some SWFs may find difficult to coordinate the fund's operations with fiscal policy; how to cope the lack of transparency, which can allow others to copy their investment strategy; effectiveness in achieving its goals; and the risk of acquiring proprietary knowledge, patented technology or trade secrets (Bernstein et al., 2013; Jory et al., 2010; Balin, 2008).

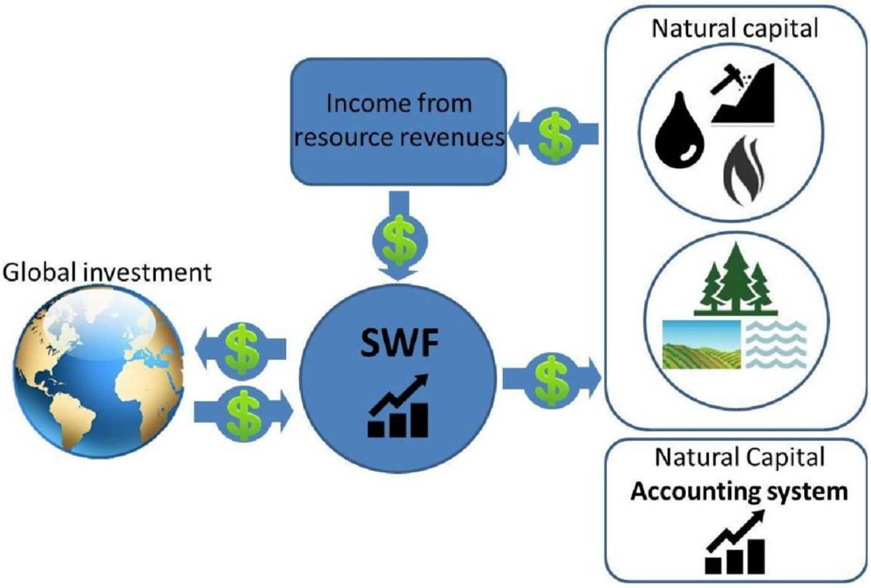


Figure 6.1: Sovereign Wealth Funds to preserve the value of natural capital

The strategic asset allocation (SAA) of SWFs can significantly differ depending on the objectives of the fund (Kunzel et al., 2011). Nevertheless, empirical works reveal most SWF portfolios focus their investments primarily in stock and bonds, with a strong predominance for the financial sector (Bernstein et al., 2013; Johan et al., 2013; Kotter and Lel, 2011; Dyck and Morse, 2011; Chhaochharia and Laeven, 2008; Jain, 2007). Moreover, Bortolotti et al. (2013, 2009) show equity investments have accounted for about 80% of the total value of investments carried out by SWFs in the past decade. The high preference towards equity can be due to the absence of incentives to commit to other long-term alternatives, as suggested by Spiegel (2012). There are, however, two major factors that are currently influencing the investment strategy of SWFs. First, the growth of equity markets has shrunk considerably after the financial crisis experienced in 2008. As a consequence, equity markets are no longer as attractive as they used to be (Bortolotti et al., 2015). The second major factor is that oil and gas markets have become more competitive with the introduction of the shale oil and gas revolution in the US. The arrival of shale oil and gas have impacted global energy markets, resulting in significantly lower oil prices in recent years, and thus reducing income for SWFs. Encouraged by the situation, these funds are taking a more active role in the direct management of their assets, and new trends are emerging in their SAA as a result (Alhashel, 2015).

The current context seems to be providing incentives for SWFs to seek long-term returns in more illiquid investments instruments. Among illiquid instruments, investments in natural assets such as timber and farmland have called the attention of some of the biggest SWFs, including both commodity and non-commodity sourced funds. As an example of this, Xuedong (2014) shows how China Investment Corp. - the worlds third largest SWF has announced their interest in including agricultural assets as part of their new investment strategy. Similarly, Cohen and McClelland (2015) report that Angola's US$5 billion SWF is seeking investments in timber and agriculture to diversify it asset allocations and increase returns. Investments in natural assets are not new to SWFs. The New Zealand Superannuation Fund and Canada's Alberta Heritage Fund are SWFs that have been investing in timber assets since 2005. Other SWFs have followed this trend too. The SovereignWealthFundCenter (2015) reports that 14 different SWFs have executed 51 deals into land, farm, forestry and agricultural businesses over the last 10 years, valued over US$ 11.1 billion. These include the Abu Dhabi Investment Council, Singapore's GIC and Temasek Holdings. The reasons for SWFs to invest in these assets are motivated by the potential of increasing returns, stabilizing volatility, providing portfolio diversification and protection against inflation (TheEconomist, 2014). Yet, only a small portion of SWF portfolios is allocated in natural assets due to liquidity concerns. Timberland and farmland are very illiquid assets compared to bonds or stocks. They take a long time to sell and their returns are driven in many cases by a slow biological growth process. This raises the concern of how to re-balance a portfolio with a significant weight on natural assets, making timberland and farmland unsuitable for many investors with horizons shorter than 10 years. Most institutional investors limit allocations in timberland and farmland to 1-5% of their portfolio, with only exceptional investors allocating up to 10% (Binkley et al., 2006). Nevertheless, more recent commercial managers research has started to project that institutional investors may well begin to increase the percentages of portfolio allocation in real assets (which include natural assets) to the range of 15-25% over the next several years (McNamara, 2015; AquilaCapital, 2014; Azelby, 2012).

In view of these considerations, the present analysis examines the effect of including natural assets in the investment strategy of an SWF. We specifically focus on SWFs funded by oil revenues as they represent the largest fraction of this class of investors. The objective in this part of our research work is, therefore, to evaluate the performance of an oil-based SWF when including natural assets in its SAA. To address this objective, the author models the investment portfolio of an SWF over a nine-year period extending from March 2007 to March 2016. The model is developed taking as a case study the portfolio of the world's largest oil funded SWF: The Norwegian Government Pension Fund Global (GPFG). Our findings support the notion that including timber and agricultural investments in the SAA provide high returns, portfolio stability, and resilience against financial downturns. Moreover, we confirm that these assets represent an excellent option for commodity-risk diversification. Based on our results, we argue that SWFs, because of their lower liquidity constraints compared to other investors, can challenge their traditional SAA to increase investments in natural assets. In so doing, these funds can clearly benefit from these investments and ultimately contribute to the preservation of natural wealth.

## 6.1 Literature review on Sovereign Wealth Funds

The literature on SWFs can be grouped into a number of different streams as shown by Alhashel (2015). A significant part of the works on SWFs focuses on the relationship between the investment decisions of these funds, the global financial landscape and the impact of investments on markets stability. Jensen and Seele (2013), for instance, investigate the ethical investment guidelines driving decisions in SWF asset allocations and their impact on corporate behaviour. Beck and Fidora (2008) discuss the wealth transfers of SWFs from developed economies to emerging markets as a result of an asset allocation driven by market capitalization rather than liquidity considerations. Gieve (2009) studies the impact of SWFs on global financial markets and the interaction between global imbalances and the rapid growth of this class of funds. And Balin (2008) evaluates the benefits and critics associated with SWF investments, arguing that these funds can lead to more market liquidity and lower cost of capital. Another group of works focuses on the transparency issue of SWFs. This is the case of Dixon and Monk (2012) who examine the trade-off between transparency and long-term investing strategy of SWFs. Moreover, Kotter and Lel (2011) study the investment strategy of SWFs and its association with the transparency policy. The authors find that transparent SWFs are more likely to invest in financially constrained firms compared to opaque SWFs. Caner and Grennes (2010) argue that the lack of transparency and data limitations in SWFs have made difficult to conduct a systematic analysis of their investment behaviour. The authors also point that the openness of Norway's GPFG has made this particular SWF to be considered as a case study in a large number of analyses.

An important stream of the literature gathers empirical works which examine the SAA of SWFs. Most of these studies indicate that the financial sector has traditionally been, by far, the preferred target of SWFs investments (Johan et al., 2013; Bertoni and Lugo, 2013; Dyck and Morse, 2011; Bortolotti et al., 2013, 2009). Boubakri et al. (2016) perform a comparative study between the SAA of SWFs and pension funds, finding that SWFs are more likely to invest in strategic industries such as the financial sector, natural assets, transportation, and telecommunications. Consistent with Johan et al. (2013), findings suggest that SWFs tend also to prefer countries with sustainable economic growth and weak legal and institutional environment. Miceli (2013) identifies a distinctive behaviour of SWFs when allocating assets across industries in equity markets compared with another type of investors. Fotak et al. (2008) research the financial impact and wealth effect of SWF investments in global stock markets. And Bernstein et al. (2013) analyse how political involvement influences the investment patterns of SWFs, suggesting that funds with higher political involvement tend to support domestic firms in opposition to funds that relies on external managers.

The stream of the literature probably most related to our work addresses SWFs asset allocation models and risk-return analysis. Scherer (2011) shows how to model the optimal asset allocation for an oil-based SWF as a function of the oil extraction policy of the owning country. The author finds that SWFs decision-making problems can be modelled as an optimal asset allocation with endowed and non-tradable wealth. Moreover, Gintschel and Scherer (2008) develop an optimization model for oil-sourced SWF portfolios considering the oil endowment of the owning country as an inherited risk the SWF portfolio wants to diversify; this work provides the theoretical framework to analyse investment decisions of commodity based SWFs. Following this framework, Bertoni and Lugo (2013) build a mean-variance model to statistically test the actual SAA of the GPFG to a theoretical optimum. Their empirical analysis demonstrates that the deviations shown by the GPFG's portfolio are consistent with theoretical predictions, meaning that the SAA of the GPFG takes into account the diversification of the risk linked to Norway's oil reserves. Papaioannou and Rentsendorj (2015) also analyse the SAA of the Norwegian fund using Markowitz portfolio theory. Their analysis suggests that the GPFG's SAA is broadly consistent with the allocations generated by the one-period Markowitz model. Finally, vandenBremer et al. (2016) introduce a new framework to coordinate the management of below- and above-ground sovereign wealth by integrating portfolio allocation theory with precautionary saving and optimal oil extraction under oil price volatility. The authors, in addition, provide suggestions to improve the GPFG management. Regarding the return-to-risk analysis, one of the most prominent works evaluating the GPFG is presented by Ang et al. (2009). In their work, authors show that the optimal SAA is the most significant source of total returns for Norway's fund.

In relation to natural asset investments (i.e. timberland and farmland), several works in the literature have dedicated to studying their effect when included into the investment portfolio of institutional investors. Findings seem nonetheless to be contradicting, suggesting in some cases positive effects and in other cases failing to find evidence of significant improvement. Kaplan (1985) describes the return characteristic of farmland investments and assesses their diversification potential when included as an asset in an investment portfolio. Using Markowitz optimization, the author concludes that farmland investments contribute to improving the efficient frontier of portfolios by providing a higher return-to-risk characteristic. In line with these findings, Lins et al. (2016) found that adding farmland to a portfolio of stocks, corporate bonds, and real estate results in higher risk-adjusted returns. Rubens and Webb (1995) show farmland to be a good inflation hedge and to provide low positive to negative correlation with equities. However, more recent works including Hardin and Cheng (2002) and Hardin and Cheng (2005) suggest that there is no evidence of any significant benefits from including farmland to a portfolio of real estate while using alternative risk assumptions. As for timber assets, a number of studies report improvement in the return-risk characteristic of a portfolio when timber is included. Healey et al. (2005) argue that the unique attributes of timber investments (i.e. higher expected returns, low associated risk, timber's economy, and inflation hedging) allow a portfolio with a timberland component of 10 percent to yield highly positive results. Zhang et al. (2011) and Waggle and Johnson (2009) also find significant benefits when timberland is added into a portfolio of stocks, bonds, and T-bills. On the contrary, the analysis presented by Scholtens and Spierdijk (2010) concludes that, after removing the appraisal smoothing bias from timberland returns, there is no evidence that adding timber into a portfolio mix of traditional assets can increase mean-variance efficiency.

This research work contributes to the latest above-mentioned stream of the SWF literature and with the literature on natural assets investments. By modelling the investment portfolio of an oil-sourced SWF, based on the theoretical framework developed by Gintschel and Scherer (2008) and the methodological approach introduced by Bertoni and Lugo (2013), we test the long-run performance of an SWF portfolio when timber and farmland are included in the SAA. Our findings show that natural asset investments can yield to higher return-risk ratio, diversify commodity risk of price fluctuation, and reduce capital losses, suggesting that these assets can be considered as a serious alternative in the long-time strategy of SWFs. To the best of our knowledge, no analysis in the existing literature examines the effect in the long-term performance of adding natural assets into the SAA of an oil-based SWF.

## 6.2 Case study: Norway's Government Pension Fund Global

Norway is one of the most developed economies in the world. Much of Norway's economic growth has been supported by its abundance of natural resources, including exports of fishery, hydro-power, and most significantly, petroleum products. As for 2015, Norway was ranked the 8th-largest oil exporter in the world, and the 3th-largest natural gas exporter (NPD, 2015). Oil reserves in this country are estimated at 6.5 billion barrels, which roughly translate into a market value of US$ 325 billion (considering a $50 oil barrel). Part of the revenues derived from oil activities is channelled into Norway's SWF: The Government Pension

Fund Global (GPFG). The GPFG is currently the world's largest SWF, managing assets valued in over US\$820bn (SWFI, 2016). Thus, the ratio of oil reserves to aggregated wealth for the Norwegian fund approximates to $\omega = 0.28$. The fund was formally set up in 1990 as a petroleum fund to manage Norway's natural wealth in the long-term and to contribute to Norway's strategy for sustainable development (MinistryOfFinance, 2008b). The idea behind establishing the fund was to channel revenues from oil activities into a diversified portfolio of international securities. Since its inception, the GPFG has received about 3,499 billion kroner (approx. US\$423.6bn at present exchange rate) from oil revenues. Table 6.1 shows the oil production trajectory, together with oil revenues and capital transfer to the fund, experienced by Norway in the past decade. Oil production in Norway has been declining at an average rate of 5% per year since 2005, going from nearly annual 932 MMbarrel to 572 MMbarrel. Revenues perceived from oil are the result of different petroleum-related activities, including taxes, environmental taxes, royalties, government direct participation in the oil business, and dividends from the national oil company Statoil. Total revenues have been fluctuating between US\$ 1,400bn and US\$ 2,700bn per annum, decreasing in the last three years as a result of falling oil prices. The portion of total revenues annually transferred to the fund is estimated to oscillate in the range of 47-87% per year, averaging 67.7% over the past ten years.

The GPFG portfolio model focuses on public traded securities depending mainly on beta returns rather than alpha returns, in contrast with the Swensen model (Chambers et al., 2012). Regarding the most distinctive characteristics, Dimson et al. (2010) and the MinistryOfFinance (2015) highlight the fund's large size, its long-term investment horizon, the absence of specific liabilities, its ownership and governance structure, and its high level of transparency. These characteristics provide the fund with a greater than average risk tolerance that, in combination with an effective SAA, have allowed the GPFG to excel in performance achieving rates of return higher than those of many other equity investors (Caner and Grennes, 2010). The fund's market size has grown approximately 173% over the period Q1 2007 - Q1 2016, reporting an average quarterly return of 1.3% with a volatility

TABLE 6.1: Norway's annual petroleum production, petroleum revenues and capital transferred to the fund Source: Norwegian Petroleum Directorate (NPD, 2015)

| | 2015 | 2014 | 2013 | 2012 | 2011 | 2010 | 2009 | 2008 | 2007 | 2006 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil production (MMbarrels) | | | | | | | | | | | |
| Annual production | 572.2 | 551.9 | 534.3 | 561.1 | 613.4 | 656.6 | 723 | 771.5 | 806.9 | 859.1 | 931.8 |
| Petroleum revenues (US$ bn) | | | | | | | | | | | |
| Taxes | 674.1 | 1,021.2 | 1,204.2 | 1,373.8 | 1,216.3 | 1,022.3 | 1,146.4 | 1,486.8 | 1,249.4 | 1,595.5 | 1,289.6 |
| Environment Taxes | 31.9 | 27.6 | 19.4 | 13.4 | 12.9 | 14.5 | 15.7 | 23.1 | 25.8 | 25.7 | 26.4 |
| Royalties and Area Fees | 12.4 | 9.0 | 10.0 | 10.5 | 9.0 | 9.1 | 10.1 | 11.3 | 5.3 | 17.9 | 4.5 |
| SDFI Net cash flow | 608.4 | 678 | 742.8 | 894.1 | 754.8 | 683.7 | 661.5 | 953.6 | 744.8 | 947.3 | 770.8 |
| Statoil Dividends | 100.1 | 136.2 | 86.4 | 83.2 | 79.1 | 84 | 107.4 | 104.8 | 93.8 | 95 | 63.8 |
| Total Revenues | 1,426.70 | 1,871.9 | 2,062.9 | 2,375.7 | 2,072.0 | 1,813.3 | 1,941.1 | 2,579.9 | 2,119.1 | 2,681.1 | 2,154.9 |
| Capital transferred to GPFG | | | | | | | | | | | |
| Inflows (US$ bn) | - | 882.0 | 1,404.6 | 1,606.6 | 1,519.6 | 1,100.2 | 1,061.6 | 2,164.3 | 1,837.7 | 1,850.3 | 1,419.8 |
| Percentage of revenues (%) | - | 47.1% | 68.1% | 67.7% | 73.3% | 60.7% | 54.7% | 83.9% | 86.7% | 69.0% | 65.9% |

of 5.15%, and an oil sensitivity of 0.11. The SAA of the GPFG is defined by the mandates introduced by NorgesBank (2016). Table 6.2 summarizes the mandates for the Norwegian fund adopted in early 2016. The strategy adopted by the GPFG defines a portfolio invested in three main instruments: equities (61%), fixed-income (36%), and real estate (3%). The equity portfolio is invested in companies listed in recognized marketplaces in Europe (excluding Norway), North America, Asia and Emerging Markets. Top listed companies include Nestle SA, Apple Inc., Roche Holdings AG, Novartis AG, Alphabet Inc., Microsoft Corp., BalckRock Inc., HSBC Holdings Plc, Royal Dutch Shell Plc, Prudential Plc, and Exxon Mobil Corp. The fixed-income portfolio is invested in tradable government and corporate bonds and debt instruments. Due to liquidity risk limits, the mandates dictate that a minimum of 10% of the portfolio shall be held in liquid instruments, defined as treasury bonds issued by the governments of the US, UK, Germany, France, or Japan. Finally, the real estate portfolio is invested according to a policy of geographic diversification including markets in the US, UK, Europe, and Asia. These investments include rights acquisition of office, retail, logistic, and dwelling buildings, but exclude investments in infrastructure projects. The mandates also introduce limits for the management costs as a percentage of assets under management. Limits to the cost are approved in advanced based on estimations for the following year and historically they have not exceeded 0.1% of total assets under management in the last ten years.

