UNIVERSIDADE TÉCNICA DE LISBOA

INSTITUTO SUPERIOR DE ECONOMIA E GESTÃO

MESTRADO EM: Economia

ECONOMIC INCENTIVES FOR CARBON SEQUESTRATION IN GRASSLAND SOILS:

AN OFFER YOU CANNOT REFUSE

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Março 2008

Glossary

ALE	Alentejo
BI	Beira Interior
CDM	Clean Development Mechanism
CBT	Chow's Breakout Test
CFT	Chow's Forecast Test
CU	Cattle Unit
DM	Dry Matter
EKC	Environmental Kuznets Curve
EU	European Union
FNG	Fertilized Natural Grasslands
GDP	Gross Domestic Product
GHG	Greenhouse Gas
JI	Joint Implementation
KP	Kyoto Protocol
LULUCF	Land Use, Land Use Change and Forestry
NG	Natural Grasslands
NPV	Net Present Value
PCF	Portuguese Carbon Fund
PNAC	National Programme for Climate Change
QF	Quinta da França
RO	Ribatejo e Oeste
SBPPRL	Sown Biodiverse Permanent Pastures Rich in Legumes
SOM	Soil Organic Matter
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

In this dissertation in Economics we determine the market price for contracts between farmers and an economic agent who wishes to compensate its emissions by financing carbon sequestration in grassland management projects. We focus on sown biodiverse permanent pastures rich in legumes, which are a Portuguese innovation that will be accounted under the item "grassland management" of Article 3.4 of the Kyoto Protocol. The sum each farmer receives must be: (1) a function of sequestered carbon, and (2) interesting enough for him to adopt the system.

After an overview on greenhouse gases and agriculture, we start by determining the carbon sink potential of the system, as well as the costs and revenue associated with the land use option. This is our base information to build supply and demand curves for a specific case, the case of the Portuguese Carbon Fund, who may finance these projects if they prove to be a competitive alternative to other mechanisms of emissions reduction. We use the concept of Net Present Value for the calculations, and introduce farmer revenue expectations in a microeconomic model for land use choice.

We found that price is completely demand-driven, while the total quantity sequestered is supply-driven. Price depends on the discount rate and the type of contract (whether it is a "per hectare" or a "per tonne" contract). We obtained, as a market equilibrium price for "per hectare" contracts, a range of 4.80-39.20 € per hectare, which would yield an additional quantity of 1.26 Mton CO_2 sequestered. We also obtained the market price in "per tonne" contracts, which is 1.02-8.50 € per tonne of sequestered carbon, and a quantity of 1.65-1.86 Mton CO_2. We also found that "per tonne" contracts are more cost-effective, since the higher sequestration compensates the monitorization costs.

Keywords

Carbon sequestration, resource conservation contracts, grassland management, supply curve, demand curve, market equilibrium price.

Resumo

A presente dissertação de Mestrado em Economia tem por objectivo determinar o preço de mercado para contratos a oferecer a agricultores por um agente económico que pretenda diminuir as suas emissões de gases de efeito de estufa financiando projectos de gestão de pastagens. Estudam-se pastagens permanentes biodiversas ricas em leguminosas, que são uma inovação Portuguesa que será contabilizada no item "gestão de pastagens" do Artigo 3.4 do Protocolo de Quioto. A quantia a oferecer ao agricultor é função do carbono efectivamente sequestrado e deve ser interessante o suficiente para que este aceite adoptar este sistema.

Após uma contextualização da ligação entre gases de efeito de estufa e o sector agrícola, começa-se por determinar o potencial de sequestro de carbono do sistema, tal como custos e receitas associados à sua adopção. Esta foi a informação de base que permitiu construi curvas de procura e oferta para um caso específico, o Fundo Português de Carbono, que poderá financiar estes projectos caso se demonstrem competitivos face a alternativas de redução de emissões. Utiliza-se o conceito de Valor Presente Líquido para os cálculos, e foram introduzem-se expectativas dos agricultores num modelo microeconómico para escolha de uso do solo.