## 6.3 Research methodology

### 6.3.1 Analytical model

To address the objective of this part of the research, we model the portfolio of investment of an SWF based on Norway's model and test its performance when including natural asset investments into its SAA. The analysis extends over a 9-year time span starting from Q1 2007 and ending in Q1 2016, discretized on a quarterly basis (37 quarters). For the purpose of this analysis, we are assuming

TABLE 6.2: Mandates adopted by the Government Pension Fund Global in January 2016. Source: NorgesBank (2016)

| Mandate | Description | Percentage Range |
|---|---|---|
| 1 | The fund is to be invested in three asset classes: equities, real estate, and fixed income instruments. | |
| 2 | The fund should be invested aiming to improve the risk-return relationship. | |
| 3 | Exposure to equities of the investment portfolio | 50%-70% |
| 4 | Exposure to Fixed-income instruments | 10%-30% |
| 5 | Exposure to Real Estate of the investment portfolio | 0%-5% |
| 6 | The real estate portfolio shall be diversified in accordance to: | 0%-5% |
| | US | 30%-70% |
| | UK | 10%-40% |
| | Europe (mainly Germany and France) | 0%-20% |
| | Asia (Japan) | 0%-20% |
| | Other countries | 0%-10% |
| 7 | The fund may not be invested in infrastructure (e.g. roads, railways, harbours, airports, and others) | |
| 8 | Management cost shall not exceed 0.1 % of assets under management | |

an oil-funded SWF that wants to diversify its commodity risk. The fund is set up with an initial market value at the beginning of the period that changes over time depending on return on investments, management expenses, and fluctuations in oil revenues. We also assume that the fund follows a global investment strategy with allocations in equity, real estate, and fixed-income instruments. These investments are geographically diversified across North America, Europe, Asia, and Latin America. Equity investments include stock acquisition in listed companies from eight different sectors, namely: consumer goods, consumer services, energy, finance, healthcare, industrial, technology, and utilities. Investments in real estate include property markets in the US, UK, Europe, and Asia. Fixed-income investments have been limited to the US bond market. In addition to these traditional assets, investments in timber and farmland assets are included into the portfolio. Investments in timber refer to the acquisition of trees and forestland, including the operations of growing, harvesting, processing and distributing timber products. Farmland investments encompass the purchase and management of agricultural operations, including crops and livestock.

The performance of the fund over time is assessed by measuring the variations of its size, average quarterly returns, volatility, inflows from oil activities, and portfolio exposure to oil risk. The market value of the fund at time $t$, $v_t$, depends on the size at a previous time instant, and the current difference between inflows and outflows perceived by the fund, expressed as

$$v_t = v_{t-1} + (I_t - C_t), \qquad \forall t \in [1, T] \tag{6.1}$$

where the term $(I_t - C_t)$ represents the difference between inflows and outflows experienced at time $t$. The outflows of the fund are primarily given by the management cost, $C_t$, assumed to be a fraction of the total value of assets under management, given by

$$C_t = \phi M_{t-1} \tag{6.2}$$

where $0 < \phi < 1$. The inflow of the fund, $I_t$, is given by two components: the revenues derived from oil income allocated to the fund, and the returns derived from the global investment portfolio. Oil revenues depend on both export levels, $e_t$, and oil prices, $p_t$, written as

$$r_t = \gamma e_t p_t, \tag{6.3}$$

where $\gamma$ is the fraction of oil revenues allocated to the fund.

The returns on global investments are given by the composite returns obtained for the asset classes equity, $r_t^{eq}$; real estate, $r_t^{re}$; fixed-income, $r_t^{fi}$; and natural assets $r_t^{na}$. If we have $N^{eq}$, $N^{re}$, $N^{fi}$, and $N^{na}$ risky investment alternatives for equity, real estate, fixed-income, and natural assets, respectively, the composite returns for each asset class is computed as

$$r_t^{eq} = \mathbf{z}_t^{eq\mathrm{T}} \mathbf{w}_t^{eq} \tag{6.4}$$

$$r_t^{re} = \mathbf{z}_t^{re\mathrm{T}} \mathbf{w}_t^{re} \tag{6.5}$$

$$r_t^{fi} = \mathbf{z}_t^{fi\mathrm{T}} \mathbf{w}_t^{fi} \tag{6.6}$$

$$r_t^{na} = \mathbf{z}_t^{na\mathrm{T}} \mathbf{w}_t^{na} \tag{6.7}$$

where $\mathbf{z}_t^{eq}$, $\mathbf{z}_t^{re}$, $\mathbf{z}_t^{fi}$ and $\mathbf{z}_t^{na}$ are the vectors containing the individual returns for each equity, real estate, fixed-income, and natural asset, respectively. And $\mathbf{w}_t^{eq}$, $\mathbf{w}_t^{re}$, $\mathbf{w}_t^{fi}$ and $\mathbf{w}_t^{na}$ denote the weights for the equity, real estate, fixed-income, and natural assets portfolio, respectively.

Global efficient portfolios, $\mathbf{w}_{G,t}^{eq}$, $\mathbf{w}_{G,t}^{re}$, $\mathbf{w}_{G,t}^{fi}$ and $\mathbf{w}_{G,t}^{na}$ for each asset class are estimated every quarter taking into account the commodity risk. Following Bertoni and Lugo (2013), we compute the global efficient portfolios using Monte Carlo resampling technique, as described by Michaud (1998). Resampling techniques provide a stronger reduction in the under diversification of the estimated portfolio, particularly when constraints are added to weights (Scherer, 2002). In order to avoid null weights, we impose constraints to the minimum and maximum weights assigned to particular assets. In the case of equities, we apply a minimum of 0.5% and a maximum of 11% for each sub-asset. For real estate, the minimum and maximum weights are 0.5% and 25%, respectively. And for natural assets, a minimum of 10% and a maximum of 90% is imposed. When using resampling, 500 Monte Carlo simulations were run to generate 300 portfolios. In each simulation, the covariance matrix  and the oil sensitivity vector $\mathbf{b}$ are estimated using part of the historical quarter returns for scenario generation, and the rest of the historical data for evaluating the performance of the investment strategy. This technique is referred to as out-of-sample analysis. The optimal portfolio derived from resampling is chosen as the one that maximizes the Sharpe ratio, using US Treasury Bills as the risk-free asset.

By combining Equation (6.3) and Equations (6.4)-(6.7), the inflows of the fund can be expressed as follows

$$I_t = \gamma e_t p_t + v_{t-1}(\alpha^{eq} r_t^{eq} + \alpha^{re} r_t^{re} + \alpha^{fi} r_t^{fi} + \alpha^{na} r_t^{na}), \tag{6.8}$$

where the variables $\alpha^{eq}$, $\alpha^{re}$, $\alpha^{fi}$, and $\alpha^{na}$ are introduced to represent the allocation mandate policy established by the fund to invest in equity, real estate, fixed-income, and natural assets, respectively. Substituting Equations (6.2) and (6.8) into Equation (6.1) and reorganizing, allow us to rewrite the fund market value as

$$v_t = \gamma e_t p_t + v_{t-1}\left[1 + (\alpha^{eq} r_t^{eq} + \alpha^{re} r_t^{re} + \alpha^{fi} r_t^{fi} + \alpha^{na} r_t^{na})\right] - \phi v_{t-1}. \tag{6.9}$$

This equation is used to model and evaluate the growth trajectory of the fund when inputting the data described in the following section.

### 6.3.2 Data and portfolio construction

Following the SAA of the GPFG, the construction of the portfolio considers an investment universe composed of 25 equity markets, 4 real estate markets, and 1 bond market. These investments are assumed to be geographically distributed across North America, Europe, Asia, and Latin America. Table 6.3 shows the detailed investment universe considered in our analysis. The data required to model the investment universe has been obtained from Thomson Reuters and Bloomberg databases, and it consists of historical time series of quarterly returns over a nine-year period (Q1 2007-Q1 2016). Additional 28 observations (Q1 2000-Q4 2006) have been taken to perform the out-of-sample analysis for the first point in the modelled period. Equity investments include stock acquisitions in the sectors of consumer goods, consumer services, energy, finance, healthcare, industrial, technology, and utilities. These investments are proxied using indices from US Dow Jones, Stoxx Euro 600, Thompson Reuters, and MSCI. Investments in real estate include the property markets in the US, UK, Europe, and Asia and South Pacific and their returns are represented by Thompson Reuters property indices from their respective regions. As for fixed income, investments are limited to the US bond market represented in the Barclay's Capital US Aggregated Bond Index.

In addition, based on the mandates adopted by the Norwegian fund, we assume that 60% of total assets is allocated to equities, 35% to fixed-income instruments,

TABLE 6.3: Investment universe for the Sovereign Wealth Fund portfolio model

| Instrument | Index | Data source |
|---|---|---|
| Equity | | |
| Basic Materials North America | Dow Jones US Basic Materials Index | Thomson Reuters |
| Basic Materials Europe | STOXX EUR 600 Basic Materials Index | Thomson Reuters |
| Basic Materials Asia | Thomson Reuters Asia/Pacific Basic Materials Index | Thomson Reuters |
| Consumer Goods North America | Dow Jones US Consumer Goods Index | Thomson Reuters |
| Consumer Goods Europe | STOXX EUR 600 Consumer Goods Index | Thomson Reuters |
| Consumer Goods Asia | Dow Jones Asia/Pacific Consumer Goods Index | Thomson Reuters |
| Consumer Services North America | Dow Jones US Consumer Services Index | Thomson Reuters |
| Consumer Services Europe | STOXX EUR Consumer Services Index | Thomson Reuters |
| Consumer Services Asia | Dow Jones Asia/Pacific Consumer Services Index | Thomson Reuters |
| Energy North America | Thomson Reuters US Energy Index | Thomson Reuters |
| Energy Europe | Thomson Reuters EUR Energy Index | Thomson Reuters |
| Energy Asia | Dow Jones Asia/Pacific Oil & Gas Index | Thomson Reuters |
| Financial North America | Dow Jones US Financial Services Index | Thomson Reuters |
| Financial Europe | STOXX EUR 600 Financial Services Index | Thomson Reuters |
| Financial Asia | Thomson Reuters Asia/Pacific Financial Services Index | Thomson Reuters |
| Health Care North America | Dow Jones US Health Care Index | Thomson Reuters |
| Health Care Europe | STOXX EUR 600 Health Care Index | Thomson Reuters |
| Health Care Asia | MSCI All country Asia/Pacific Health Care Index | Thomson Reuters |
| Industrial North America | Dow Jones US Industrial Index | Thomson Reuters |
| Industrial Europe | STOXX 600 Industrial Index | Thomson Reuters |
| Industrial Asia | Dow Jones Asia/Pacific Industrial Index | Thomson Reuters |
| Technology North America | Dow Jones US Technology Index | Thomson Reuters |
| Technology Europe | STOXX 600 Technology Index | Thomson Reuters |
| Technology Asia | Thomson Reuters Asia/Pacific Technology Index | Thomson Reuters |
| Utility North America | Dow Jones US Utility Index | Thomson Reuters |
| Utility Europe | STOXX 600 Utility Index | Thomson Reuters |
| Utility Asia | Thomson Reuters Asia/Pacific Utilities Index | Thomson Reuters |
| Telecommunications North America | Dow Jones US Telecom Sector Index | Thomson Reuters |
| Telecommunications Europe | STOXX EUR 600 Telecom Index | Thomson Reuters |
| Telecommunications Asia | Thomson Reuters Asia/Pacific Technology Index | Thomson Reuters |
| Equities overall Latin America | MSCI Latin America Price Index | Thomson Reuters |
| Real Estate | | |
| North America | Thomson Reuters US Property Index | Thomson Reuters |
| UK | Thomson Reuters UK Property Index | Thomson Reuters |
| Europe (ex. UK) | Thomson Reuters Europe (ex. UK) Index | Thomson Reuters |
| Asia | Thomson Reuters Asia Property Index | Thomson Reuters |
| Fixed-income | | |
| North America | Barclays Capital US Aggregated Bond Index | Blomberg |
| Natural Assets | | |
| Timberland | NCREIF Timberland Property Index | NCREIF website |
| Farmland | NCREIF Farmland Index | NCREIF website |

and 5% to real estate. This strategic asset allocation is referred as the baseline portfolio in the remainder of the analysis, and it constitutes the benchmark to compare the performance of other investment portfolios. In addition to the aforementioned traditional asset classes, we include investments is timberland and farmland assets. Investments in timberland and farmland can be broadly classified into privately and publicly held assets investments, with each of them exhibiting different performance profiles in terms of risk and returns (Riddiough et al., 2005). Private equity investments in timberland and farmland are generally targeting at institutional investors and their performance is captured by the NCREIF indexes. The NCREIF indexes consist of quarterly time series composite returns of the investment performance of a large pool of individual timber and agricultural properties in three regions of the United States: the South, Northeast, and Pacific Northwest. Returns on the NCREIF Timberland and Farmland Indexes are determined by the income and appreciation returns on the timber and farm properties managed by Timberland Investment Management Organizations (TIMOs) and Farmland Investment Trusts in the US, respectively. Income returns arise from sales of timber and farm products according to production, whereas appreciation returns results from timber, farm and land appreciation. NCREIF indexes are computed based on the appraisal of recent property transactions; therefore, the indexes suffer from appraisal smoothing bias that makes the volatility of the observed returns too low in comparison to the true unobserved returns (Scholtens and Spierdijk, 2010). To avoid an over-optimistic picture of the diversification potential of the NCREIF indexes, we consider unsmoothed index returns using the unsmoothing approach introduced by Fisher et al. (1994) (see Appendix E). In doing so, the volatility condition adopted is based on the assumptions that the volatility of commercial timber and farm properties is approximately 1/2 the volatility of the S&P500 Index.

### 6.3.3 Portfolio analysis

The performance analysis is done by developing a simulation model in Matlab of the investment portfolio of an SWF funded by the revenues derived from oil activities. The revenues from oil activities are modelled using historical trajectories of oil production in Norway (Table 6.1) as reported by the Norwegian Petroleum Directorate (NPD, 2015), and historical time series of quarterly oil prices using the Brent Spot FOB as a reference. The oil inflows to the fund are assumed to be given by a constant fraction of 70% of total oil revenues. This fraction is introduced based on the average relationship between the oil inflows reported by the GPFG and the total oil revenues from oil activities reported by the Norwegian government between 2007 and 2014. The test case fund is set up with an initial market value of $305.4bn at the beginning of the evaluation period. This number is in line with the market value of the GPFG reported during the first quarter of 2007. Total management cost per quarter has been considered to be 0.02% of the total value of assets under management. This consideration is based on the average quarterly costs reported by the Norwegian fund between 2004 and 2015.

In order to evaluate the effects of including timber and farmland investments in the SWF allocation strategy, 16 different portfolios are analysed. Table 6.4 provides a description of the different portfolios compared in our analysis. The different portfolios include the baseline portfolio (portfolio 1) and the portfolios resulting from displacing investments from traditional assets into natural assets at three different levels: 15%, 20%, and 25%. Therefore, we find the cases when supplanting equity investments (portfolios 2-4), fixed-income investments (portfolios 5-7) and real estate investments (portfolios 8-10) by investments in natural assets. These portfolios have been chosen to compare the effects that natural assets replacement has when applied to the different traditional asset classes. In addition, we consider the portfolios resulting from reducing equity investments at the expenses of increasing investments in fixed-income (portfolio 11-13) and real estate (portfolios 14-16) while excluding allocations in natural assets. These portfolios are considered with the purpose of comparing the effects of displacing equity investments into another traditional asset class rather than into natural assets. Each of the tested portfolios is ranked based on their performance when considering net growth, average returns, overall risk (i.e. considering oil and financial assets), maximum draw down, and the portfolio exposure to oil sensitivity. Additionally, we examine the effects that oil risk has over the oil inflows to the fund and its contribution to market value growth.

## 6.4 Results

### 6.4.1 Analysis of asset returns

We begin our analysis by comparing the performance of historical returns of the different assets considered in our investment universe. Table 6.5 shows the descriptive statistics of the assets quarterly returns based on their historical performance during the period Q1 2007- Q1 2016. From the table, it can be observed that different assets exhibit significant different performance. North American equities

Table 6.4: Strategic asset allocation of the evaluated portfolios

| Portfolio | Description | Strategic Asset Allocation | | | |
|---|---|---|---|---|---|
| | | Eq | Fi | Re | Na |
| **1** | **Baseline. No natural assets included.** | **60.00%** | **35.00%** | **5.00%** | **0.00%** |
| 2 | Shifting 15% of Eq into Na | 51.00% | 35.00% | 5.00% | 9.00% |
| 3 | Shifting 20% of Eq into Na | 48.00% | 35.00% | 5.00% | 12.00% |
| 4 | Shifting 25% of Eq into Na | 45.00% | 35.00% | 5.00% | 15.00% |
| 5 | Shifting 15% of Fi into Na | 60.00% | 29.75% | 5.00% | 5.25% |
| 6 | Shifting 20% of Fi into Na | 60.00% | 28.00% | 5.00% | 7.00% |
| 7 | Shifting 25% of Fi into Na | 60.00% | 26.25% | 5.00% | 8.75% |
| 8 | Shifting 15% of Re into Na | 60.00% | 35.00% | 4.25% | 0.75% |
| 9 | Shifting 20% of Re into Na | 60.00% | 35.00% | 4.00% | 1.00% |
| 10 | Shifting 25% of Re into Na | 60.00% | 35.00% | 3.75% | 1.25% |
| 11 | Shifting 15% of Eq into Fi | 51.00% | 44.00% | 5.00% | 0.00% |
| 12 | Shifting 20% of Eq into Fi | 48.00% | 47.00% | 5.00% | 0.00% |
| 13 | Shifting 25% of Eq into Fi | 45.00% | 50.00% | 5.00% | 0.00% |
| 14 | Shifting 15% of Eq into Re | 51.00% | 35.00% | 14.00% | 0.00% |
| 15 | Shifting 20% of Eq into Re. | 48.00% | 35.00% | 17.00% | 0.00% |
| 16 | Shifting 25% of Eq into Re | 45.00% | 35.00% | 20.00% | 0.00% |

Note. Eq: Equity; Re: Real estate; Fi: Fixed-income; Na: Natural assets

and real estate registered a better performance compared with their similar markets in Europe and Asia, exhibiting generally higher average returns and lower volatilities. The best performances within equities, when considering the Sharpe ratio, were found for North American consumer goods (0.209), consumer services (0.226), healthcare (0.250), and technology (0.166). These relatively high ratios may promise preference toward these assets when allocating weights within equities. Other equity markets exhibiting a moderate performance includes European consumer goods (0.129) and healthcare (0.182), and Asian consumer goods (0.012). Real estate markets, excluding the North American market, did not perform well during the examined period showing negative average returns and high levels of volatility. Particularly, the UK real estate (-0.086) and European real estate (-0.030) markets presented some of the lowest Sharpe ratios, together with the Asian property market (-0.028). On the contrary, the US bond market exhibits one of the best performances among the assets in our universe, registering an average quarterly return of 1.14%, a volatility of 1.60%, and a Sharpe ratio of 0.603. Unsmoothed timber and farmland are among the assets with higher returns and lower volatility too, comparable with the best performing equities and the US bond market. The average quarterly return for unsmoothed timberland and farmland during the considered period were 1.40% and 2.79%, respectively, with a standard deviation of 3.73% and 3.20% in each case. The Sharpe ratios of timber (0.329) and farmland (0.816) confirm their good performance, ranking within the top three performing assets together with the US bond market.

Table 6.5: Historical performance of quarterly returns for assets in our investment universe, Q1. 2007 - Q1. 2016

| Asset | Mean | Std Dev | Sharpe ratio | Oil sensitivity | Correlation with oil |
|---|---|---|---|---|---|
| N. America Consumer goods | 1.70% | 7.27% | 0.209 | 0.11 | 0.34 |
| N. America Consumer services | 2.08% | 8.43% | 0.226 | 0.138 | 0.368 |
| N. America Energy | -0.31% | 12.69% | -0.038 | 0.395 | 0.698 |
| N. America Financial | -0.63% | 13.39% | -0.06 | 0.279 | 0.467 |
| N. America Health care | 2.03% | 7.42% | 0.25 | 0.126 | 0.38 |
| N. America Industrial | 1.35% | 11.06% | 0.106 | 0.222 | 0.451 |
| N. America Technology | 1.82% | 9.90% | 0.166 | 0.256 | 0.581 |
| N. America Utilities | 0.82% | 7.81% | 0.082 | 0.083 | 0.238 |
| Europe Consumer goods | 1.42% | 9.59% | 0.129 | 0.194 | 0.454 |
| Europe Consumer services | 0.37% | 8.35% | 0.023 | 0.031 | 0.083 |
| Europe Energy | -1.49% | 13.19% | -0.126 | 0.369 | 0.628 |
| Europe Financial | -0.86% | 14.08% | -0.074 | 0.334 | 0.532 |
| Europe Health care | 1.46% | 7.07% | 0.182 | 0.148 | 0.469 |
| Europe Industrial | 0.39% | 13.13% | 0.016 | 0.313 | 0.535 |
| Europe Technology | -0.22% | 12.43% | -0.032 | 0.257 | 0.464 |
| Europe Utilities | -1.71% | 10.94% | -0.173 | 0.24 | 0.492 |
| Asia Consumer goods | 0.28% | 8.74% | 0.012 | 0.229 | 0.588 |
| Asia Consumer services | 0.47% | 7.94% | 0.037 | 0.119 | 0.336 |
| Asia Energy | -0.51% | 13.66% | -0.05 | 0.44 | 0.723 |
| Asia Financial | -0.54% | 27.88% | -0.026 | 0.454 | 0.365 |
| Asia Health care | 0.90% | 8.21% | 0.088 | 0.058 | 0.157 |
| Asia Industrial | -0.08% | 11.29% | -0.023 | 0.285 | 0.566 |
| Asia Technology | 0.16% | 11.19% | -0.002 | 0.256 | 0.514 |
| Asia Utilities | -0.53% | 7.00% | -0.1 | 0.007 | 0.022 |
| Latinamerica All Equities | -0.89% | 16.06% | -0.067 | 0.502 | 0.702 |
| NorthAmerica (Real Estate) | 1.27% | 7.66% | 0.143 | 0.061 | 0.179 |
| UK (Real Estate) | -1.04% | 14.09% | -0.086 | 0.123 | 0.195 |
| Europe (Real Estate) | -0.25% | 13.97% | -0.03 | 0.237 | 0.381 |
| Asia (Real Estate) | -0.08% | 9.29% | -0.028 | 0.178 | 0.429 |
| NorthAmerica (Bonds) | 1.14% | 1.60% | 0.603 | -0.02 | -0.286 |
| Timberland (Unsmoothed) | 1.40% | 3.73% | 0.329 | 0.01 | 0.058 |
| Farmland (Unsmoothed) | 2.79% | 3.20% | 0.816 | 0.004 | 0.029 |

When examining the relationship of assets with oil risk (last two columns in Table 6.5), we find that the oil sensitivity for North American bonds (-0.020), timberland (0.010), and farmland (0.004) are very low or even negative compared with the rest of the assets. Thus, placing allocations among these assets may provide advantages in hedging oil price risk. We can expect higher weights to be allocated, in particular, to those assets with lower oil sensitivity and higher expected return. Other assets exhibiting low oil sensitivity includes North American real estate (0.061), North American utilities (0.083), Europe consumer services (0.031), and Asian healthcare (0.058) and utilities (0.007). Some of these assets, however, also present significantly low or even negative expected returns. Therefore, they are unlikely to have an impact on the asset allocation. North American consumer goods (0.110), consumer services (0.138) and healthcare (0.126), European consumer goods (0.194), healthcare (0.148) and utilities (0.240), and Asian consumer services (0.119) and technology (0.256) are among the assets exhibiting a moderate oil sensitivity. While energy, financial, and industrial sectors in all the geographical zones, together with the Latin American equity market, show significantly higher levels of oil sensitivity. Moderate and high levels of oil sensitivity may be tolerated depending on whether assets promise high levels of return or not. From the initial examination of the historical performance of the data, we can expect that portfolios with a significant component of those assets with low oil sensitivity and high Sharpe ratio, could in principle lead to better performance of the overall portfolio.

### 6.4.2 Analysis of the SWF performance

Figure 6.2 shows the performance of the modeled SWF when using the SAA defined by the baseline portfolio (portfolio 1, excluding natural assets) during the evaluated period. The figure also compares this with the actual performance registered by the GPFG during the same period. From the figure, it can be observed that our baseline portfolio mirrors the behaviour of the GPFG. The correlation between the returns of the baseline portfolio and the GPFG is 0.951, and the correlation between their market value trajectories is 0.996. This represents a fairly good approximation of the Norwegian fund for the purpose of our analysis. A more precise replication of its behaviour would require more detailed data of the GPFG's allocation strategy. The market value of the modelled fund when using the baseline portfolio was steadily increasing until the last quarter of 2007. As a consequence of the financial crisis, significant negative returns were experienced during the period Q4 2007-Q3 2008, resulting in a fall of the fund value due to the downturn of global markets. From the summer of 2009, the fund started to recover again continuously growing until the first quarter of 2014 when the market value stabilized due to the fall of oil prices. Using the baseline portfolio, the SWF experienced a net growth of 191.5% on its market value, going from its initial US\$ 305.4 bn in Q1 2007 to US\$ 890.2 bn in Q1 2016. Total returns of the portfolio averaged 0.67% per quarter (2.7% a year) with a volatility of total wealth (oil and financial assets) of 9.2%. The average return to overall risk ratio achieved is 0.072 and the oil exposure of the overall portfolio is 0.138, with a high positive correlation with oil prices of 55.5%. When introducing changes in the SAA of the baseline portfolio, significant variations in the performance of the SWF were found. Table 6.6 summarizes the results obtained for the sixteen different portfolios tested. The table ranks the portfolios according to their performance as reflected by the return to overall risk ratio, where the overall risk is defined in Equation (3.12) to consider the aggregated wealth. A careful examination of the figures in the table allows extracting some interesting observations.

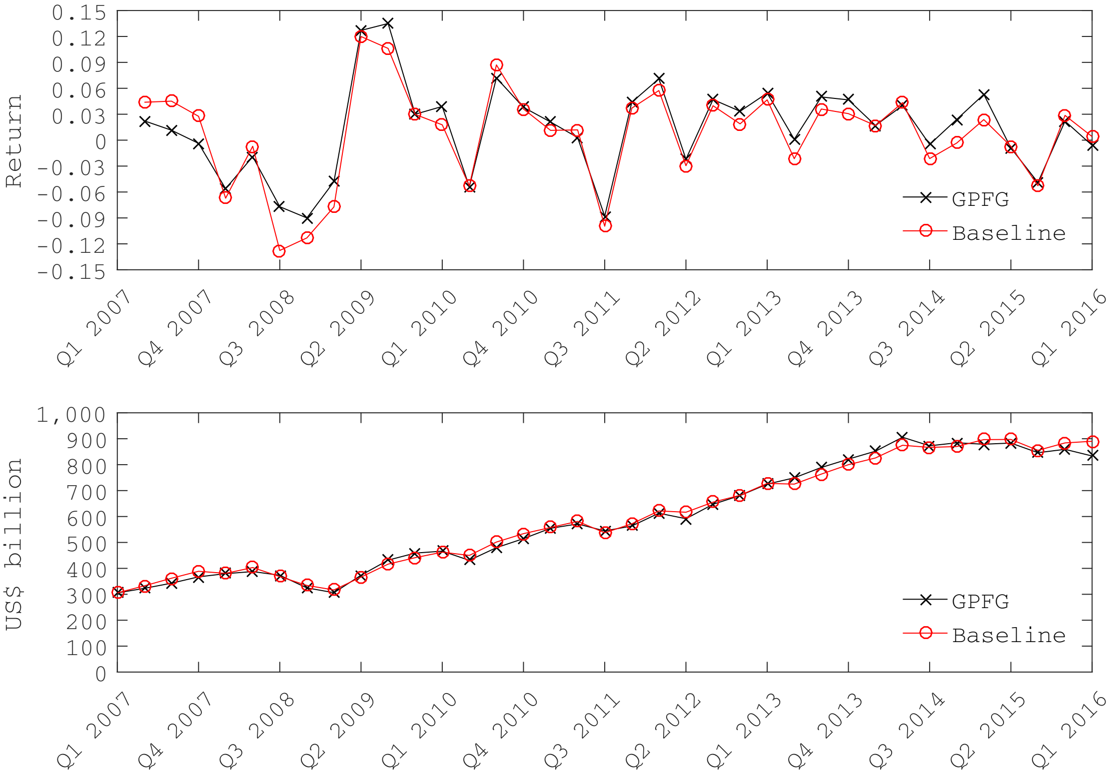


FIGURE 6.2: Returns and market value evolution for the baseline portfolio (Eq=60%, Fi=35%, Re=5%) and the GPFG, Q1. 2007 - Q1. 2016

First, out of the sixteen portfolios analysed, the baseline portfolio is ranked 13 (shown in bold in the table) suggesting that most changes of transferring equity investments into another asset type actually benefit the SWF performance. This observation is particularly true when equity investments are replaced by investments in natural assets (portfolios 2, 3, 4) or fixed-income instruments (portfolios 11, 12, 13). However, the observation does not hold true when the replacement

Table 6.6: Statistics on the performance of the tested portfolios ranked according to the risk to overall return ratio

| Portfolio | Average Q-return | Financial Volatility | Financial Sharpe ratio | Max. Drawdown | Oil correlation | Growth | Oil exposure | Overall Risk | Return / Over. Risk ratio |
|---|---|---|---|---|---|---|---|---|---|
| 4 | 0.96% | 4.33% | 0.1881 | 28.3% | 0.547 | 218.4% | 0.1047 | 0.0846 | 0.114 |
| 3 | 0.90% | 4.59% | 0.1649 | 30.5% | 0.550 | 212.9% | 0.1114 | 0.0861 | 0.105 |
| 2 | 0.84% | 4.84% | 0.1440 | 32.7% | 0.552 | 207.5% | 0.1180 | 0.0876 | 0.096 |
| 13 | 0.77% | 4.31% | 0.1442 | 29.1% | 0.527 | 201.0% | 0.1005 | 0.0840 | 0.091 |
| 12 | 0.75% | 4.57% | 0.1316 | 31.1% | 0.534 | 199.1% | 0.1080 | 0.0856 | 0.087 |
| 7 | 0.78% | 5.64% | 0.1122 | 38.8% | 0.563 | 201.1% | 0.1404 | 0.0926 | 0.084 |
| 11 | 0.73% | 4.83% | 0.1203 | 33.1% | 0.541 | 197.3% | 0.1155 | 0.0872 | 0.083 |
| 6 | 0.76% | 5.64% | 0.1083 | 38.9% | 0.562 | 199.2% | 0.1399 | 0.0925 | 0.082 |
| 5 | 0.73% | 5.63% | 0.1044 | 39.0% | 0.560 | 197.2% | 0.1394 | 0.0924 | 0.079 |
| 10 | 0.70% | 5.52% | 0.0998 | 38.2% | 0.557 | 193.6% | 0.1360 | 0.0917 | 0.076 |
| 9 | 0.69% | 5.54% | 0.0984 | 38.4% | 0.557 | 193.2% | 0.1364 | 0.0918 | 0.075 |
| 8 | 0.69% | 5.56% | 0.0969 | 38.6% | 0.556 | 192.8% | 0.1368 | 0.0919 | 0.075 |
| **1** | **0.67%** | **5.62%** | **0.0925** | **39.2%** | **0.555** | **191.5%** | **0.1379** | **0.0922** | **0.072** |
| 14 | 0.62% | 5.57% | 0.0848 | 39.9% | 0.535 | 191.5% | 0.1318 | 0.0914 | 0.068 |
| 15 | 0.60% | 5.56% | 0.0821 | 40.1% | 0.528 | 191.4% | 0.1298 | 0.0911 | 0.066 |
| 16 | 0.59% | 5.56% | 0.0793 | 40.3% | 0.520 | 191.4% | 0.1277 | 0.0909 | 0.065 |

is done in real estate. Reducing equity investments to increase allocations in real estate was found to be counterproductive as the resulting portfolios (portfolios 14, 15, 16) underperformed the baseline portfolio. Second, the best performance results from replacing equity investments with natural asset investments (portfolios 2, 3 and 4) rather than fixed-income or real estate. Increasing allocations in natural assets at the expenses of reducing equity investments, contribute to significantly improve all the performance indicators. Moreover, it is found that the higher the percentage displaced from equities into natural assets, the better the performance. For instance, when 15% of the Equity allocation is shifted to natural assets (portfolio 2), the return-to-overall risk ratio of the portfolio improved from 0.072 to 0.096. The maximum drawdown was diminished from 39.2% to 32.7%, allowing a faster recovery of the market value to the pre-crisis level. And the net growth in market valued was enhanced from 191.5% to 207.5%. The oil exposure of the overall portfolio is also decreased from 0.1379 to 0.1180. These improvements in the indicators are even higher when shifting 25% of equity allocations into natural assets (portfolio 4). In this case, the return-to-risk ratio is improved to 0.114, the maximum drawdown is reduced to 28.3%, the net growth is enlarged to 218.4%, and the oil exposure is reduced to 0.1047, registering the best performance among all the portfolios compared. The second best effects are observed when moving equity investments into fixed-income (portfolios 11, 12 and 13). Although all the indicators show significant improvements compared with the baseline portfolio too, the level of improvement is not as high as the one achieved with natural assets.

Finally, portfolios including natural asset investments, in general, perform better compared with those without natural assets. No portfolio containing allocations in natural assets underperform the baseline. Among those portfolios with natural assets component, those ones in which natural assets replace real estate (portfolios 8, 9, 10) rank the lowest. This is due to the low fraction allocated to these assets. In this sense, it is observed that the net benefits of including natural asset investments is subjected to the structure of the investment portfolio. Those portfolios in which natural assets investments are included at the expenses of reducing allocation in equities, tend to capitalise greater net benefits in terms of the metrics considered. Whereas portfolios with reduced real estate share in sake of including allocations in natural assets experienced less net benefits.

We now focus attention on those portfolios resulting from displacing 25% of equity investments into natural assets (portfolio 4), fixed income (portfolio 13) and real estate (portfolio 16) respectively, together with the baseline portfolio. Figure 6.3 shows the quarterly returns and market value trajectories for these portfolios. The figure illustrates how portfolio 4 (Eq=45%, Fi=35%, Re=5%, Na=15%) exhibits the best performance, achieving an average return 0.29% higher, an overall volatility 0.76% lower, and a growth 27% greater compared to the baseline. Portfolio 13 (Eq=45%, Fi=50%, Re=5%, Na=0%) also improves the performance relative to the baseline portfolio providing an average return 0.1% higher, an overall volatility 0.82% lower and a net growth 9.5% larger. Yet the improvement provided by this portfolio is still lower compared to portfolio 4. As for portfolio 16 (Eq=45%, Fi=35%, Re=20%, Na=0%), its effects on the performance were rather negative. Despite the overall risk decreased 0.14%, the average return also decreased 0.08%, providing a return-to-risk ratio 0.008 lower and shrinking growth in 0.1% in comparison to the baseline.

In Figure 6.4, we present the global efficient allocations for portfolio 4 across the evaluation period. Efficient allocations in equity are well diversified among the different sectors. Some of the sectors that receive the greatest weights steadily throughout the period include North America consumer good, European consumer goods and healthcare, and Asian energy and utilities. That is, in general, sectors

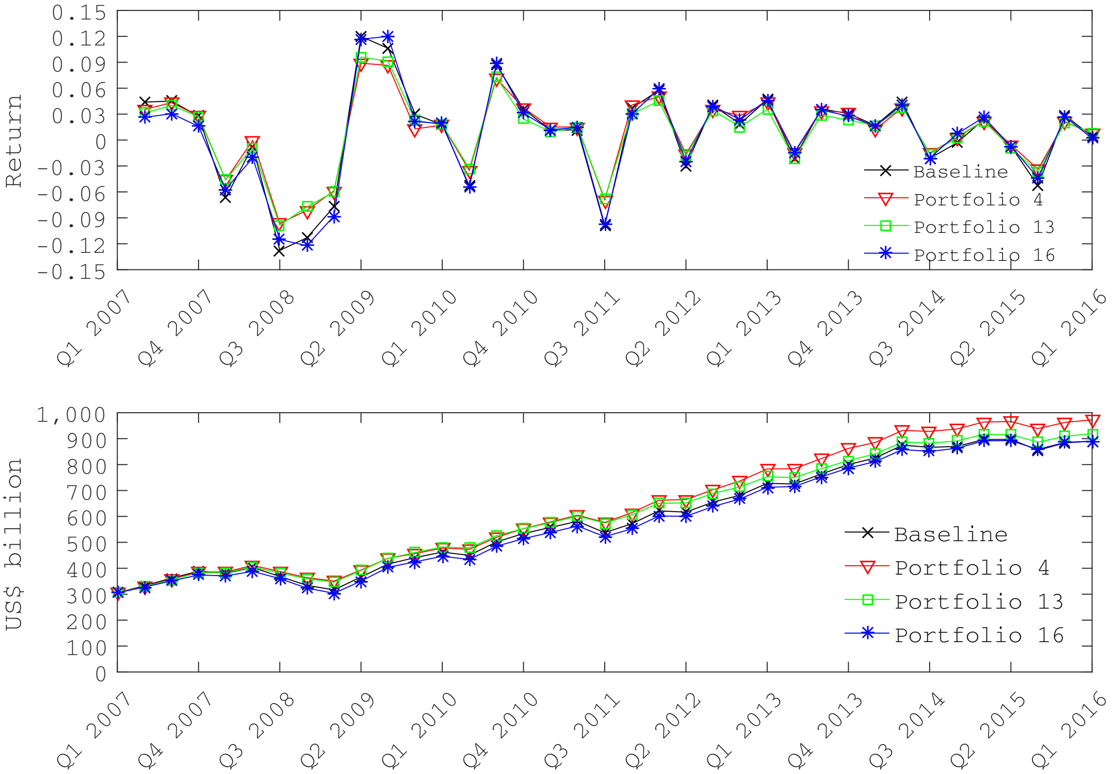


FIGURE 6.3: Returns and market value evolution for portfolios 1, 4, 13 and 16, Q1. 2007 - Q1. 2016

with lower oil sensitivity and higher expected returns. Sectors with a relatively low expected return and high volatility, such as European and Asian consumer services, or sectors with a high oil sensitivity compared to their Sharpe ratio such as finance, industrial and technology in the three continents, receive low weights during the whole period. Other sectors with a variable performance, such as North American healthcare and utilities, and Asian healthcare, received low weight during the quarters close to the crisis that progressively increased in the quarters after the crisis. A contrary behaviour is observed for Latin American equity, which receives significant weights during the crisis quarters that diminish in the most recent quarters. As for real estate markets, the highest weights are given to the North American, European and Asian markets, while the UK receives the lowest weight staying almost invariant during the examined period. The weights given to the fixed income instrument remain constant (35%) as only one asset is considered in this category. Regarding the natural asset components, we find that farmland is noticeably favoured receiving the largest proportion of the allocation along the period, while timberland receives the smallest one. Farmland returns are associated with a higher expected return and lower oil sensitivity when compared with timberland.