Concluiu-se que o preço é determinado pela procura e a quantidade total sequestrada pela oferta. O preço depende da taxa de desconto e do tipo de contrato (se é por hectare ou por tonelada). Obteve-se então um preço de equilíbrio em contratos por hectare de 4,80-39,20 €.ha^{-1}, o que representaria um sequestro anual adicional de 1,26 Mton CO_2. O preço de equilíbrio obtido em contratos por tonelada é de 1,02-8,50 €.ton^{-1} CO_2, para uma quantidade adicional sequestrada de 1,65-1,86 Mton CO_2. Concluiu-se ainda que os contratos por tonelada são mais eficientes, pois um sequestro mais elevado compensa os custos de monitorização.

Palavras-chave

Sequestro de carbono, contratos de conservação de recursos, gestão de pastagens, curva de oferta, curva de procura, preço de equilíbrio de mercado.

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Acknowledgements

First and foremost, I would like to thank my advisor, Miguel St. Aubyn, for the interest and patience for the twists and turns that the present dissertation was subjected to. I also thank my co-advisor, Tiago Domingos, without whom I would not have enrolled in the Masters course in Economics, and without who this dissertation would have never been completed.

I thank my work colleagues, Ana Simões, Tatiana Valada, Ana Rosa Trancoso, Cristina Marta-Pedroso, Rui Mota, Gonçalo Abrunhosa, João Rodrigues, Gonçalo Marques, Oriana Rodrigues and Tânia Sousa. I thank them for useful comments and recommendations, but, above all else, I thank them for a fun and healthy working environment. On a personal note, I wish to thank my dear friend Clara Fiúza, who is always there, my parents for the long hours of waiting, and particularly Lígia Reyes.

I would also like to thank the co-authors of the papers resulting from this dissertation, namely João Dias, A.P.S.V. Costa, Ramiro Oliveira, Lídia Farroupas, Fátima Calouro, Ana Barradas, João Paulo Carneiro, Paulo Canaveira, Teresa Avelar, Gotlieb Basch, Carlos Carmona Belo, David Crespo, Vítor Góis Ferreira and Casimiro Martins. I also acknowledge useful comments by Nuno Calado, Pedro Chambel Leitão and Alexandra Lopes. Furthermore, I wish to thank all my professors and colleagues during the lectoral part of the course, namely Nuno Costa, José Jardim, Renata Mesquita and Gui Pedro Mendonça, who made Economics appeal to me.

I also thank most data I used to projects "AGRO 87 – Biodiverse Permanent Pastures Rich in Legumes", developed between 2001 and 2004, and "AGRO 71 – Recovery and Improvement With Pastures of Degraded Soil in Alentejo", from 1997 to 2004. Part of this work was supported by project Extensity – Environmental and Sustainability Management Systems in Extensive Agriculture, funded by the Life Program of the European Commission (LIFE03 ENV/P/505) and by Project PTDC/AGR – AAM/69637/2006, funded by Fundação para a

Ciência e Tecnologia. Some of this work is also integrated in my PhD. Thesis, which is supported by Fundação para a Ciência e Tecnologia by grant SFRH/BD/25399/2005.

1. Introduction

For more than two decades, there has been an increasing worry with large scale climate changes, assumingly caused by human intervention. Global warming has been acknowledged by most countries, which also recognize the need for an effective fight on anthropogenic causes. The main driver of the effect is the emissions of greenhouse gases (GHG), namely carbon dioxide (CO_2)[1], methane (CH_4) and di-nitrogen monoxide (N_2O)[2], all of which result from human activities.

1.1. The Kyoto Protocol

1.1.1. Setting international goals

The urgent need to respond to the threats of climate change led to the United Nations Framework Convention on Climate Change (UNFCCC, 1998). The framework of this Convention paved the way for the appearance of a mandatory agreement between most countries, stipulating for each a maximum emissions scenario (Harvey, 2004). This agreement was named after the Japanese city in which it was signed, and became known as the Kyoto Protocol (KP). The KP set quantitative targets for each country or assembly of countries, in order to reach a worldwide reduction in net GHG emissions of 5% by 2010, in relation to 1990. The finishing level is obtained by averaging emissions in the years between 2008 and 2012. If any country cannot keep its designated upper bound, there are four mechanisms that it can recur to:

- The carbon-trading scheme, in which over-compliers sell their exceeding credits to under-compliers using a market price;

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[1] Throughout the present dissertation, we use the terms "CO_2", "carbon dioxide" and "carbon" as synonyms.