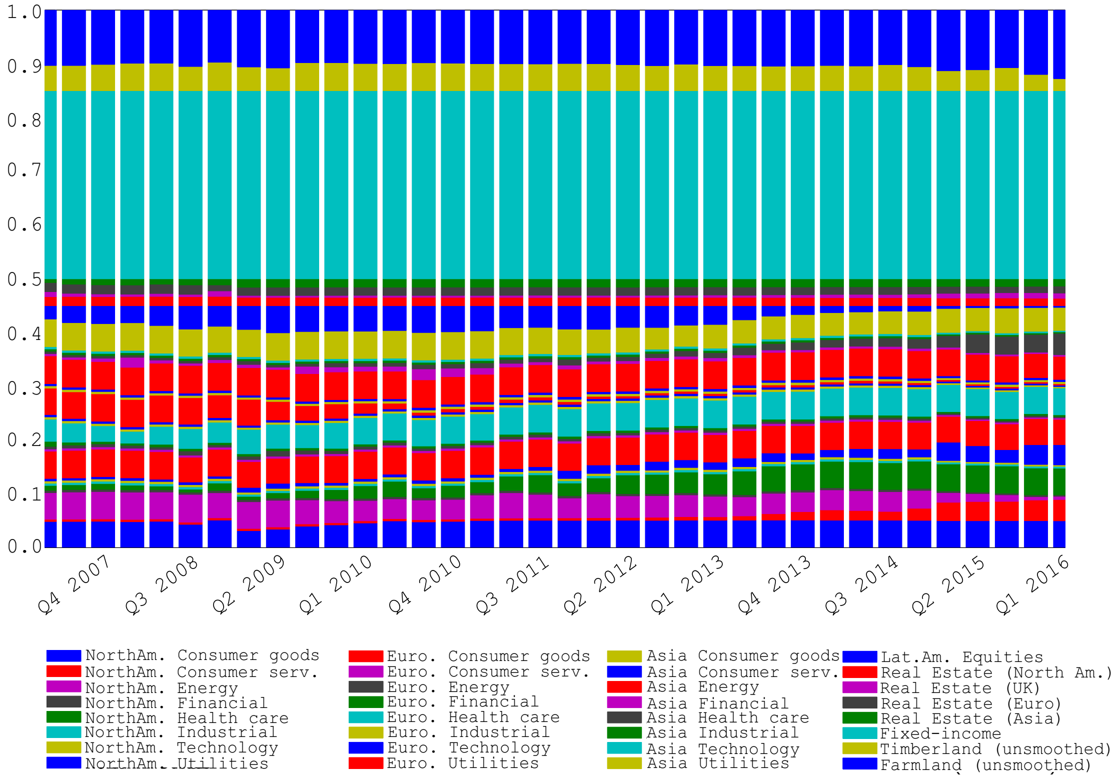


FIGURE 6.4: Globally efficient allocations for portfolio 4 (Eq=45%, Fi=35%, Re = 5%, Na=15%)

### 6.4.3 Oil exposure analysis

Oil inflows to the fund are a direct expression of the oil risk. Figure 6.5 shows the oil inflows perceived by our modelled SWF during the studied period. Inflows to the fund were steadily increasing until the second quarter of 2008, driven by the rapid rise of oil prices experienced in the quarters before the crisis. By the second half of 2008, oil prices plummeted from approximately US$140 to just US$39.9 per barrel. As a result, inflows to the fund were severely affected too, falling nearly 70% from US$ 25.3bn in Q2 2008 to only US$ 7.7bn in Q4 2008. From the first quarter of 2009, with the partial recovery of oil prices inflows exhibited a slow growth that extended until Q1 2011, when it reached US$ 17.8bn. Since early 2011, inflows started to progressively fall again until reaching their lowest value of US$ 2.9bn at the beginning of 2016. The fall was particularly significant after the second quarter of 2014, affected by the conditions experienced in oil markets during the recent years. In Figure 6.6, we illustrate the normalized cumulative value of oil inflows received by the fund since the beginning of the evaluation period. In addition, we also compare the inflow with the normalized growth trajectory of the fund when using the baseline portfolio (our reference) and portfolio 4 (the best performing). The cumulative capital transferred to the fund was increasing at an average rate of 5.2% per quarter from Q2 2007 to Q2 2008. After the second quarter of 2008, the increase of capital transfer slowed down to an average of 2.5% per quarter until Q2 2014. The growth rate was slowed further after the second half of 2014, as a result of the collapse of oil prices, averaging only 0.8% per quarter from Q3 2014 to Q1 2016. The speed at which the cumulative value of oil inflows increases is affected by the oil risk. Higher prices of oil would in principle lead to a rapid increase, while lower prices would slow it down.

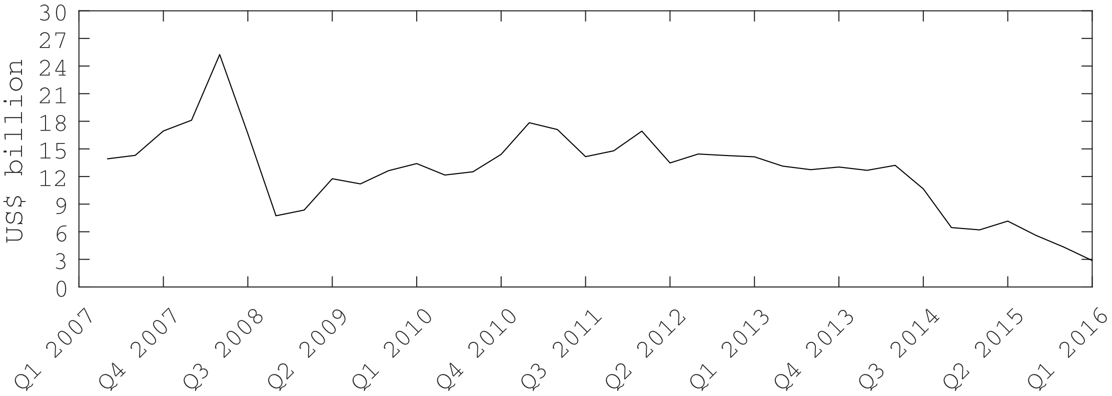


FIGURE 6.5: Oil inflows perceived by the Sovereign Wealth Fund

The hedging capability of the investment portfolio against the oil risk, together with its expected return, contributes to the speed at which the portfolio grows. A portfolio presenting better hedging properties is able to offset oil risk, and therefore, reduce losses from oil prices fall. The analysis of the oil exposure for the tested portfolios reveals that a portfolio with natural assets can provide significant hedging against oil risk compared to the baseline. Figure 6.7 presents the oil exposure registered for portfolios 1, 4, 13, and 16 across the evaluation period. For the different portfolios examined, the SWF registered a negative exposure to

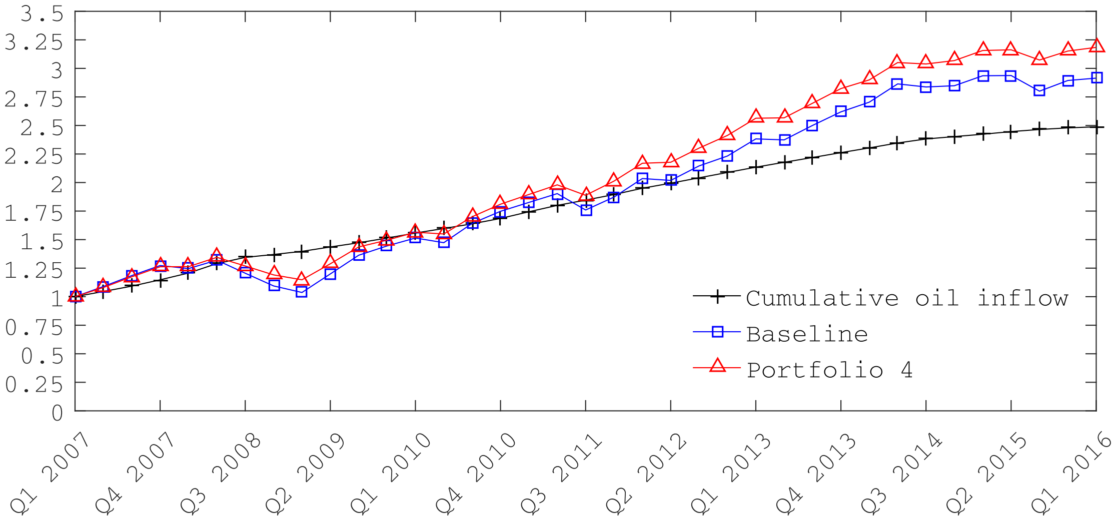


FIGURE 6.6: Normalized cumulative capital transferred to the fund and portfolio growth

the commodity risk until the third quarter of 2008. When oil prices were rising and global financial markets were performing well, the allocation strategies defined by the global portfolios allow the allocations to exhibit the negative oil sensitivity necessary to output a negative exposure. The baseline portfolio, in this case, presented the least negative exposures averaging -0.0060 between Q2 2007 and Q3 2008. A portfolio in which 25% of equities allocations are replaced by natural assets (portfolio 4) exhibits a more negative exposure during the same period with an average of -0.0161. An even greater improvement is obtained for the cases in which the 25% of equity investments are shifted to fixed income (portfolio 13) or real estate (portfolio 16) averaging -0.0221 and -0.0275, respectively. After the final quarter of 2008, oil prices failed together with most equity markets. As a result, a positive exposure is exhibited for the portfolios during the remaining quarters. In this case, the baseline portfolio presents the highest exposure to oil risk, averaging 0.1159 during the period Q4 2008-Q1 2016. Portfolio 4, which include natural assets, significantly reduces the oil exposure compared to the baseline. The average exposure for this portfolio was reduced to 0.0855 for the same period. It is worth noticing here, that the reduction achieved by portfolio 4 (0.030) compared to the baseline is comparable with that of portfolio 13 (0.033), which provides the minimum exposure among all portfolios compared with an average of 0.0828. From this figure, we can observe that natural assets, given their lower sensitivity with oil risk, can contribute to reducing the oil exposure of the overall portfolio. This observation shows the hedging property associated with natural asset investments.

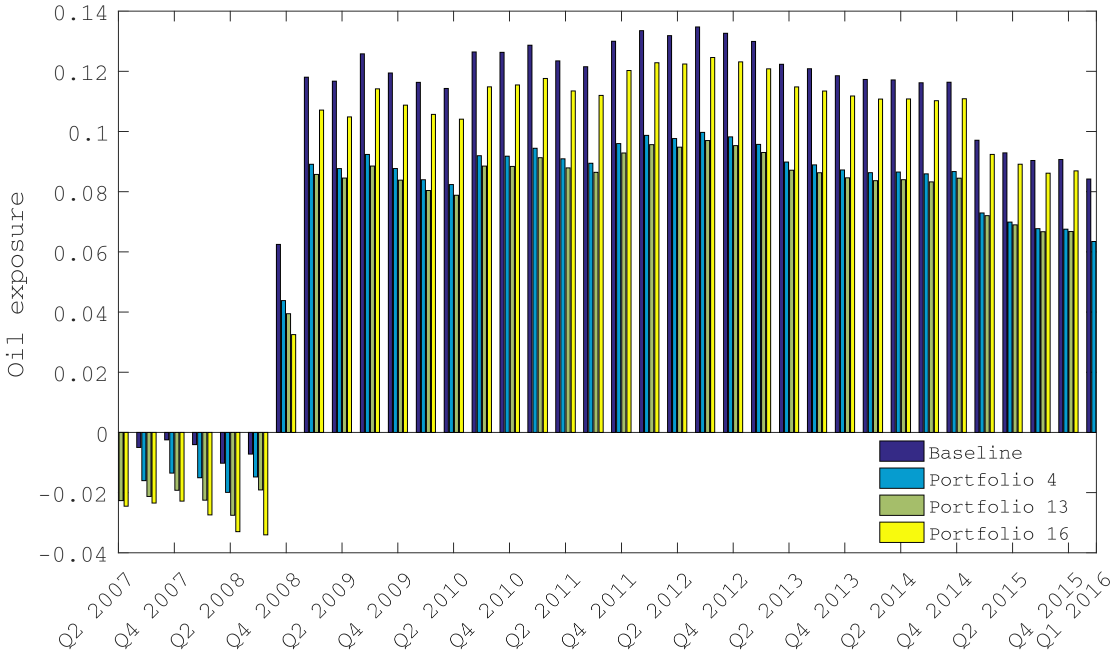


FIGURE 6.7: Oil risk exposure for portfolios 1, 4, 16 and 16

## 6.5 Discussion

In this part of our research, we have examined the effect of including natural assets (i.e. timber and farmland) in the SAA of an oil-sourced SWF. We model the investment portfolio of the fund following the theoretical approach introduced by Gintschel and Scherer (2008) and assess its performance based on growth rate, average return, volatility, and portfolio exposure to oil risk during the period Q1 2007- Q1 2016. The allocation strategy and investment universe in our analysis are built taking the portfolio model and mandates from Norway's GPFG as a reference. Historical data on quarterly returns are inputted into our model to represent a global investment universe comprised of equity, fixed-income, real estate, and natural asset instruments. We also conducted a comparison of 16 investment portfolios resulting from different SAA with and without natural assets.

The obtained results indicate that adding timberland and farmland investments in the SAA of an oil-based SWF have a positive effect on the performance of the portfolio. The positive effects are particularly significant when supplanting equity investments with investments in these alternative instruments. Allocating 15% in timberland and farmland assets can yield a net growth of the fund market value 27% larger compared to a portfolio composed of traditional assets only, over a nine-year period. In addition, it is found that timberland and farmland assets provide significant reductions in the exposure to commodity risk and improve the return-to-risk characteristic of the portfolio. The benefits of timberland and farmland investments result from the higher average return and lower volatility experienced by these assets in recent years when compared with most equity and real estate markets. This was found to be the case even when adjusted (unsmoothed) returns are considered. Moreover, timberland and farmland tend to exhibit low oil sensitivity that provides them with a hedging property against oil price risk. Our findings suggest that investments in natural assets may be a desirable choice for oil-based SWFs seeking to diversify their investment strategy in the current oil market turmoil. Although, current performance is not guarantee of future prices, further research could investigate whether similar finding are observed in other past or future periods of low oil prices, in order to extend the generalization of the results. Nevertheless, the results obtained in this analysis do support the idea envisioned by some commercial wealth managers that real assets, including natural assets, have the potential to evolve into a mainstream asset class of comparable importance to traditional equity and fixed income assets. Increasing investments in natural assets mean that investors will need to face increasing liquidity risk. Managing this risk, however, can pay off with a return premium. In addition, by investing in assets such as timberland and farmland, SWFs could not only benefit from these investments, but they would be redirecting wealth derived from non-renewable natural assets into renewable natural assets. This investment approach implies a circular relationship with natural resources that is in accordance with the

Hartwick-Solow[1] rule of economics. Thus, SWFs could be though as mechanisms that can be adapted to promote sustainable asset allocations and support natural wealth preservation.

One of the main limitations of our study is the constraints found in the data when modelling SWFs. The detailed data required to reconstruct the investment universe and oil inflows of an SWF includes having access to their portfolio composition, the fund's mandates, major investment recipients (e.g., firms, bond class, real estate markets, etc), time series of monthly or quarterly returns, levels of oil exports, oil revenues allocated to the fund, among others. Many of this required data often remain highly confidential in most SWFs. For this reason, we have used Norway's GPFG as our case study since it is one of the few funds with a high degree of transparency when reporting its activities. Another limitation is found when representing investments in natural assets. This asset class has been limited to investments in timberland and farmland in the US private market. Timberland markets in the US have reached maturity, in consequence, returns have gradually decreased and stabilized in recent years. In search of new opportunities, many institutional investors are currently turning their attention to alternative timber markets in Africa, Asia, and Latin America (UNECE-FAO, 2015). Regarding farmland, despite the US market showing a steady growth in recent years, the higher returns and grow rates have been actually reported in emerging markets such as Romania, Hungary, Poland, Zambia, Mozambique, and Brazil (SavillsResearch, 2014). Timber and farmland markets are opening significant opportunities for SWFs in order to add value to their performance, and therefore, should be promoted as serious alternative investment options for investors seeking for alternatives to traditional assets. The opportunities offered by timber and farmland investments will be more apparent for large institutional investors rather than for smaller short-term focused funds, since the firsts have the ability to manage higher levels of liquidity risk and capitalize long term benefits.

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[1] In the economics literature, the Hartwick-Solow rule refers to compensating the depletion of non-renewable natural capital by reinvesting the economic rent from depletion in renewable capital forms (see Hartwick (1977) and Solow (1974)).

The geographical limitations of the analysis presented in this chapter leads to findings to be applicable mainly in the context of a rich develop economy, with solid institutions and high levels of transparency, such as Norway. In order to extend our results to other, non “so ideal”, contexts it would be interesting for future research to apply a similar analysis to SWFs located in developing, less transparent, or less democratic countries, provided that data is available. Future work can also investigate the effect that investments in emerging timberland and farmland markets may have over oil-founded SWFs portfolio to assess their potential. A study combining these two aspects could provide insights on how feasible and effective it would be to implement the SWF approach to finance and recover natural capital in developing economies where the majority of the non-renewable resources actually lie.

# 7

# Conclusions

## 7.1 Summary and implications

Natural capital value has been falling steadily in the last decades, and although this decline has been recognised and studied by scholars, the use of accounting and finance as disciplines for addressing and preventing this decline is new. Specifically, the loss of natural capital around the world has motivated the development and implementation of accounting and finance mechanisms designed to measure and recover the value of natural capital. As a result, research efforts have increasingly focused on assessing the extent to which natural capital accounting and finance can contribute to identifying the drivers of change in relation to the value of natural capital stock over time, and have attempted to better understand how to allocate major investments in natural capital assets. The present thesis has studied three relevant aspects of natural capital accounting and finance. First, we have investigated the use of natural capital accounts as an integral part of wealth accounting in order to track changes in the value of natural capital, and also analysed the major factors driving those changes in the specific case study of the UK. Second, we have examined the financial performance of investments in natural capital and compared it with the performance of other asset classes, such as equities, bonds, real estate, and infrastructure. Our aim in this area has been to identify benefits and challenges for private investors. And thirdly, we have evaluated the capability of Sovereign Wealth Funds (SWFs) to dedicate significant investments into natural capital. A number of relevant implications for policy makers, investors, and researchers emerge from our findings. Table 7.1 summarises of the research objectives, methodologies and results corresponding to each analytical component of the present thesis. Additionally, Table 7.2 summarizes the main implications and lessons learned derived from this research.