[2] The greenhouse effect potential of each gas is defined in relation to the potential of CO_2. Therefore, all emissions are measured as equivalent CO_2, or CO_2eq.

- Clean Development Mechanisms (CDM), in which developed signatory countries execute projects leading to a GHG emissions reduction in developing countries, and the credits revert to their favor;
- Joint Implementation (JI), in which developed signatory countries execute projects in other signatory countries, with the same effect as CDM;
- Investments in funds managed by independent third parties, or other alternative instruments.

Unlike many important polluters, like most notably the United States of America, Portugal signed the KP. We now turn to the national consequences of the agreement.

1.1.2. The Portuguese target

In the KP, Portugal agreed not to increase its GHG emissions, in relation to 1990, by more than 27%. According to the Portuguese Environmental Agency (APA, 2006), Portugal is one of European Union (EU) with the lowest *per capita* GHG emissions. However, in the period from 1990 to 2003, its emissions increased 37%, an increase over the KP limit (APA, 2006b). The Portuguese deficit will likely be about 3,73 Mton $CO_2eq.yr^{-1}$.

Faced with the risk of under-compliance of the KP, Portugal created an instrument of analysis, which was the National Programme for Climate Change (PNAC, 2006). The function of PNAC is to assess the current situation in terms of the compliance of the KP, build scenarios for future trends, and try to determine additional measures necessary to meet the national goal.

PNAC defined additional measures in almost all economic sectors, and gave birth to an emissions limit for polluting industries within the country (APA, 2006a). Amongst those additional measures, Portugal decided to elect some optional mechanisms, which countries are not required to account for in their inventories. The next section is about such mechanisms.

1.1.3. Optional mechanisms of the Kyoto Protocol

There are strict stipulations in the KP as to how a country's emissions inventory is made, namely regarding what to account. However, there are some items that remain as an option for each signatory country. These options relate to the agro-forestry sector, and are the so-called Land Use, Land Use Change and Forestry (LULUCF) activities. LULUCF activities do not promote a decrease in emissions, but the sequestration of CO_2 in soils and living biomass. Carbon sequestration is not permanent, which is a problem we will address in due time. However, the KP does not tackle the issue of permanence, and therefore this mechanism, in the present period, is equivalent to emissions reduction.

Portugal plays a leading role in its account in the KP, since it decided to elect, in the framework of these voluntary LULUCF activities under Article 3.4 of the KP, the activities: "Grassland Management", "Cropland Management" and "Forest Management". The rationale for this choice will be addressed latter.

However, even using such additional measures as these, PNAC (2006) still points to an excess in emissions. This requires Portugal to search for new possibilities to compensate the high emissions. To such effect, a Carbon Fund was established, and we now characterize it in the next section.

1.2. The Portuguese carbon fund

The Portuguese Carbon Fund (PCF) is an operational instrument which intends to finance several actions with positive returns regarding a decrease in GHG emissions. These actions must be additional to those considered by PNAC, since they mean to fill the current gap of emissions. The fund was started in 2006, with an initial sum of 6 000 000 €.

The fund may be used to acquire credits using one of the four resorts considered in the KP, or, alternatively, it may be used to finance national projects. Even though the political priorities are yet to be defined, it is possible to assume that national projects are the most interesting option. First, the use of any KP scheme would mean that Portugal would be indirectly investing in forestation or energy efficient projects elsewhere in the world. Second, while CDM and JI have many practical implementation difficulties, carbon-trading is subjected to market uncertainties and price fluctuations that make it unreliable as a long-term policy. The emissions trading scheme was, however, designed to guarantee that reductions occur where it is cheaper to generate credits (Wagner and Wegmayr, 2006). The international price thus sets a standard for the price of national projects.

If national projects were used, then the investments would occur in national territory, and since projects may be selected by the PCF itself, there is a possibility of strong complementarities between GHG reduction and other environmental and policy objectives. Carbon sequestration via LULUCF activities becomes especially interesting due to this desirable quality of complementarity, since the contemplated activities present a wide array of other advantages, which are referred in Chapter 3. In the following chapter, we explore the impact of the agro-forestry sector in national emissions, to justify the choice of grassland management in our study.