The analysis introduced in Chapter 4 has addressed the objective of evaluating changes in natural capital value within the framework of total wealth for the specific case of the UK. Results obtained in this chapter show that the UK's national wealth is predominantly comprised by its human and produced capital that, when taken together, accounts for more than 94% of total wealth. Whereas the value of natural capital, on the contrary, represents only a small fraction of 6% of wealth. A wealth composition of this type is standard in most developed economies and makes the major drivers of wealth changes contingent upon variations in the values of human and produced capital, i.e., factors such as employment and unemployment rate, average wages, and levels of investment in infrastructure largely shape the aggregate wealth trajectories. Given that the majority of these factors may be significantly affected by changes in GDP, changes in wealth value are also positively associated with changes in GDP. A financial shock in the form of an economic crisis can therefore have a detrimental effect on wealth trajectories, turning upward trends into downward ones. Conversely, we found that the value of natural capital is less associated to GDP changes when compared with human or produced capital. Nevertheless, given the current low share of natural capital in terms of total wealth, it is unlikely at present that changes in the value of this capital form can have a direct influence on the risk of declining per capita wealth. Our analysis of the UK wealth composition has revealed that recovering the value of natural capital and increasing its contribution to wealth is fundamental in order to introduce resilience in levels of aggregate wealth against the threat of financial shocks.

In the analysis of the condition of the UKs natural capital, we found that most of the natural capital value (in the considered set of natural assets measured) is concentrated in ecosystem services. The ecosystem services of outdoor recreation and GHG sequestration represent nearly 90% of the value of all the natural assets quantified in the UK. This is followed by the value of non-renewable natural capital, which accounts for nearly 6%, and renewable natural capital with the remaining 4%. Moreover, results from our analysis also indicate that the value of all the forms of natural capital, i.e., non-renewable, renewable and ecosystem services, have been in steady decline in the last 10 years. It is noteworthy that the rate of decline has been faster for non-renewable natural capital in particular, over the period 2003-2013, due to depleting oil and gas reserves. Thus, variations in the value of outdoor recreation, determined by the number of people visiting recreational sites, as well as reductions in oil, gas and coal production rates, represent the major drivers of aggregate natural capital value losses since approximately the year 2000. Nevertheless, as oil and gas reserves continue to deplete to exhaustion levels, and coal production progressively slows, the drivers of resources over the period 2015-2020 are expected to change. Factors from renewable natural capital, such as the outputs from the agriculture and water supply industry, will begin to take precedence over the factors from non-renewable natural capital, such as oil, gas and mineral production in affecting the risk of losing natural capital value. This finding provides a hint about the specific natural assets to which attention should be paid in the coming years in order to reverse the declining trajectory traditionally followed by natural capital value. That is, to increase the value of natural capital in the UK, priority should be given to investments and decisions that enhance the value of renewable natural capital and ecosystem services, with particular focus on outdoor recreation, agricultural production and water supply.

The research in Chapter 4 has contributed to the theory of using natural capital accounts as a useful tool to manage natural assets more efficiently based on the information generated by the accounts. In this sense, we have demonstrated that, with the help of natural capital accounts, we can track changes in natural capital (and other capital forms) value, identify the major drivers of change, and distinguish from those assets that require more attention. The analysis carried in this work, hence, confirmed the general principle exposed by other works in the literature (e.g., Guerry et al. (2015), Helm (2015), Bateman et al. (2015), Benwell et al. (2014), WAVES (2014)), establishing that accounting is necessary to informing about a sustainable natural capital management. A major implication for policy makers derive from this analysis. Natural capital accounting approach is important to support effective decision making when designing strategies and policies aiming at preserving the value of natural capital in a country. Accounting methodologies for natural capital may be in many cases inaccurate, partial or lead to significantly different estimates (Engelbrecht, 2016). Moreover, they may offer a simplified picture of the real condition of natural resources given the underlying assumptions found in the valuation methodologies used (Cairns, 2013; Arrow et al., 2012; Smulders, 2012). Nevertheless, despite these drawbacks, natural capital accounts still generate valuable information that can be useful to produce guidelines to managing natural resources more efficiently. As evidenced by our research and in accordance with the literature, natural capital accounts provide a more comprehensive picture of the wealth composition of a country. Furthermore, accounting systems facilitate tracking trajectories and changes in the value of natural assets over time, as well as, identifying the most significant drivers (including ecological, macroeconomic, and market factors) affecting natural capital stock and testing the sensitivity of natural capital trajectories to economic shocks. Understanding the factors that produce changes in natural capital value is essential to design interventions that minimize negative impacts. Therefore, the information generated by natural capital accounts can be used by policy makers to rank assets based on their relevance and design more effective initiatives in order to recover the value of natural capital. Additionally, researchers can use this information to increase the understanding of the different drivers affecting the value of natural assets and their relationship with other social and economic factors. In our research, we have to some extent demonstrated this for the UK, one of the leading countries in the implementation of natural capital accounting. We were able to able to do so because the UK have already produced initial estimates of its natural capital, and the country has elaborated extensive statistics on the different elements of natural capital accounts over the past decade.

Nevertheless, the applicability of accounting approaches for natural capital in other countries is subjected to the ability of collecting large amount of data over long periods of time. Natural capital accounts are data intense as they require having comprehensive statistics about a wide range of ecological, economic, social, and market issues with a relatively high level of detail (Hein et al., 2015). Moreover, the data has to be consistently collected over several years in order to produce trends that allow noticing changes. This large data requirement, may limit the implementation of the approach to countries with robust statistical systems and institutions, where the information necessary for natural asset valuation exists and is well documented. Developing countries with weaker data records may be particularly prone to this limitation. Policies, in these cases, should be oriented at creating reliable and transparent statistical records that enable the elaboration of natural capital accounts. Good examples of efforts in this direction can be found in Mozambique, Botswana, Namibia, and India (see e.g., Ollivier and Giraud (2011), Lange (2004), Dasgupta (2014)). Similarly, it is also important for international organizations, such as the UN, The World Bank, OECD, among many others, to continue intensifying their efforts on generating global standards and guidelines that facilitate the adoption of accounting methodologies and norms for natural capital around the world. Efforts from these organizations to date include the publication of natural capital estimates for multiple countries (TheWorldBank (2001) UNEP&UNU-IHDP (2014)) and the development of general natural capital accounting frameworks (SEEA-CF (2012)). Yet, further efforts are still required to facilitate a wide adoption of the natural capital accounting approach, and to extend the number of natural capital assets currently considered in the existing frameworks. Additionally, leading nations in the implementation of natural capital accounts, such as Norway, Canada, Australia, or the UK could also contribute by spreading the lessons learnt from the implementation of their accounting systems, highlighting the major benefits and challenges encountered. This would facilitate the adoption of natural capital accounting in lagging nations.

In addition to the accounting approach, the present thesis also points that recovering values of natural capital will require significantly increasing direct investments in natural assets. The contribution of private investors in this regards will be essential. Private investors have traditionally regarded investments in natural capital as poor performers, and as a consequence given relatively little importance to these investments. In the aim to increase awareness of their benefits for investors, our work introduced in Chapter 5 has investigated the performance of investments in natural capital assets and compared it with the performance of other traditional asset classes (e.g., equity, real estate and fixed income) as well as non-traditional assets, e.g., infrastructure. The results obtained from this analysis demonstrate that direct investments in real natural capital may certainly be attractive to both private and institutional investors due to their financial benefits. Real natural assets, in the form of timberland and farmland properties, have exhibited higher average expected returns during the period 2004-2016, in addition to lower volatility and greater diversification potential, than those exhibited by traditional assets, such as equities, bonds and real estate. The differences in performance were more notorious, particularly after the 2008 financial crisis, i.e., we demonstrated that real natural assets can provide private investors with protection against unexpected inflation and hedging against the risk of liquidity shocks in stock markets. Nevertheless, all of the aforementioned benefits were absent in non-real forms of natural capital assets, which were shown to underperform when compared to the rest of the assets. The differences in performance comparisons between real and non-real forms of natural capital assets were also confirmed in our investigation of the effects of their inclusion in investment portfolios composed of traditional asset classes and infrastructure. By modeling investment portfolios using out-of-sample simulation techniques with Markowitz portfolio optimisation, we showed that portfolios containing real natural assets outperform those excluding them in all the metrics tested (i.e., mean return, volatility, Sharpe ratio, and maximum drawdown). Conversely, the portfolios with investments in non-real natural assets tended to underperform the portfolios that excluded them. This part of the research contributed with insights to the empirical evidence reported by other works (e.g., Miroshnychenko et al. (2017), Silva and Cortez (2016), Chan and Walter (2014), Eichholtz et al. (2012), Olsson (2007), Derwall et al. (2005))

on the relationship between green investments and the financial performance of portfolios. In this sense, our finding helped to clarify the question of what type of green investment can be attractive for investors and under which conditions they can benefit portfolios compounded by traditional assets. A number of implications for private investors derive from this analysis. Private investors seeking financial benefits in natural capital investments should focus on direct investments in real natural assets rather than indirect investments in non-real natural assets. The focus on real natural assets would allow investors to design green portfolios that can be environmentally beneficial and, at the same time, financially profitable. By recognizing these benefits, investors can gain comfort in increasing their allocations toward natural capital and support the adoption of sustainable investments. Therefore, the general investors perception on green investments as bad performers could be challenged. Nevertheless, the lack of liquidity and long holding periods associated with real natural asset also implies that investors have to be willing to accept higher levels of liquidity risk and, thus, adopt appropriate strategies to manage it.

The analysis of natural capital investments conducted in this research was limited to two forms of real natural assets, namely private timber and farmland properties specifically traded in the US market. Moreover, the analysis was constrained to the time span 2000-2016 due to data availability. In this sense, it can be argued that findings are limited to investments in developed and well mature markets. In order to generalize the findings derived from this work, it would be advisable to extend a similar analysis to include information from other important timber and farmland markets around the world, and in particular from developing economies in South America, Eastern Europe, Sub-Saharan Africa and Southern Asia, which have experienced the greatest growth in recent years. Attempting this, however, faces two major challenges. Firstly, financial indexes tracking the performance of timberland and farmland markets, as well as other real green assets, in developing countries are scarce or inexistent. Therefore, creating more indexes able to track the performance of natural capital investments in these markets is essential to facilitate research and motivate investors to increase allocations in natural capital traded in emerging economies. And secondly, natural assets traded in those markets and included on those indexes have to be associated to sustainable management. Timberland and farmland assets traded in emerging markets are in many cases associated to unsustainable practises (e.g., illegal deforestation, over exploitation, etc.) (Sun and Bogdanski, 2017; Leblois et al., 2017; Faria and Almeida, 2016; Dieter, 2009). A wide adoption of recognized certification schemes is, therefore, necessary to guarantee the sustainable management of the underlying natural assets and to enable the finance of truly sustainable instruments. On the other hand, an investigation of the performance of natural capital investments for future time period will be interesting too, in order to evaluate whether similar findings can be also obtained in future economic contexts.

The final part of the thesis looked at new investment mechanisms to finance natural capital. In this part of the research, we show that with the emergence of SWFs as major global investments in the last decade, private and institutional investors can overcome some of the barriers associated to natural capital investment. Unlike other types of investors, SWFs meet the requirements set by real natural assets due to their large size and commitment to long-term investment. Moreover, since the majority of SWFs worldwide are funded by rents received from non-renewable natural capital exploitation, these funds have the opportunity to compensate for the depletion of non-renewable resources by investing their rents in renewable forms of natural capital. Our objective to address the capability of SWFs to invest significantly in natural capital was addressed in Chapter 6. Here, we have evaluated the performance of an SWF portfolio when dedicating major allocations in real forms of natural capital assets. Analysis results are robust; they provide evidence showing that, when real natural assets were included in an SWF portfolio, the funds performance improved significantly in terms of a better return-risk characteristic, greater market value growth, saved losses, and less exposure to commodity risk. Importantly, our results also revealed that the benefits of natural capital investments for an SWF are more apparent during times of financial hardship when equity investments tend(ed) to underperform. Furthermore, results also showed that levels of asset allocations by SWFs in natural capital, which are presently in the range of 2-5%, can be raised further to 15-20% with these funds still benefitting. The results here obtained have implications for authorities considering the use of SWFs to support a sustainable management of their natural capital. SWFs are normally established as financial vehicles with specific purpose, including stabilization, saving, or preserving pensions (IWG, 2008). Given their capability to dedicate significant investments into renewable natural capital while managing revenues from non-renewable resources, a further purpose for SWFs could be defined towards preserving natural capital. An SWF may be set by national or regional authorities to support investments in sustainable forestry or farmland assets, and simultaneously preserving the value of exploited oil, gas, or minerals for future generations. The use of an SWF with this purpose can be suitable in countries and regions rich in non-renewable natural resources that are also aiming at maintaining the value of their renewable natural capital.

The extent to which SWFs will dedicate larger allocations to natural assets depends on their ability to manage liquidity risk, as well as, their capability to define clear long term investment strategies. Moreover, the extent to which increased allocations in natural assets will be sustainable depends on the capability of managing the underlying assets sustainably. In well developed markets, such as the case of the US considered in our study, timber and farm assets are generally managed by Timber Investment Management Organizations (TIMOs) and Real Estate Investment Trusts (REITs). These managing institution are required to obtain certification of sustainable and responsible asset management in order to operate and trade their products in the US market (Zhang et al., 2012). Certification, generally includes a management addendum associated to a forest area or farmland property authenticated by certified office. Internationally recognized certification offices include the Forest Steward Council (FSC), the Programme for the Endorsement of Forest Certification Schemes (PEFC), and the International Organisation for Standardization (ISO). Although, certification is key to support sustainability of these natural capitals, certification only in not enough. As suggested by Mason (2017), certification schemes should be complemented with traceability and mapping along the supply chain to identify and prevent illegal logging. Moreover, the author considers that certification must be also complemented with an increased awareness of the importance of the sustainability aspect of natural asset investments for investors. SWFs targeting at natural assets should adhere to principles of responsible investments such as the UN's PRI, which includes guidelines for sustainable investments in timberland and agriculture (AquilaCapital, 2015). Therefore, policies encouraging the adoption of certification schemes should be embraced and also supported with business regulations that aim at improving the natural asset investment strategy of SWFs, if sustainability is to be delivered to their increased allocations. As previously discussed, the challenge will be also to extend these initiatives to other timber and farmland markets around the world that can be attractive for SWFs investments, such as Australia, New Zealand, Brazil, Romania, Hungary, Poland, Zambia, or Mozambique, for instance.

The overall thesis results, obtained from the different analyses on natural capital accounting and finance, provide strong support for the idea that recovering the value of natural capital is indeed feasible. We have argued that the use of accounting mechanisms, combined with greater understanding of the performance of natural capital investments as well as the adaptation of new investment mechanisms such as SWFs, can contribute significantly to the reversal of the losses traditionally experienced by natural capital value. Accounting frameworks for natural capital were proven in this thesis to be useful for generating information on the condition of natural assets, tracking changes in value over time, and identifying the major drivers of value changes. The information provided by natural capital accounting can therefore be used to design effective policies oriented to the recovery of countries natural capital stocks. Moreover, this information may also assist in identifying which particular natural asset investments should be prioritised. In addition, knowledge about the financial performance of natural capital investments and their potential benefits for traditional investment portfolios could be a decisive factor in encouraging private and institutional investors to increase their investments in natural capital. In this regard, we have demonstrated that natural assets have the potential to be considered by investors at the same level of relevance as traditional and infrastructure assets. Increasing direct allocations in natural capital is a fundamental decision towards recovering the stock of renewable resources, improving the condition of ecosystem services, and achieving more efficient use of non-renewable resources. Similarly, the contribution of new investment instruments such as SWFs is also important in the process of increasing investments in natural capital in a significant way. If set appropriately, SWFs can provide a mechanism to extend the value of non-renewable forms of natural capital and also dedicate major investments destined to recover renewable natural capital. Therefore, the research conducted in this thesis demonstrates that the adoption of accounting and finance mechanisms for natural capital is absolutely essential to the recovery of natural capital value.

## 7.2 Research limitations

Despite the main contribution of this thesis, which has demonstrated the importance of accounting and finance in the recovery of the value of natural capital, we have nevertheless encountered several limitations. In regard to natural capital accounts, one of the major limitations faced by accounting systems is the limited number of natural assets that can actually be accounted for. Quantifying the value of natural assets requires complex models and the recording of extensive data on a wide array of environmental factors. Complex models are normally based on a large number of assumptions that may be considered improbable in many cases. Moreover, gathering the data required to make monetary estimations of natural capital is challenging and requires sufficient time in order to generate long-enough time series. In addition, many natural assets are intangible and their value happens to be difficult to quantify. The limitations of quantifying the value of many forms of natural assets lead us to natural capital estimates which are only partial rather than comprehensive. Information extracted from partial estimates of natural capital accounts, although useful, may be skewed. These limitations in natural capital accounting may be overcome in the future as new methodologies and approaches emerge, or existing ones are further developed.

A significant limitation found when analysing the performance of investments in natural capital corresponds to data unavailability. Financial indexes which track the performance of real natural assets, are scarce, and can only be found for well-developed markets like the US. Whereas other important markets for natural capital investments, particularly in developing countries, are difficult to evaluate due to the scant reportage of financial data. This limitation imposes constraints on the number of natural capital investments that can be studied. Therefore, a major challenge is to develop more financial indexes that are capable of tracking the performance of natural assets, and in particular, real natural assets.

In relation to the analysis of SWFs as a mechanism for investing in natural capital, one of the major limitations found relates to the constraints in the data required to model an SWF portfolio. Most SWFs are opaque and do not openly provide information on their activities nor do they report their investment strategies in detail. The lack of transparency associated with these funds is the main focus in much of the literature. We had to refer to Norway's GPFG as our case study, as it was one of the few SWFs that provides public access to sufficient data in order to replicate its performance fairly accurately. In this part of our research we also encountered the same data limitations mentioned above in terms of natural asset investments; the investments used in this thesis were proxied using the timberland and farmland markets in the US, while excluding other relevant markets emerging in developing countries.

## 7.3 Future research

The limitations found in the analyses of natural capital accounting and finance presented in this thesis nevertheless have implications for future research, providing opportunities for future contributions. Further research can embark on developing new methodologies or refining existent ones to account for the value of more natural capital assets and ecosystem services, and include them in the national accounts. For example, the Office for National Statistics has announced that they are developing the accounts for valuing biodiversity in the UK. This effort could be extended to the quantification of the value of other ecosystem services, such as flood hazard reduction, cultural heritage and aesthetic experiences. As new methodologies are formulated and data continue to emerge, they can be included in an expansion of the model presented in Chapter 4, and thereby provide a more comprehensive representation of total natural wealth. The constructed model can also be expanded by incorporating more empirical relationships between capital assets. Doing so would facilitate the study of the impacts that other significant variables might have on the risk of following decreasing trajectories of wealth and natural capital. The effect on the risk of declining natural capital of other economic factors of interest, such as discount rates, commodity price fluctuations, changes in the inflation rate, or average duration of visits to recreational sites, can also be investigated. The study of discount rates for natural capital accounting in particular represents a great opportunity for researchers to contribute further as the existing literature has not reached any consensus on what discount rates is more suitable for natural capital studies (Khan and Greene, 2013).

In the case of the performance evaluation for natural capital investments, further assets can be included in the analysis, provided that data is available. Moreover, the performance of direct investments in timberland and farmland assets traded in developing markets in Africa, Eastern Europe and South America, can also be analysed to provide broader insights for investors about the most attractive markets relative to natural capital investment. Future efforts can also be dedicated to the development of new financial indexes that track the performance of different forms of green investments, with an emphasis on real natural assets. A larger number of financial indexes for natural capital assets would promote the research on the benefits of these investments, thereby incentivising private investors to dedicate greater allocations in natural capital. Another interesting research strand would be to combine the models developed for total wealth management with the model of SWF investments. The outcome could lead to the development of a general model for assessing the impacts of establishing an SWF on natural capital management and sustainable development with the purpose of preserving natural capital value. Such a model could, for example, assist the UK in support of the decision to develop natural capital funds to be applied in the possible adoption of fracking technology for the extraction of oil and gas resources.

Table 7.1: Summary of research objectives, methodology, results and impacts

| Objective | Methodology | Results | Recommendations | Chapter |
|---|---|---|---|---|
| To evaluate changes in natural capital value within the framework of total wealth by considering the UK case study. | Developing a stochastic model for risk analysis applied to UK wealth to measure the risk of declining per capita wealth and natural capital value given the management of capital assets. Using regression models, the model incorporates existing empirical relationships among capital assets and economic variables of interest. A sensitivity analysis, based on global sensitivity techniques, is employed to identify the most influential variables on the risk of declining per capita natural capital and wealth in scenarios projected for the period 2015-2020. | -UK wealth is mainly constituted by human and produced capital (94%), while natural capital represents a minor share (6%).<br>-Natural capital is unlikely to have a direct effect on the risk of declining per capita wealth.<br>-Changes in natural capital value are less associated with GDP fluctuations, compared with human or produced capital.<br>-Most of the UK's natural capital value is found in ecosystem services, particularly outdoor recreation.<br>-The aggregated value of natural capital is mainly driven by changes in the value of ecosystem services, particularly for outdoor recreation.<br>-Between 2003 and 2013, all forms of natural capital in the UK declined in value, even though the decline rate was particularly fast for non-renewable natural capital.<br>-For the period 2015-2020, elements of renewable natural capital will overtake factors of non-renewable natural capital in their influence on the risk of natural capital decline. | -Implement and extend natural capital accounting systems to track changes in the value of natural assets and understand the main drivers of change.<br>-Increase levels of natural capital to provide diversification of wealth.<br>-When recovering the value of natural capital, attention should be paid particularly to elements or renewable natural capital and ecosystem services.<br>-Consider the implementation of investment mechanisms for natural capital. | 4 |
| To study the performance of investments in natural capital. | Analysis return time series for real and non-real natural assets and comparison of their financial performance with those of equities, bonds, real estate, and infrastructure assets. The analysis focuses on quantifying average returns, volatility, downside risk, diversification potential, inflation protection, and liquidity risk hedging. | -Real natural assets outperform investments in traditional asset classes such as equities, bonds, real estate and non-traditional ones, namely, infrastructure.<br>-Investments in real natural assets provide hedging against unexpected inflation, reduce downside risk, and lower exposure to liquidity shocks in financial markets.<br>-Major challenges of natural capital investments include their long investment horizon and low liquidity, as compared with equities or bonds.<br>-Investments in real natural assets require investors with long investment horizons, long holding capability, and low liquidity constraints. | -Investors seeking to invest in natural capital should focus on investments in real, rather than non-real natural assets.<br>-Portfolios composed of traditional asset classes should consider including investments in real natural assets to improve performance.<br>-Real natural assets should be considered by institutional investors at the same level of importance as equities, bonds, real estate and infrastructure assets.<br>-Investments in real natural assets are particularly suitable for investors with large assets under management, long investment horizons and low liquidity constraints (e.g., Sovereign Wealth Funds). | 5 |
| To investigate the capability of SWFs to dedicate significant investments in natural capital. | Modelling the investment portfolio of oil-funded SWFs using Norway's Government Pension Fund Global as a case study and assessing its performance when investing in real natural capital assets. The model uses the out-of-sample simulation technique to recreate the performance of the portfolio over the period March 2007 to March 2016. The model also uses Gintschel and Scherer's (2008) optimization method to estimate global efficient portfolios for asset allocation. | -Including natural asset investments in an oil-based SWF portfolio yields positive effects on its performance.<br>-Benefits are made manifest in the forms of higher expected returns, lower volatility, greater savings, and hedging against oil price risk.<br>-The benefits of natural asset investments are more significant during times of crisis: when equities perform poorly.<br>-The benefits of natural asset investments are more prominent when these investments replace investments in equity assets, rather than bonds or real estate. | -SWFs should reconsider their traditional allocation levels in natural assets (2-5%), shifting to a higher range (15-20%).<br>-SWFs can be adapted as an investment mechanism to manage both forms of natural capital: renewable and non-renewable and still benefit from this role.<br>-SWFs should increase their transparency in order to facilitate research on their investment performance and capability to support allocations in natural capital. For this purpose, SWFs should disclose data on their asset allocation strategy, monthly or quarterly returns, mandates, main companies targeted, governance policy, and objectives, as well as, information on their inflow source (e.g., commodity income). Incentives for SWFs to disclose their data could be provided, for example, by facilitating analysis and research on their performance, and based on that suggesting recommendations for improvement or allowing comparison with other funds. | 6 |

Table 7.2: Summary of lessons learned and implications

| | **Lessons learned** | **Implications** |
|---|---|---|
| **For policy makers** | -Natural capital accounts generate useful information on the condition of natural resources in a country<br>-Accounting for NC allows to identify main drivers of changes in natural capital stock | -Policy makers are allowed to design more effective initiatives to manage natural resources efficiently.<br>-Natural assets in a country can be prioritized based on their relevance for delivering sustainability.<br>-Factors driving changes in natural capital value can be identified and their relationship with the economy can be better understood.<br>-Authorities are encouraged to develop robust statistical record that favour the creation of natural capital accounts. |
| **For Investors** | -Real natural assets can be good financial performers.<br>-Investing in real natural assets may increase liquidity risk for most investors<br>-A portfolio compounded by traditional asset classes can benefit from investing in real natural assets in the long run.<br>-A limited number indexes exist to track the performance of green investments in developing economies. | -Institutional investors can significantly their investments into natural capital assets.<br>-Investors can create green portfolios that are both environmentally beneficial and financially profitable.<br>-There is an opportunity for private investors to get more involved into supporting green investment and natural capital initiatives.<br>-There is a need for developing more indexes capable of tracking natural capital investments in developing markets.<br>-Investors may support initiative to widely adopt certifications that guarantee the sustainable management of investable assets such as timber and farmland. |
| **For Authorities** | -SWFs can manage the rent resulting from non-renewable resources exploitation and re-direct it to renewable forms of natural capital | -Local and national authorities may consider the implementation of SWF initiative in favour of the sustainable management of their natural resources.<br>-The UK may consider the creation of a SWF in the future if shale oil and gas resources are to be exploited in this country. |
| **For researchers** | -Implementing the accounting approach for natural capital is data intensive.<br>-Accounting methodologies are in practice partial and inaccurate. Yet, they still generate useful insights. | -Challenging to be implemented in countries with weaker statistical records and institutions.<br>-A lot of research opportunities in generating more methodologies for natural capital accounting.<br>-There is a research need to enhance the understanding of natural capital investment performance in developing markets. |

# A

# Globally efficient portfolios

This demonstration has been taken from Gintschel and Scherer (2008). As show in Chapter 3, the standard Mean-Variance approach to estimate efficient portfolios (i.e. locally efficient portfolios), minimises $\mathbf{w}^{\mathrm{T}}\mathbf{\Sigma}\mathbf{w}$ subject to the constrains that the portfolio achieves a target expected return $\mathbf{w}^{\mathrm{T}}\mathbf{z} = \mu$ and the budget constrain $\mathbf{w}^T\mathbf{1} = 1$. Ingersoll (1987) demonstrates that the optimal portfolio weights in this case are

$$\mathbf{w}_L(\mu) = \mathbf{\Sigma}^{-1}\mathbf{1}\frac{1}{\Delta}[\mu(\mathbf{1}^T\mathbf{\Sigma}^{-1}\mathbf{1}) - (\mathbf{z}^T\mathbf{\Sigma}^{-1}\mathbf{1})] + \mathbf{\Sigma}^{-1}\mathbf{1}\frac{1}{\Delta}[\mathbf{z}^T\mathbf{\Sigma}^{-1}\mathbf{z} - \mu(\mathbf{1}^T\mathbf{\Sigma}^{-1}\mathbf{z})]$$

where

$$\Delta = (\mathbf{1}^T\mathbf{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^T\mathbf{\Sigma}^{-1}\mathbf{z}) - (\mathbf{z}^T\mathbf{\Sigma}^{-1}\mathbf{1})^2.$$

The equivalent problem of finding globally efficient portfolios minimizes $Var(r) = \omega^2\sigma_o^2 + (1-\omega)^2\mathbf{w}^T\mathbf{\Sigma}\mathbf{w} + 2\omega(1-\omega)\sigma_o^2\mathbf{w}^T\mathbf{b}$ subject to the constraints $\mathbf{1}^T\mathbf{w} = 1$ and $\mathbf{z}^T\mathbf{w} = \mu$. The Langragian for the problem is

$$L = (1-\omega)\mathbf{w}^T\mathbf{\Sigma}\mathbf{w} + 2\omega\sigma_o^2\mathbf{w}^T\mathbf{b} + \lambda(1 - \mathbf{1}^T\mathbf{w})\gamma(\mu - \mathbf{z}^T\mathbf{w})$$

The first order conditions are

$$2(1-\omega)\mathbf{\Sigma}\mathbf{w}_G(\mu) + 2\omega\sigma_o^2\mathbf{b} - \lambda\mathbf{1} - \gamma\mathbf{z} = 0,$$

which solved for the portfolio weights one obtains

$$\mathbf{w}_G(\mu) = \frac{1}{2(1-\omega)\boldsymbol{\Sigma}^{-1}(\lambda\mathbf{1} + \gamma\mathbf{z} - 2\omega\sigma_o^2\mathbf{b})}.$$

If we substitute this equation into the constrain equations, solving for the constraints, and substituting these again into the optimal portfolio weights

$$\begin{aligned}\mathbf{w}_G(\mu) =& \frac{1}{2(1-\omega)}\{\frac{2(1-\omega)}{\Delta}[\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{z} - \mu\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{z}] \\ &+ \frac{2\omega\sigma_o^2}{\Delta}[(\mathbf{1}^T\Sigma^{-1}\mathbf{b})(\mathbf{z}^T\Sigma^{-1}\mathbf{z}) - (\mathbf{z}^T\Sigma^{-1}\mathbf{z})(\mathbf{1}^T\Sigma^{-1}\mathbf{z})]\}\Sigma^{-1}\mathbf{1} \\ &+ \frac{1}{2(1-\omega)}\{\frac{2(1-\omega)}{\Delta}[\mu\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{1} - \mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{1}] \\ &+ \frac{2\omega\sigma_o^2}{\Delta}[(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})((\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{b}) - (\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{b})]\}\boldsymbol{\Sigma}^{-1}\mathbf{z} \\ &- \frac{2\omega\sigma_o^2}{2(1-\omega)}\boldsymbol{\Sigma}^{-1}\mathbf{b}\end{aligned}$$

where $\Delta = (\mathbf{z}^T\Sigma^{-1}\mathbf{z})(\mathbf{1}^T\Sigma^{-1}\mathbf{1}) - (\mathbf{1}^T\Sigma^{-1}\mathbf{z})(\mathbf{z}^T\Sigma^{-1}\mathbf{1})$. Reorganizing

$$\begin{aligned}\mathbf{w}_G(\mu) =& \frac{1}{\Delta}[\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{z} - \mu\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{z}]\boldsymbol{\Sigma}^{-1}\mathbf{1} + \frac{1}{\Delta}[\mu\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{1} - \mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{1}]\boldsymbol{\Sigma}^{-1}\mathbf{z} \\ &+ \frac{\omega\sigma_o^2}{(1-\omega)}\{\frac{1}{\Delta}[(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{b})(\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{z}) - (\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{z})]\boldsymbol{\Sigma}^{-1}\mathbf{1} \\ &+ \frac{1}{\Delta}[(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{b}) - (\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{b})]\boldsymbol{\Sigma}^{-1}\mathbf{z} - \boldsymbol{\Sigma}^{-1}\mathbf{b}\}\end{aligned}$$

The first two terms in this equation represent $\mathbf{w}_L(\mu)$. Therefore,

$$\begin{aligned}\mathbf{w}_G(\mu) =& \mathbf{w}_L(\mu) + \frac{\omega}{(1-\omega)} \times \sigma_o^2\{\frac{1}{\Delta}[(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z}) - (\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{z})]\boldsymbol{\Sigma}^{-1}\mathbf{1} \\ &+ \frac{1}{\Delta}[(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{b}) - (\mathbf{z}^T\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^T\boldsymbol{\Sigma}^{-1}\mathbf{b})]\boldsymbol{\Sigma}^{-1}\mathbf{z} - \boldsymbol{\Sigma}^{-1}\mathbf{b}\}\end{aligned}$$

The hedge portfolio is a zero-net investment portfolio, meaning that $\mathbf{w}_H^{\mathrm{T}}\mathbf{1} = 0$. The net position of the portfolio is

$$\begin{aligned}\mathbf{1}^{\mathrm{T}}\mathbf{w}_H =& \sigma_o^2\mathbf{1}^T\{\frac{1}{\Delta}[(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z}) - (\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{z})]\boldsymbol{\Sigma}^{-1}\mathbf{1} \\ &+ \frac{1}{\Delta}[(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b}) - (\mathbf{z}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\mathbf{b})]\boldsymbol{\Sigma}^{-1}\mathbf{z} - \boldsymbol{\Sigma}^{-1}\mathbf{b}\}\end{aligned}$$

Expanding the previous expression we obtain

$$\begin{aligned}\mathbf{1}^{\mathrm{T}}\mathbf{w}_H =&\frac{\sigma_o^2}{\Delta}\{(\mathbf{z}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b}) - (\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b})\\ &+ (\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{1})(\mathbf{z}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b}) - (\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})^2(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b})\\ &- (\mathbf{z}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{1})(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b}) + (\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{z})^2(\mathbf{1}^{\mathrm{T}}\mathbf{\Sigma}^{-1}\mathbf{b})\}\\ =&\frac{\sigma_o^2}{\Delta}0\end{aligned}$$

As we also claim that $\mathbf{w}_H$ has zero expected return (i.e. $\mathbf{z}^{\mathrm{T}}\mathbf{w}_H = 0$),

$$\mu = \mathbf{z}^{\mathrm{T}}\mathbf{w}_G(\mu) = \mathbf{z}^{\mathrm{T}}\mathbf{w}_L(\mu) + \frac{\omega}{(1-\omega)}\mathbf{z}^{\mathrm{T}}\mathbf{w}_H = \mu + \frac{\omega}{(1-\omega)}\mathbf{z}^{\mathrm{T}}\mathbf{w}_H$$

Therefore, $\mathbf{z}^{\mathrm{T}}\mathbf{w}_H = 0$ since $\omega/(1-\omega) > 0$.

B

# List of assumptions

The stochastic model developed for wealth accounting is based on a number of assumptions adopted in the methodologies to estimate the value of each capital asset. The results obtained from the evaluation of the model; therefore, are valid only in the presence of these assumptions. Due to these assumptions and the complexity of the model, there is the possibility that certain wealth components, or the value of total wealth, may be over or underestimated. Moreover, the values obtained for the risk of declining per capita natural capital and wealth may also vary if some of these assumptions are relaxed. Thus, our findings and results are interpreted within the conditions defined by these assumptions. Below, the major assumptions considered in the model are given.

## A. Produced capital

- The value of produced capital is assumed to be associated entirely with the land use category settlement. Thus, all the produced capital is assumed to be found in the settlements.
- Future values of produced capital per area of settlement are assumed to follow the historical linear trajectory exhibited between 1999 and 2013.

### B. Human capital

- It is assumed that labour earnings depend only on labour marginal productivity. Therefore, other factors affecting wages, such as market conditions, discrimination, unions, etc, have been neglected.

- An individual of a given age, gender, and educational level is assumed to maintain the same labour income, employment rate, mortality rate, and the probability of upgrading its educational level over a year period between year $t$ and $t + 1$.

- It is assumed that an individual cannot go down in its educational attainment level.

- The mortality rate is assumed to be a good proxy for the survival rate, which determines the chances of an individual to remain alive for the next time period.

- The labour productivity growth rate is assumed to be 2% per year, as suggested by Lindsay (2004).

- The discount rate is assumed to be 3.5% per year, as recommended in the Green Book by HMTreasury (2003).

- No further educational enrolment is allowed for individuals having achieved the highest educational level considered.

- Is has been assumed that the probability of an individual at a given educational level to upgrade to a higher educational level increases at a constant annual rate of 0.08% for all educational levels. This is based on the average historical education enrolment rates changes registered over the period 1999-2013.

## C. Natural capital

### On minerals and coal

- Mineral and coal reserves are assumed to provide value flows for 25 years. In other words, the asset life for mineral and coal is assumed to be 25 years.
- The patterns of future resource rent ratio is assumed to be constant based on the average of the latest 5 years data.

### On oil and gas

- The valuation of oil and gas assets is based on proven and probable reserves. Proven reserves are defined as those having at least 90% chance of being available for future extraction, while possible reserves are those with no less than 50% chance (SPEandWPC, 2017).
- Future values for oil and gas operational total cost are assumed to increase at a constant rate based on the average growth registered for the past 16 years of data.
- The asset live for oil and gas assets is assumed to be determined by the years to depletion of proven and probable reserves.
- Future levels of proven and probable oil and gas reserves are assumed to follow an exponential decrease trajectory base on the trajectory described in the past 16 years.

### On agricultural land, water supply and fishery

- The asset live for agriculture, water supply, and fishery assets is assumed to be 25 years.
- Future values of resource rent ratio are assumed to follow a constant trajectory based on the average of the latest 5 years of data.

- Future values for the total cost (i.e. intermediate consumption, compensation of employees, difference between taxes and subsidies, fixed capital consumption, and return to produced assets) associated with the agricultural, water supply and fishery industry, are assumed to growth at a constant rate given by the average of the past 14 years data.