2. GHG and the agro-forestry sector

In the second chapter, we present the motivation for this work. In Chapter 1, we started by reviewing the path to the signing of the Kyoto Protocol, which led to the need for Portugal to restrain its carbon dioxide emissions to a given maximum value. We also showed how the fact that Portugal exceeded its maximum emissions required further measures, in order to keep its goal, and what that meant to a specific economic sector, namely agriculture. We now characterize the sector in terms of its contributions to the national carbon budget, thus building the bridge to the third chapter, which refers to grassland management.

2.1. Overview

The rise in GHG concentrations in the atmosphere is mostly due to fossil fuel consumption. However, a significant fraction of the responsibility for emissions is due to land use changes, such as intensive agriculture, livestock production of deforestation. It is believed that land use and land management practices are responsible for 12 to 42% of total GHG emissions (Watson *et al.*, 2000). It is also estimated that about 80% of terrestrial carbon pools are stored in soils (Watson *et al.*, 2000).

While most sectors are net polluters, where all that can be done is to minimize CO_2 emissions, the agro-forestry sector is responsible for CO_2 sequestration in soils and living biomass. Energetic biocrops and many sub-products may also be used to produce renewable energy, which substitutes fossil fuels.

However, the current balance of this sector is negative. According to APA (2006b), the Portuguese agro-forestry sector contributes to 10% of the country's total GHG emissions. This sector has increased its emissions in 7% since 1990, thus contributing to the national deficit. Considering particular GHG, agriculture is responsible for 65% of national N_2O emissions (APA, 2006b), associated with nitrogen fertilizer use and manure management (EEA, 2006).

Agriculture is also responsible for 35% of national CH_4 emissions (APA, 2006b), mainly due to animal production (EEA, 2006).

These emissions are not neglectable in the Portuguese or in any case. Greenhouse gases and livestock production are deeply related, as shown in a recent FAO report (Steinfeld *et al.*, 2006). This report states that the world's livestock sector is responsible for 18% of greenhouse gases emissions (measured in CO_2 equivalent), which is a higher share than transport. Emissions from livestock are deeply related to meat consumption.

It may still be argued that animal CH_4 emissions decrease with economic growth, considering CH_4 as a proxy for sustainable meat production, and therefore also consumption. This hypothesis states that an emergent developing country tends to demand increasing quantities of meat. But since meat is an inferior good, as the country gets richer, animal emissions will necessarily decrease, both from (1) less meat demand and from (2) product differentiation. In case (1), CH_4 emissions drop directly. In case (2), people prefer sustainable meat products, obtained through extensive animal production. Note that this may not be the case if self-provisioning levels change significantly.

To test such hypothesis, in a recent working paper, Giles and Mosk (2005) explicitly relate GDP and animal CH_4 emissions from enteric fermentation for New Zealand with an Environmental Kuznets Curve (EKC). The Kuznets curve came up in 1955 as a way to plot a country's inequality level and its income by an inverted U-shaped curve (Kuznets, 1955). In the 1990's, some studies (World Bank, 1992; Grossman and Krueger, 1993) largely broadened the concept's scope by interpreting the pattern as a relation between environmental impact and income. This is referred to as an EKC. The underlying theory is that, at an early stage of its development, an economy requires a large amount of resources, but at a given point technological development and consumer choice lead to a cleaner growth path (Giles and Mosk, 2003).

Since then, several studies focused on assessing the relation between environmental degradation and Gross Domestic Product (GDP) for particular pollutant impacts, but mainly from industry emissions. Panayoto (2003), in a review of such studies, states the existence of mainly three patterns: linear, quadratic (inverted U-shaped) and cubic (N-shaped, corresponding to a rebound effect). It is common for EKC studies to use cross-section estimation methods (Panayoto, 2003), even though there are some examples of panel data or time series models.

Giles and Mosk's (2005) study finds evidence of the quadratic relation that supports the idea that emissions "naturally" decrease with economic growth for New Zealand. Before focusing on the need to offset livestock emissions, regarding the Portuguese KP deficit, we needed to determine if we could find such a pattern in the national case. Therefore, the next section is the application of the EKC concept to emissions from livestock in Portugal.