### On timber resources

- The net return of timber resource rent is received when the timber is harvested.
- The harvesting age is assumed to be 50 years and all timber is assumed to be available for wood supply.
- The volume of standing timber for each age class is assumed to be fixed at $304m^3$/ha, the expected volume at harvesting age estimated by Khan et al. (2013).
- The total area covered by timber resources in the UK is assumed to match that of the area of land use classified as forestland by the LULUCF sector.
- The proportion of standing timber in each age class in a given year is assumed to follow the dynamic given by

| Year | Age category | | | | | |
|---|---|---|---|---|---|---|
| | 1<br>(0-20) | 2<br>(21-40) | 3<br>(41-60) | 4<br>(61-80) | 5<br>(81-100) | 6<br>(+100) |
| $\leq$ 2009 | 23.6% | 32.6% | 24.1% | 10.3% | 5.1% | 4.3% |
| 2010-2012 | 2.8% | 44.7% | 43.3% | 7.2% | 1.5% | 0.5% |
| 2013-2017 | 2.4% | 34.3% | 50.2% | 10.6% | 2.0% | 0.5% |
| 2018-2022 | 2.3% | 30.2% | 51.6% | 12.8% | 2.5% | 0.6% |
| $\geq$ 2027 | 2.7% | 28.5% | 48.9% | 16.1% | 2.8% | 1.0% |

based on the historical and projected figures on timberland area by age category compiled from the following sources: UKFC (2015); Malcolm et al. (2013); NFI (2012) and NFIR (2011).

- The asset life for timber resources is assumed to be given by the time to harvesting age. Therefore, it is given by subtracting the middle point of the age category from the harvesting age.

### On outdoor recreation

- Private transport fuel cost and the cost of visiting time are assumed to be a good proxy to estimate the value of outdoor recreational sites.
- It is assumed that there could be a mechanism to charge visitors for their average willingness to pay if a market existed for outdoor recreational sites.
- It is assumed that all visitors to recreational sites are working people. Thus, the cases of retirees, children, or unemployed people are not taken into account.
- An asset life of 25 years is assumed to discount the resource rent of outdoor recreation in the net present value.

- Visitors of recreational sites are assumed to incur in transport fuel and visiting time cost for the sole intention of enjoying the outdoor recreation provided by the natural environment.
- 75% of the average hourly wage is assumed to be a good approximation of the opportunity cost of time.
- Due to the lack of available data, it has been assumed that the average expenditure per person on petrol and diesel per visit is given by a normal distribution.
- Similarly, the average duration of a visit to a recreational site is assumed to be described by a normal distribution.

**On greenhouse gas sequestration**

- The market price for carbon is assumed to be the same as the social price of carbon.
- The asset life for carbon capture is assumed to be 25 years.
- The total land area of the UK has been assumed to remain fixed during the evaluation period.
- Greenhouse gases emission/capture from forestland, cropland, settlement and others are assumed to mainly depend on the area of land associated with their corresponding land category (i.e. land use) and not on the transition to another land use (i.e. land use change).
- Greenhouse gas emissions from grassland are assumed to mainly depend on the land transition to or from another land use category, rather than on the area of grassland.
- Greenhouse gas emissions from wetlands are assumed to depend mainly on peat extraction rather than on the area of wetlands.

C

# Empirical relations defined in the wealth model

### Relationship between changes in UK employment rate and GDP growth

Employment rate and wages, fundamental variables determining the value of human capital, can be affected by trajectories of economic growth (GDP). These relationships are included in the developed model in order to capture the effects of GDP changes over human capital estimation. Following Seyfried (2005), a lagged model is used to represent changes in employment rate, $e_t$, as a function of GDP growth, $D_t$, such that

$$e_t = \beta_0^e + \beta_1^e D_t + \beta_2^e D_{t-1} + \alpha_1^e e_{t-1} + \alpha_2^e e_{t-2} + \alpha_3^e e_{t-3} + \epsilon^e \tag{C.1}$$

where $\varepsilon^{(\Delta E)} \sim N(\mu^{(\Delta E)}, \sigma^{(\Delta E)})$. The lag structure in the model have been adapted to UK data using Akaike's information criterion (AIC). The value of the regression coefficients and the regression statistics for this empirical relationship are presented in Table C.1.

### Relationship between annual wages and changes in unemployment

In the case of the annual labour income, $B_{g,d,t}$ is first expressed as a function of the unemployment rate, which is given later as a function of GDP growth. The relationship between unemployment rate and changes in real wages has been modelled following the approach proposed by Gregg et al. (2014). This approach relates the log of real wages with changes in unemployment, lagged unemployment

Table C.1: Regression coefficients for the relationship changes in employment rate and GDP growth, expressed in Equation (C.1)

| | Dependent variable: $e_t$ |
|---|---|
| *Coefficients* | |
| $\beta_0^e$ | -0.0603 |
| | (0.001) |
| $\beta_1^e$ | 0.0606 |
| | (0.000) |
| $\beta_2^e$ | 0.058 |
| | (0.000) |
| $\alpha_1^e$ | 0.3558 |
| | (0.000) |
| $\alpha_2^e$ | 0.1781 |
| | (0.023) |
| $\alpha_3^e$ | 0.1654 |
| | (0.022) |
| *Statistics* | |
| $R^2$ | 0.60 |
| AIC | -577.84 |
| Observations | 172 |
| | |
| *Residuals* | |
| Mean | 0.000 |
| Std. Dev. | 0.181 |
| Shapiro-Wilk | 0.328 |
| Kolmogorov-Smirnov | 0.200 |

Note. The p-values are presented in parentheses

and a trend. Thus, the relationship is represented as follows

$$\log(B_{g,d,t}) = \alpha_0^B + \alpha_1^B \log(U_t) + \alpha_2^B \log(U_{t-1}) + \alpha_3^B \log(U_{t-3}) + \beta_0^B t + \epsilon^B, \quad \text{(C.2)}$$

where $U_t$ is the unemployment rate at time $t$ and $\epsilon^B \sim N(\mu^B, \sigma^B)$. Table present the values obtained for the correlation parameters in Equation (C.2).

### Unemployment rate and GDP growth

The relationship between unemployment rate and GDP growth, also known as Okun's law, is taken from Olusegun (2015) who has demonstrated the validity of this relationship for the case of the UK between 1971 and 2013. Therefore, $U_t$ is given by

Table C.2: Regression coefficients for the relationship annual wages and unemployment, expressed in Equation (C.2)

| | Dependent variable: $\log(B_{g,d,t})$ |
|---|---|
| *Coefficients* | |
| $\alpha_0^B$ | 10.419 |
| | (0.000) |
| $\alpha_1^B$ | 0.0802 |
| | (0.017) |
| $\alpha_2^B$ | -0.1984 |
| | (0.001) |
| $\alpha_3^B$ | -0.1545 |
| | (0.000) |
| $\beta_0^B$ | 0.00863 |
| | (0.000) |
| *Statistics* | |
| $R^2$ | 0.962 |
| AIC | -119.84 |
| Observations | 13 |
| | |
| *Residuals* | |
| Mean | 0.00 |
| Std. Dev. | 0.007 |
| Shapiro-Wilk | 0.709 |
| Kolmogorov-Smirnov | 0.200 |

$$U_t = \alpha_0^U + \alpha_1^U D_t + \epsilon^U. \tag{C.3}$$

the value for the regression coefficients in Equation (C.3) are presented in Table C.3 with their respective statistics.

### Mortality rate and time

The mortality rate for the population in each age group varies with the pass of the years given the progress in health care and technology that allow extending life expectancy. In order to capture this dynamic, mortality rates have been modelled as a function of time using simple linear regression, and their trajectories are assumed to be followed by future years. Hence, they are modelled as

$$h_{g,t} = \alpha_0^h + \alpha_1^h t + \epsilon^h, \quad \forall g \in G \tag{C.4}$$

Table C.3: Regression coefficients for the relationship between UK unemployment rate and GDP growth, expressed in Equation (C.3)
Source: Olusegun (2015).

| | Dependent variable: $U_t$ |
|---|---|
| *Coefficients* | |
| $\alpha_0^U$ | 0.134996 |
| | (0.000) |
| $\alpha_1^U$ | -0.074496 |
| | (0.000) |
| *Statistics* | |
| R$^2$ | 0.388 |
| AIC | -0.273 |
| Observations | 168 |
| *Residuals* | |
| Mean | 0.00 |
| Std. Dev. | 0.209 |
| Shapiro-Wilk | - |
| Kolmogorov-Smirnov | - |

where the value for the regression coefficients are provided in Table C.4

Table C.4: Regression coefficients for the relationship between UK mortality rate by age and time, expressed in Equation (C.4)

| | Dependent variable: $h_{g,t}$ | | | | | |
|---|---|---|---|---|---|---|
| | Age 16-20 ($g=1$) | Age 21-30 ($g=2$) | Age 31-40 ($g=3$) | Age 41-50 ($g=4$) | Age 51-60 ($g=5$) | Age 61-64 ($g=6$) |
| *Coefficients* | | | | | | |
| $\alpha_0^h$ | 0.0194 | 0.0105 | 1.17E-2 | 0.0117 | 0.3222 | 0.6844 |
| | (0.000) | (0.001) | (0.000) | (0.000) | (0.000) | (0.000) |
| $\alpha_1^h$ | -9.48E-6 | -4.962E-6 | -5.36E-6 | -3.64E-5 | -1.58E-4 | -3.36E-4 |
| | (0.000) | (0.001) | (0.000) | (0.000) | (0.000) | (0.000) |
| *Statistics* | | | | | | |
| R$^2$ | 0.909 | 0.502 | 0.798 | 0.954 | 0.969 | 0.989 |
| AIC | -350.8 | -333.8 | -354.4 | -317.33 | -274.5 | -267.14 |
| Observations | 17 | 17 | 17 | 17 | 17 | 17 |
| *Residuals* | | | | | | |
| Mean | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Std. Dev. | 3.0E-5 | 5.0E-5 | 3.0E-5 | 8.0E-5 | 2.9E-4 | 3.5E-4 |
| Shapiro-Wilk | 0.359 | 0.787 | 0.057 | 0.459 | 0.117 | 0.231 |
| Kolmogorov-Smirnov | 0.200 | 0.200 | 0.037 | 0.2 | 0.130 | 0.200 |

### Hourly wages and unemployment

Average hourly wage, $Z_t$, is also related to GDP growth through unemployment rate as we did for annual wages. In this case, the empirical function linking hourly wages with unemployment rate takes the form

$$\log(Z_t) = \alpha_0^Z + \alpha_1^Z \log(U_t) + \alpha_2^Z \log(U_{t-1}) + \alpha_3^Z \log(U_{t-3}) + \beta_o^Z t + \epsilon^Z, \qquad \text{(C.5)}$$

where $U_t$ is given by Equation (C.3). The correlation coefficients for Equation are presented in Table C.5.

TABLE C.5: Regression coefficients for the relationship hourly wages and unemployment, expressed in Equation (C.5)

| | Dependent variable: $\log(Z_t)$ |
|---|---|
| *Coefficients* | |
| $\alpha_0^Z$ | 2.6871 |
| | (0.000) |
| $\alpha_1^Z$ | 0.1063 |
| | (0.002) |
| $\alpha_2^Z$ | -0.1720 |
| | (0.001) |
| $\alpha_3^Z$ | -0.1461 |
| | (0.000) |
| $\beta_0^Z$ | 0.00812 |
| | (0.000) |
| *Statistics* | |
| $R^2$ | 0.962 |
| AIC | -122.9 |
| Observations | 13 |
| *Residuals* | |
| Mean | 0.00 |
| Std. Dev. | 0.006 |
| Shapiro-Wilk | 0.709 |
| Kolmogorov-Smirnov | 0.200 |

### GHG sequestration and land use

The amount of gases sequestered or emitted for forestland, cropland, settlements and others is calculated as the product between the average emission per area, $\lambda_t^j$, and the land area of the respective category, $L_t^j$. Average emissions per area are modelled as a function of time using polynomial regression in order to capture the dynamics involved in the variations of emissions. The model can be written as

$$\lambda_t^j = \sum_w \alpha_w^j \cdot (t)^w + \epsilon^j, \quad \forall j \in J \tag{C.6}$$

where the degree of the polynomial model, $w$, is determined for each case using AIC, and $\epsilon^j$ is a zero-mean error term with standard deviation $\sigma^j$. The value obtained for the correlation coefficients in Equation (C.6) are summarized in Table C.6.

TABLE C.6: Regression coefficients for GHG sequestration per land area of forestland, croplands, and others, expressed in Equation (C.6)

| | Dependent variable: $\lambda_t^j$ | | | | | |
|---|---|---|---|---|---|---|
| | Forestland ($j = 1$) | Cropland ($j = 2$) | | Settlement ($j = 5$) | | Others ($j = 6$) |
| | (1999-2050) | (1999-2012) | (2013-2050) | (1999-2012) | (2013-2050) | (1999-2050) |
| *Coefficients* | | | | | | |
| $\alpha_{w=0}^j$ | -6.0179<br>(0.000) | 2.73<br>(0.000) | 4.1877<br>(0.000) | 4.1<br>(0.000) | 3.317<br>(0.000) | -4.1204<br>(0.000) |
| $\alpha_{w=1}^j$ | -0.4385<br>(0.000) | | -0.2315<br>(0.000) | -0.099<br>(0.000) | 2.676E-3<br>(0.000) | 0.8133<br>(0.000) |
| $\alpha_{w=2}^j$ | 0.065<br>(0.000) | -1.16E-3<br>(0.000) | 7.348E-3<br>(0.000) | 0.0106<br>(0.000) | -2.175E-4<br>(0.000) | -0.1615<br>(0.000) |
| $\alpha_{w=3}^j$ | -3.8E-3<br>(0.000) | | -1.512E-4<br>(0.000) | -6.941E-4<br>(0.000) | | 0.0118<br>(0.000) |
| $\alpha_{w=4}^j$ | 1.061E-4<br>(0.000) | | 1.7615E-6<br>(0.000) | 1.5415E-5<br>(0.000) | | -3.9311E-4<br>(0.000) |
| $\alpha_{w=5}^j$ | -1.372E-6<br>(0.000) | | -8.519E-9<br>(0.000) | | | 6.1244E-6<br>(0.000) |
| $\alpha_{w=6}^j$ | 6.75E-9<br>(0.000) | | | | | -3.623E-8<br>(0.000) |
| *Statistics* | | | | | | |
| $R^2$ | 0.987 | 0.973 | 0.999 | 0.998 | 0.999 | 0.879 |
| AIC | -254.00 | -154.581 | -522.50 | -207.79 | -475.04 | -102.51 |
| Observations | 52 | 23 | 38 | 23 | 38 | 52 |
| *Residuals* | | | | | | |
| Mean | 0.00 | 0.00 | 0.00 | 0.00 | 0 | 0.00 |
| Std. Dev. | 0.0768 | 0.0325 | 0.0009 | 0.009 | 0.002 | 0.329 |
| Shapiro-Wilk | 0.163 | 0.312 | 0.330 | 0.069 | 0.36 | 0.316 |
| Kolmogorov-Smirnov | 0.088 | 0.079 | 0.200 | 0.186 | 0.200 | 0.200 |

Emissions from grassland are modelled using a multivariate linear regression model built as a function of land use changes to and from grassland. The reason for this is that emissions in grassland do not primarily depend on the current area of grassland only, but instead, they depend on the land transition, particularly those resulting from converting grassland into forestland and settlements. Therefore, the model describing emissions from grassland is given by

$$\Lambda_t^j = \alpha_0^{gra} + \alpha_1^{gra} L_t^{gra-for} + \alpha_2^{gra} L_t^{gra-gra} + \alpha_3^{gra} L_t^{gra-set} + \epsilon^{gra}, \tag{C.7}$$

where $L_t^{gra-for}$, $L_t^{gra-gra}$, $L_t^{gra-set}$ are the area of grassland converted into forestland, remaining grassland, and converted into settlements respectively. The value for the correlation coefficients in Equation (C.7) are presented in Table C.7.

TABLE C.7: Regression coefficients for GHG sequestration per land area of grassland, expressed in Equation (C.7)

| | Dependent variable: $\Lambda_t^j$ |
|---|---|
| | Grassland ($j = 3$)<br>(1999-2050) |
| *Coefficients* | |
| $\alpha_0^{gra}$ | -32,658,745.17 |
| | (0.000) |
| $\alpha_1^{gra}$ | 126,315.55 |
| | (0.000) |
| $\alpha_2^{gra}$ | 1,722.08 |
| | (0.001) |
| $\alpha_3^{gra}$ | 37,010.05 |
| | (0.100) |
| *Statistics* | |
| R$^2$ | 0.913 |
| AIC | 536.15 |
| Observations | 22 |
| *Residuals* | |
| Mean | 0.00 |
| Std. Dev. | 167,164.2 |
| Shapiro-Wilk | 0.931 |
| Kolmogorov-Smirnov | 0.200 |

In the case of wetlands, GHG emissions in this land category are associated to peat extraction. Hence, we use a simple linear regression model to relate changes in peat extraction with changes in emissions from wetlands. The model has the form

$$\Lambda_{t+1}^{wet} - \Lambda_t^{wet} = \alpha_0^{wet} + \alpha_1^{wet}\xi_t + \epsilon^{wet}, \tag{C.8}$$

where $\xi_t$ are changes in peat extraction at time $t$ and the term $\epsilon^{wet}$ is normally distributed with zero-mean and standard deviation $\sigma^{wet}$. The correlation coefficients for Equation (C.8) are given in Table C.8.