2.2. Economic growth and livestock emissions in Portugal[3]

In this section we intend to determine if there is an empirical pattern between animal CH_4 emissions and GDP for Portugal. We consider emissions both from enteric fermentation and manure management. The main objective of this study was to assess the level of decoupling between both variables, but we also had several methodological sub-objectives. For example, we repeat calculations for total GDP and emissions (hereafter named "level variables") and for *per capita* GDP and emissions (hereafter named "*per capita* variables"), and compare both.

Usually, three problems are addressed when estimating an EKC: (1) economic growth unidirectionally causes environmental quality, (2) trade relations associated with growth are exogenous to the model, and thus do not influence the environment, and (3) data and estimation method problems (Mota and Dias, 2006). We tried to cope with problems (2) and (3). In order to do so, we used a time series method, as we intended to study the Portuguese growth path.

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[3] This section was submitted as a research paper to Ecological Economics (Teixeira and Dias, 2007) in September 7, and is currently under review.

This work is structured as follows. In the next sub-section, we present and briefly interpret the data used. Then, we characterize the estimation procedure and show the results obtained. Finally, we discuss those results and draw some conclusions regarding the question at hand.

2.2.1. Data

Data for Portuguese GDP time series from 1961 to 2004 was obtained in AMECO (2006). As for CH_4 emissions, we began by using FAOSTAT (2006) to collect data for animal production. We chose cattle, poultry, goats, swine and sheep, as well as the aggregated sum of all (total). Since we know the CH_4 emission factors for each type of animal (IPCC, 1997), it is easy to obtain net CH_4 emissions by multiplying them by the number of animals. We also obtained time series for live animals' imports and processed meat's imports from FAOSTAT (2006). Population data was obtained at INE (2006).

The total emissions' series shows an abrupt decline in 1974 and a steep increase after 1976. Such trace happens because of the Portuguese revolution of 1974, and the agricultural reform that followed it. In the case of 1976's production increase, it was almost completely caused by swine production. The series follows the trend previous to 1974 after 1986, when Portugal joins the European Union.

2.2.2. Modelling and estimation

We use a standard time series model to estimate the relation between GDP and CH_4 emissions for each type of animal. Since we are searching for an EKC pattern, we include non-linear terms. We used the software EViews 5.0 (2004).

The model we propose is:

$$CH_{4i,t} = \alpha_i + \beta_{1i} y_t + \beta_{2i} y_t^2 + \beta_{3i} y_t^3 + \Lambda V_{i,t} + \varepsilon_{i,t} \tag{1.1}$$

In Equation (1.1), $CH_{4i,t}$ are methane emissions for animal type i at time period t, y_t is GDP, and $V_{i,t}$ is a vector of other variables that may be included, with associated coefficients Λ. We will estimate the model for an open and a close economy, and so $V_{i,t}$ will be either zero or equal to the trade balance of imports and exports. As stated in Equation (1.1), the EKC hypothesis is that $\beta_{1i} > 0$, $\beta_{2i} < 0$ and $\beta_{3i} = 0$. If $\beta_{3i} \neq 0$, there is an N-shaped curve.

We will consider the linear, quadratic and cubic terms of GDP to assess which of the three patterns found in the literature is the most accurate. It is also for this reason that we have chosen an additive model. If we had chosen a logarithmic model, all variables considered would have to be significant, but that is exactly what we want to test (Mota and Dias, 2006).

In order to avoid the common literature procedure of blind estimation, without paying any attention to the statistical properties of data (Stern, 2004), we performed a series of tests to ensure that correlations between series were not spurious. This work's method can be separated in the following steps:

- Univariate analysis of series used:
    - Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests on each series, in order to test the null hypothesis of a unit root, which would mean that the series were I(1)[4].
    - Study structural changes and correct them in the series used. First, the year of the breaks should be determined endogenously, and then it should be tested if they are significant.
- Cointegration test:
    - Define a vector auto-regressive (VAR) model for each variable to determine lag length for the Johansen cointegration test,
    - Johansen test, to determine how many (if any) cointegration relations exist between variables.

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[4] First order integrated.

- Estimation.

2.2.3. Results for total emissions

2.2.3.1. Univariate analysis

Starting with the univariate analysis, we performed an ADF test, whose results are shown in Table 1. In each case, the null hypothesis of the existence of at least one unit root could not be rejected under the 1% critical value. Then, we repeated the test in first differences. If the null hypothesis was rejected, then the differentiated series did not have a unit root (was stationary), and we could conclude that the level series was indeed I(1). The only cases in which this did not happen were, as expected, GDP^2 and GDP^3, and also the series for sheep imports and population (which is highly non linear). Results for the PP test are similar.

Table 1 – t-statistics for the ADF test of all series used. We accepted H0 in all level cases, and rejected H0 in all first differences cases except GDP2, GDP3, ImpSheepHead, ImpSheepMton and Pop.

	H_0: at least I(1) t-statistic			
	Constant & Trend		Constant	
	Level	First Differences	Level	First Differences
GDP	-3.308820	-5.199935	1.136955	-5.012925
GDP2	-1.975812	-5.259749	4.450701	**-2.964068**
GDP3	3.526937	**-1.180628**	5.149654	**1.058671**
Cattle	-3.241903	-6.913063	-1.756199	-6.981884
Poultry	-1.697865	-5.487421	0.247374	-5.493378
Goats	-0.353001	-6.847258	-1.059581	-6.345689
Swine	-1.343992	-5.562995	-1.714519	-5.495443
Sheep	-1.813668	-7.142956	-1.393744	-7.213914
Total	-2.052542	-4.740467	-1.945773	-4.704109
ImpCattleHead	-1.868586	-10.577100	-1.638556	-10.644100
ImpCattleMton	-2.690293	-7.094334	-1.269724	-7.142691
ImpPoultryHead	-2.214729	-7.679812	-0.625849	-7.686909
ImpPoultryMton	0.974405	-6.499682	2.952021	-6.894047
ImpGoatsHead	-3.293072	-7.301701	-2.252525	-7.401804
ImpGoatsMton	0.433255	-7.496262	2.203406	-6.288844
ImpSwineHead	-0.195811	-6.871150	1.599039	-5.992616
ImpSwineMton	0.974405	-6.499682	2.952021	-6.894047
ImpSheepHead	-3.198221	**-4.181452**	-2.206671	-6.339977
ImpSheepMton	-2.290691	**-3.339368**	-1.096509	**-3.403571**
ImpTotalHead	-0.178057	-7.791161	2.024473	-6.354851
ImpTotalMton	-0.939266	-7.905806	1.049504	-7.293979
Pop	-2.637236	**-3.158539**	-0.596100	**-3.150859**
1% critical value[5]	-4.192337	-4.211868	-3.610453	-3.610453

Next, we studied structural changes. This is a problem that should always be addressed, otherwise possibly resulting in large biases on regression results (Mota and Dias, 2006). Visually, there are the aforementioned breaks around 1974 and 1976 due to the Portuguese revolution and agricultural reform. Still, the correct year to break the series, and weather it is a trend or intercept break, is hard to determine visually. Therefore, we used a method to determine the structure breaks endogenously.

We applied a crash/change additive outlier (AO) model, which maximizes the F-statistics that chooses the point that better adjusts to the break parameters (Gui Pedro Mendonça, personal communication). The years obtained for structure break in each series are shown in Table 2

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[5] H_0 is rejected if the calculated t-statistics is lower (more negative) than the critical value.

(second column). Since we did not want to over-complexify the model, we only searched for two structural breaks at maximum.

Table 2 – Year(s) of the structure break(s) for each series.

Series	Years (before Chow Test)	Years (after Chow Test)
GDP	1983	1983
GDP^2	1988, 1998	1988, 1998
GDP^3	1987, 1998	1987, 1998
Cattle	1978	-
Goats	1995	1995
Poultry	1974, 1976	1974, 1976
Sheep	1970	-
Swine	1979, 1987	1979, 1987
Total	1975, 1979	1979
ImpCattleHead	1991	1991
ImpCattleMton	1979	1979
ImpPoultryHead	1996	1996
ImpPoultryMton	1989	1989
ImpGoatsHead	1987	1987
ImpGoatsMton	1996	1996
ImpSwineHead	1994	1994
ImpSwineMton	1989	1989
ImpSheepHead	1998	1998
ImpSheepMton	1989	1989
ImpTotalHead	1994	1994
ImpTotalMton	1981	1981
Pop	1975, 1987	1975

Knowing the structure break year, we used the Chow test to see which break was significant. There are two types of Chow test that may be computed with EViews: Chow's Breakout Test (CBT) and Chow's Forecast Test (CFT). CBT fits the equation separately for each subsample in order to determine if there are significant differences in the estimated equations. If so, there is a structural change. The CFT estimates a model using the full set of data and another using a long subperiod. If significant differences exist between them, the estimated relation is unstable (EViews, 2004).