Table C.8: Regression coefficients for GHG sequestration per land area of wetlands, expressed in Equation (C.8)

| | Dependent variable: $\Lambda_{t+1}^{wet} - \Lambda_{t}^{wet}$ |
|---|---|
| *Coefficients* | |
| $\alpha_0^{wet}$ | 0.3356 |
| | (0.382) |
| $\alpha_1^{wet}$ | 0.647 |
| | (0.000) |
| *Statistics* | |
| $R^2$ | 0.998 |
| AIC | 7.25 |
| Observations | 12 |
| *Residuals* | |
| Mean | 0.00 |
| Std. Dev. | 1.196 |
| Shapiro-Wilk | 0.382 |
| Kolmogorov-Smirnov | 0.340 |

# D

# Data for UK wealth Estimation

Table D.1: Current value of UK produced capital assets (£million), 1999-2013. Source: UK National Balance Sheet by Assets, Office for National Statistics, TheBlueBook (2014)

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fixed assets | - | - | - | - | - | 5580351 | 5805392 | 6316729 | 6773557 | 6363823 | 6419841 | 6969106 | 7097817 | 7283566 | 7614753 |
| Dwellings | 1848900 | 2106500 | 2267800 | 2737100 | 3054000 | 3426979 | 3555026 | 3915330 | 4313647 | 3922602 | 4048757 | 4259804 | 4281069 | 4443681 | 4653683 |
| Other buildings and structures | - | - | - | - | - | 1328260 | 1370215 | 1497159 | 1502985 | 1378660 | 1308499 | 1585035 | 1654186 | 1652893 | 1739387 |
| Buildings and other dwellings | 541400 | 610400 | 572900 | 592100 | 611200 | 661290 | 664165 | 752050 | 701329 | 596500 | 562223 | 796869 | 808795 | 774168 | 824741 |
| Other structures | 472400 | 486700 | 52100 | 541500 | 579700 | 666970 | 706050 | 745109 | 801656 | 782160 | 746276 | 788166 | 845391 | 878725 | 914646 |
| Machinery and equipment | - | - | - | - | - | 578746 | 623054 | 634154 | 665281 | 732412 | 744231 | 772317 | 791892 | 800092 | 814331 |
| Transport equipment | 58600 | 62500 | 65900 | 72600 | 82700 | 154010 | 155845 | 160095 | 177664 | 180572 | 174841 | 192594 | 187684 | 195010 | 199428 |
| ICT equipment | - | - | - | - | - | 21881 | 20098 | 20113 | 20162 | 23246 | 25216 | 26828 | 26741 | 27901 | 28642 |
| Other machinery and equipment | 380100 | 395400 | 406300 | 410600 | 415800 | 402855 | 447111 | 453946 | 467455 | 528594 | 544174 | 552895 | 577467 | 577181 | 586261 |
| Cultivated biological resources | 53300 | 54000 | 53200 | 53800 | 54700 | 86678 | 95364 | 106093 | 123093 | 157545 | 148427 | 178097 | 192913 | 203665 | 219032 |
| Intellectual property products | - | - | - | - | - | 159688 | 161733 | 163993 | 168550 | 172604 | 169927 | 173853 | 177757 | 183236 | 188320 |
| Inventories | 174900 | 174700 | 174700 | 180400 | 184800 | 197105 | 207475 | 217093 | 233395 | 245046 | 233459 | 244890 | 255727 | 259323 | 269089 |
| Total | 3710500 | 4176300 | 4334000 | 4888600 | 5344300 | 5777456 | 6012867 | 6533822 | 7006952 | 6608869 | 6653300 | 7213996 | 7353544 | 7542889 | 7883842 |

Table D.2: UK minerals export value (£million), 1999-2012. Source: British Geological Survey (BGS), UK Mineral Yearbook 2013, (BGS, 2013)

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silver | 113.8 | 356.5 | 160.1 | 143.9 | 268.6 | 188.1 | 360.1 | 164.31 | 408.43 | 1307.18 | 266.09 | 995.49 | 2049.74 | 778.19 |
| Chalk | 3.8 | 2.7 | 1.9 | 2.1 | 2.0 | 2.1 | 2.0 | 1.67 | 2.08 | 4.51 | 1.87 | 1.54 | 1.68 | 1.34 |
| Salt | 22.13 | 16.55 | 17.47 | 20.14 | 23.20 | 26.76 | 26.52 | 29.09 | 28.11 | 33.99 | 31.509 | 35.35 | 41.55 | 38.52 |
| Sand and gravel | 30.73 | 31.27 | 32.39 | 32.10 | 36.71 | 36.41 | 40.49 | 45.50 | 46.62 | 50.03 | 48.69 | 44.82 | 45.16 | 36.05 |
| Lead (Unwrought-Bullion) | 4e-3 | 0.143 | 0.0 | 0.014 | 0.039 | 0.014 | 0.33 | 0.072 | 0.00 | 0.00 | 0.00 | 0.04 | 1.40 | 2.96 |
| Peat (thousand cubic metres) | 3.62 | 3.40 | 2.99 | 2.84 | 3.76 | 3.64 | 3.63 | 3.54 | 4.25 | 4.86 | 7.55 | 6.65 | 7.423 | 6.85 |
| Limestone | 5.19 | 4.18 | 2.09 | 2.51 | 3.63 | 3.43 | 3.99 | 5.74 | 4.89 | 3.17 | 2.76 | 3.16 | 3.44 | 2.45 |
| Coal | 39.96 | 40.09 | 34.04 | 30.37 | 32.17 | 37.19 | 39.70 | 35.53 | 41.00 | 95.73 | 72.13 | 84.88 | 77.45 | 71.50 |

Table D.3: UK minerals export volume (Tonnes '000), 1999-2012. Source: British Geological Survey (BGS), UK Mineral Yearbook 2013, (BGS, 2013)

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Silver | - | - | - | - | - | - | - | - | 2.12e-4 | 3.98E-4 | 5.14E-4 | 5.06E-4 | 5.31E-4 | 2.3E-4 |
| Chalk | 9,667 | 9,213 | 8,205 | 8,587 | 8,066 | 7,997 | 7,105 | 7,376 | 7,566 | 5,874 | 4,047 | 3,626 | 3,996 | 3,473 |
| Salt | 3,000 | 3,000 | 3,000 | 3,200 | 3,200 | 2,800 | 2,800 | 2,800 | 2,800 | 5,565 | 6,166 | 6,666 | 6,060 | 6,152 |
| Sand and gravel | 100,953 | 101,622 | 101,397 | 94,424 | 91,211 | 97,333 | 94,666 | 92,107 | 93,236 | 85,473 | 66,226 | 617,000 | 63,100 | 56,600 |
| Lead (unwrought-bullion) | 40.63 | 36.70 | 36.00 | 36.00 | 9.00 | 36.00 | 36.00 | 36 | 36 | 36 | 36 | 36 | 36 | 36 |
| Peat (th $m^3$) | 1.65 | 1.63 | 1.81 | 0.97 | 2.01 | 1.26 | 1.50 | 1.593 | 0.89 | 0.76 | 0.89 | 1.00 | 0.82 | 0.57 |
| Limestone | 86,933 | 84,348 | 88,238 | 80,688 | 78,935 | 81,648 | 77,596 | 80,228 | 83,491 | 74,145 | 60,111 | 56,985 | 58,100 | 54,800 |
| Coal | 37,077 | 31,197 | 31,930 | 29,989 | 28,279 | 25,096 | 20,498 | 18,517 | 17,007 | 18,053 | 17,874 | 18,417 | 18,627 | 17,047 |

Table D.4: Data on UK oil & gas reserves, level of production, prices, capital expenditure associated to oil & gas activities, 1999-2014.
Source: UK OilandGasAuthority (2016)

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oil & NGL reserves (MM tonnes) | 1,120.0 | 1,010.0 | 955.0 | 920.0 | 857.0 | 816.0 | 816.0 | 777.0 | 780 | 769 | 768 | 751 | 787 | 810 | 746 | 746 |
| Gas reserves (MM tonnes) | 1,166.1 | 1,105.9 | 1,018.0 | 925.5 | 837.5 | 765.4 | 673.7 | 633.0 | 598.8 | 556.2 | 522.0 | 481.2 | 455.3 | 426.6 | 418.3 | - |
| Oil & NLG production (MM toe) | 137.1 | 126.2 | 116.7 | 115.9 | 106.1 | 95.4 | 84.7 | 76.6 | 76.6 | 71.7 | 68.2 | 63.0 | 51.9 | 48.6 | 49.9 | 49.9 |
| Gas production (MM toe) | 93.8 | 102.9 | 100.3 | 97.9 | 96.9 | 90. | 83.5 | 75.7 | 68.7 | 66.9 | 56.3 | 51.5 | 40.3 | 40.3 | 39.8 | 39.0 |
| Oil price (£/barrel) | 15.74 | 16.86 | 13.13 | 19.25 | 18.68 | 22.20 | 31.46 | 33.78 | 45.79 | 22.00 | 47.57 | 52.00 | 69.20 | 74.40 | 70.20 | 65.90 |
| Gas price (p/therm) | 17.3 | 20.4 | 14.6 | 20.4 | 27.5 | 48.5 | 55.2 | 40.8 | 67.6 | 27.2 | 36.3 | 43.4 | 60.6 | 63.4 | 63.5 | 59.6 |
| Capital expenditure (£billion) | 3.52 | 3.10 | 3.99 | 3.99 | 3.75 | 3.70 | 4.83 | 6.43 | 6.39 | 6.05 | 5.94 | 6.10 | 8.90 | 12.30 | 11.30 | 10.10 |
| Operating expenditure (£billion) | 4.25 | 4.36 | 4.35 | 4.60 | 4.50 | 4.66 | 5.11 | 5.60 | 5.99 | 7.02 | 7.33 | 7.20 | 7.20 | 7.70 | 8.10 | 8.50 |
| Exploration and appraisal (£billion) | 0.65 | 0.48 | 0.57 | 0.52 | 0.43 | 0.50 | 0.56 | 0.92 | 1.27 | 1.43 | 1.11 | 1.20 | 1.40 | 1.90 | 1.80 | 1.70 |
| Decommissioning cost (£billion) | - | - | - | - | - | 0.15 | 0.41 | 0.14 | 0.16 | 0.16 | 0.39 | 0.30 | 0.40 | 0.60 | 0.90 | 0.80 |

Table D.5: Output (in current £million) for the UK agriculture, fishery, and water supply industries, 1999-2012.
Source: UK National Accounts, Supply and Use tables, TheBlueBook (2014).

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agriculture | 4,272 | 4,316 | 4,643 | 4,440 | 4,478 | 4,569 | 4,877 | 5,365 | 5,903 | 6,233 | 6,155 | 6,220 | 6,396 | 6,688 |
| Fishery | 877 | 957 | 1,000 | 995 | 1,013 | 1,036 | 1,095 | 1,135 | 1,249 | 1,313 | 1,119 | 1,128 | 1,492 | 1,481 |
| Water supply | 4,272 | 4,316 | 4,643 | 4,440 | 4,478 | 4,569 | 4,877 | 5,365 | 5,903 | 6,233 | 6,155 | 6,220 | 6,396 | 6,688 |

Table D.6: UK stumpage price of coniferous standing wood, forest stocked area, and forest new planing, 1999-2014.
Source: UK Forestry Commission and National Forest Inventory (NFI), Timber statistics.

| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stumpage price (£/$m^3$) | 11.25 | 10.63 | 10.09 | 9.28 | 7.10 | 6.79 | 7.23 | 8.39 | 8.97 | 13.71 | 9.77 | 9.99 | 13.88 | 13.96 | 13.01 | 15.03 |
| Stocked area | 2,377 | 2,982 | 2,707 | 2,716 | 2,724 | 2,730 | 2,741 | 2,743 | 2,750 | 2,841 | 2,841 | 2,846 | 3,079 | 3,080 | 3,127 | 3,138 |
| New planting (ha) | 17,000 | 17,900 | 18,700 | 14,400 | 13,700 | 12,400 | 12,000 | 8,800 | 10,800 | 7,500 | 6,400 | 5,400 | 9,100 | 12,700 | 10,800 | 12,900 |

Table D.7: UK data on the number of visits to recreational sites, duration of visits, and average expenditure per visit, 2009-2013.
Source: UK MENE (2014).

| | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|
| No of visits to recreational places ('000) | 2,857,759 | 2,493,837 | 2,726,476 | 2,849,081 | 2,930,000 |
| Avg. number of visits per person in a year | 54.9 | 47.6 | 51.6 | 53.5 | 54.6 |
| Avg. duration of visits (h) | 2.02 | 1.97 | 1.97 | 2.12 | 2.02 |
| Expenditure on petrol and diesel (£/visits) | 3.74 | 3.86 | 3.94 | 3.8 | - |

TABLE D.8: UK annual greenhouse gas emissions (tCO2e/year) for the land categories forestland,croplands, grassland, wetlands, settlements and others, 1990-2012.
Source: Centre for Ecology & Hydrology, DEFRA.

| Year | Forestland | Croplands | Grassland | Wetlands | Settlements | Others | Net |
|---|---|---|---|---|---|---|---|
| 1990 | -15853784 | 16549376 | -6279166 | 481726 | 6871327 | -1682000 | 1893778 |
| 1991 | -15697878 | 1675757 | -6244794 | 489314 | 6813965 | -1416000 | 1815839 |
| 1992 | -16001685 | 16800401 | -6387205 | 483225 | 6758676 | -1109000 | 1320755 |
| 1993 | -15962646 | 16403231 | -6751307 | 476492 | 6710855 | -1003000 | 509603 |
| 1994 | -15835719 | 16492368 | -6816163 | 594624 | 6671055 | -793000 | 571883 |
| 1995 | -15045137 | 16648333 | -6821034 | 681085 | 6618221 | -1041000 | 1517217 |
| 1996 | -15483691 | 16735867 | -7009569 | 587254 | 6592560 | -1185000 | 780168 |
| 1997 | -15504472 | 16490734 | -7013451 | 524901 | 6573067 | -1365000 | 413210 |
| 1998 | -15908845 | 16390828 | -7368985 | 404940 | 6538956 | -1468000 | -625098 |
| 1999 | -16128625 | 16312977 | -7544650 | 540906 | 6552378 | -1513000 | -1122329 |
| 2000 | -16970038 | 15895862 | -7354372 | 537000 | 6509514 | -1268000 | -2071723 |
| 2001 | -17560104 | 15515361 | -7518646 | 582893 | 6476096 | -834000 | -3093273 |
| 2002 | -17803499 | 15226990 | -7580602 | 391139 | 6418284 | -267000 | -4019116 |
| 2003 | -18169632 | 15008024 | -7470019 | 628724 | 6385146 | 42000 | -4216951 |
| 2004 | -18209270 | 14644534 | -7718509 | 458965 | 6343398 | 368000 | -5178321 |
| 2005 | -18387872 | 14297325 | -7807421 | 517389 | 6298529 | -140000 | -5670828 |
| 2006 | -18160046 | 14085627 | -8087073 | 538653 | 6238511 | -544000 | -6203296 |
| 2007 | -18016959 | 13912552 | -8170351 | 377023 | 6200259 | -1293000 | -6547927 |
| 2008 | -17849167 | 13570959 | -8178545 | 335515 | 6149227 | - | -6695453 |
| 2009 | -17701018 | 13415998 | -8201247 | 375105 | 6127210 | - | -6945757 |
| 2010 | -17723675 | 12599966 | -7830328 | 402614 | 6193213 | - | -7260176 |
| 2011 | -17631049 | 12131188 | -7679685 | 359189 | 6265465 | - | -7495834 |
| 2012 | -16652646 | 11714385 | -7634995 | 359244 | 6336303 | - | -6990212 |

Table D.9: UK land area (in Kha) for the land categories forestland,croplands, grassland, wetlands, settlements and others, 1990-2013.
Source: Centre for Ecology & Hydrology, DEFRA.

Land area (Kha)

| Year | Forestland | Cropland | Grassland | Wetlands | Settlements | Other | Total |
|---|---|---|---|---|---|---|---|
| 1990 | 2,360 | 6,110 | 13,798 | 177 | 1,718 | 253 | 24,416 |
| 1991 | 2,380 | 6,119 | 13,759 | 177 | 1,728 | 253 | 24,416 |
| 1992 | 2,399 | 6,128 | 13,721 | 177 | 1,737 | 253 | 24,415 |
| 1993 | 2,416 | 6,137 | 13,687 | 176 | 1,746 | 253 | 24,415 |
| 1994 | 2,435 | 6,146 | 13,651 | 176 | 1,755 | 253 | 24,416 |
| 1995 | 2,452 | 6,155 | 13,615 | 176 | 1,764 | 253 | 24,415 |
| 1996 | 2,472 | 6,164 | 13,578 | 175 | 1,773 | 252 | 24,414 |
| 1997 | 2,488 | 6,173 | 13,545 | 175 | 1,782 | 252 | 24,415 |
| 1998 | 2,504 | 6,182 | 13,511 | 175 | 1,791 | 252 | 24,415 |
| 1999 | 2,520 | 6,191 | 13,477 | 174 | 1,800 | 252 | 24,414 |
| 2000 | 2,536 | 6,200 | 13,445 | 174 | 1,808 | 252 | 24,415 |
| 2001 | 2,553 | 6,145 | 13,476 | 174 | 1,815 | 252 | 24,415 |
| 2002 | 2,569 | 6,090 | 13,509 | 173 | 1,822 | 252 | 24,415 |
| 2003 | 2,580 | 6,036 | 13,546 | 173 | 1,829 | 251 | 24,415 |
| 2004 | 2,590 | 5,982 | 13,583 | 173 | 1,836 | 251 | 24,415 |
| 2005 | 2,599 | 5,928 | 13,622 | 173 | 1,843 | 251 | 24,416 |
| 2006 | 2,607 | 5,874 | 13,660 | 172 | 1,851 | 251 | 24,415 |
| 2007 | 2,612 | 5,821 | 13,700 | 172 | 1,859 | 251 | 24,415 |
| 2008 | 2,619 | 5,768 | 13,739 | 172 | 1,866 | 251 | 24,415 |
| 2009 | 2,624 | 5,715 | 13,780 | 172 | 1,874 | 250 | 24,415 |
| 2010 | 2,627 | 5,662 | 13,823 | 172 | 1,881 | 250 | 24,415 |
| 2011 | 2,628 | 5,666 | 13,800 | 172 | 1,899 | 250 | 24,415 |
| 2012 | 2,633 | 5,672 | 13,771 | 172 | 1,916 | 250 | 24,414 |
| 2013 | 2,643 | 5,678 | 13,738 | 172 | 1,942 | 250 | 24,423 |

# E

# Unsmoothing approach

Fisher et al. (1994) introduce a formal smoothing model to represent the smoothing phenomena experienced by NCREIF timber and farmland indices. The proposed model relates the *observed* returns $r_t^*$ in each time period with the *true* unobserved returns (i.e. not smoothed) $r_t$, using a weighted expression of the form

$$r_t^* = w_0 r_t + w(B) r_{t-1}, \tag{E.1}$$

where $w_0$ is a scalar between 0 and 1, and $w(B)$ is a polynomial function in terms of the lag operator $B$, such that

$$w(B) = w_1 + w_2 B + w_3 B^2 + \dots \tag{E.2}$$

From equation (E.1), the smoothed return can be represented by an autoregressive model as follows

$$r_t^* = \psi(B) r_{t-1}^* + w_0 r_t, \tag{E.3}$$

where $\psi(B)$ is a lag polynomial operator specified as $\psi(B) = \psi_1 + \psi_4 B^3$ to deal with seasonality in the appraisal smoothing. Thus, the smoothing model takes the form

$$r_t^* = \psi_0 + \psi_1 r_{t-1}^* + \psi_4 r_{t-4}^* + w_0 r_t. \tag{E.4}$$

Assuming that the mean of the observed returns remains the same as the true returns, and this is given by $E(r_t) = \mu$, we can now rewrite Equation (E.4) is terms of the true returns as

$$r_t = \mu + \frac{r_t^* - \psi_0 - (\psi_1 + \psi_4 B^3) r_{t-1}^*}{w_0} \tag{E.5}$$

The coefficients $\psi_0$, $\psi_1$, and $\psi_4$ can be empirically estimated from the observable data by assuming that the underlying true returns are uncorrelated across time, implying that the term $w_0 r_t$ is white noise. To estimate the value of $w_0$ an additional condition must be imposed over the volatility of the true returns (i.e. the volatility of the true returns is $\kappa\%$). This results in

$$w_0 = \frac{\sigma(r_t^* - \psi(B) r_{t-1}^*)}{\sigma(r_p)} = \frac{\sigma(r_t^* - \psi(B) r_{t-1}^*)}{\kappa}, \tag{E.6}$$

At this point, Fisher et al. (1994) assume that the volatility of the true unsmoothed returns of the type represented in the NCREIF indexes equal approximately one-half that of the S&P500 (i.e. $\kappa = \sigma_{SP}/2$), based on practitioners perception. This notion seems to be supported by Cremers (2013), Malinowski et al. (2012) and Davis et al. (2014) on their analysis of timber and farmland returns. Alternatively, Scholtens and Spierdijk (2010) report that the true volatility of the unsmoothed NCREIF timberland index is 'likely' to be in the range 3-12%.

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