In order to perform the CBT and CFT in each series, we estimated a simple regression with an intercept and a trend, and used the breakout points in the second column of Table 2. The years which are significant structural breaks are shown in the third column. Next, we reanalyzed the series with a significant structure break with an ADF test that contemplates breaks (Nunes, 2004; Vogelsang and Perron, 1998).

2.2.3.2. Cointegration test

Then, we performed a cointegration test. In a non-spurious non-stationary time series regression two criteria have to be met: (1) at least one of the exogenous variables has to be integrated in the same order as the endogenous variable, and (2) the variables must be cointegrated. Two series are cointegrated if there is a stationary, i.e., I(0), linear combination of them. Most common cointegration tests analyze the residuals of the regression, in order to assess if they are stationary. In this work, we chose the Johansen cointegration test.

Since the Johansen test, among other specifications, is sensitive to lag length, we began by building VAR models for all series. That allowed us to withdraw optimum lag length with which to run the cointegration test. This is done in EViews by estimating an unrestricted VAR with intercept and trend for each variable, and then studying lag length criteria. The maximum lag is determined with a 5% critical value for the sequential modified LR test statistic.

We then used the Johansen test with the lag length indicated for each case. We included in the test four common exogenous variables: GDP, GDP^2, GDP^3 and population. For each type of animal, we included imported animals and meat. Results summary is shown in Table 3. There is always a data trend and test type combination that yields at least one cointegration relation. These results allowed us to estimate our model.

Table 3 – Number of cointegration relations for each series, depending on data trend and test type. Exogenous variables included are GDP, GDP^2, GDP^3 and those specific to each case. At least one relation exists for each case studied.

	Number of Cointegrating Relations				
Data Trend:	None	None	Linear	Linear	Quadratic
Test Type:	No Intercept	Intercept	Intercept	Intercept	Intercept
	No Trend	No Trend	No Trend	Trend	Trend
Cattle	1	1	1	1	1
Goats	1	1	1	1	1
Poultry	1	1	1	1	1
Sheep	1	1	1	0	1
Swine	1	0	1	1	1
Total	1	1	1	1	1

2.2.3.3. *Estimation*

We could then finally estimate our model as follows

$$\begin{aligned} Total_t &= C(1) + C(2)t + C(3)D_t + C(4)y_t + C(5)y_t^2 + C(6)y_t^3 \\ &+ C(7)\mathrm{Pop} + C(8)\mathrm{ImpTotalHead} + c(9)\mathrm{ImpTotalMton} + \varepsilon_{i,t} \end{aligned} \quad (1.2)$$

This is an example for total emissions. The second term is the trend term, and the third one is the dummy due to the structural break of Total. Note that for each of the other series, the corresponding dummy is represented in results with the suffix "1". For example, we have chosen C(4) to be the coefficient referring to GDP. Therefore, the GDP dummy has the associated coefficient C(41).

Since there are a lot of variables, we used an iterative method that eliminated the least significant variables in each iteration, and then re-estimated the model until only 5% significant variables subsided. It should be noticed that between the model with all variables included and the corresponding simplified model there is almost no loss of R^2. Final results from the ordinary least squares (OLS) regression are shown in Table 4 for each type of animal, as well as total emissions.

Table 4 – Summary of the estimation results for each type of animal.

	Cattle	Goats	Poultry	Sheep	Swine	Total
C(1)	7.16E+07	3.06E+06	2.12E+08	1.10E+08	8.20E+07	
C(2)		-1.36E+05		1.11E+06	2.30E+06	
C(31)			3.53E+07		6.45E+07	-2.35E+07
C(32)						4.42E+07
C(4)				-3.21E+06		
C(41)						
C(5)	7.49E+06	1.82E+06	-5.55E+06	3.84E+04		3.18E+04
C(51)		-1.13E+06			-2.68E+07	-3.32E+07
C(6)	-4.54E+06		4.70E+06	-1.55E+06		-1.79E+06
C(61)					-3.70E+07	-4.57E+07
C(7)			-2.32E+06			2.24E+06
C(71)						
C(8)	-2.92E+06					-5.02E+06
C(81)						
C(9)					-3.98E+06	
C(91)						1.33E+07
R-squared	8.25E-01	8.75E-01	6.58E-01	7.59E-01	9.58E-01	9.81E-01
Adjusted R-squared	8.12E-01	8.66E-01	6.23E-01	7.34E-01	9.53E-01	9.76E-01
S.E. of regression	3.40E+00	2.50E-01	4.87E+00	3.38E+00	7.02E+00	6.01E+00
Sum squared resid	4.62E+08	2.50E+06	9.24E+08	4.45E+08	1.87E+09	1.27E+09
Log likelihood	-7.22E+00	-6.07E+00	-7.37E+00	-7.21E+06	-7.53E+06	-7.44E+06
Mean dependent var	8.82E+01	4.57E+01	7.57E+01	4.89E+01	1.31E+02	2.80E+02
S.D. dependent var	7.83E+00	6.82E+00	7.92E+00	6.55E+00	3.22E+01	3.91E+01
Akaike info criterion	3.30E+00	2.78E+00	3.37E+00	3.30E+00	3.45E+00	3.42E+00
Schwarz criterion	3.32E+00	2.79E+00	3.39E+00	3.32E+00	3.47E+00	3.46E+00
Durbin-Watson stat	1.08E+00	1.57E+00	1.70E+00	8.06E-01	1.80E+00	2.50E+00
EKC?	**No**	**No**	**No**	**No**	**No**	**No**

We can see that in every case there is no statistical evidence of an EKC. Population growth is only statistically significant in the case of swine. The impact of imports is usually negative, which is probably explained by the fact that there is substitution between domestic production and importation. The Durbin-Watson statistics indicates that there are no serial correlation traces in the residues[6]. Figure 1 plots original and estimated data for total emissions. It may be seen that our (simplified) model adjusts perfectly to the data.

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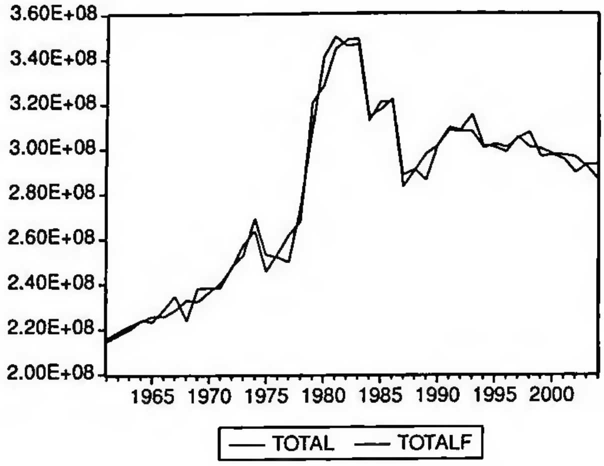
[6] The Durbin-Watson critical values for 13 variables and 44 observations are D_L=0.86856 and D_H=2.31237. Our test statistics is in between.

Figure 1 – Comparison between original data (TOTAL) for total emissions and the estimated model (TOTALF).



2.2.4. Results for per capita emissions

In order to study whether different model specifications would yield different results, we estimated the same model again, but this time using *per capita* variables. Therefore, we divided all the series used by the population level.

2.2.4.1. Univariate analysis

Again, we began by performing an ADF test to determine if the series used are still I(1). Results are shown in Table 5. The test indicates that GDP^2 and GDP^3 are of a higher order than I(1), and ImpSheepMton is I(0) (since we reject H_0 with the level series).

We also did a PP test that confirmed the findings of the ADF test in what respects to GDP^2 and GDP^3, but this test indicates that the ImpSheepMton series is I(1). We assumed that is the case in the rest of this chapter. Another difference is that the test indicates that GDP may not be I(1). Still, since this is an isolate case, we assumed that it is I(1), based on the ADF test results.

Table 5 – t-statistics for the ADF test of all series used in per capita terms. We accepted H0 in all level cases, and rejected H0 in all first differences cases except GDP2, GDP3 and ImpSheepMton.

	H_0: at least I(1) t-statistic			
	Constant & Trend		Constant	
	Level	First Differences	Level	First Differences
GDP	-3.267770	-4.531634	-0.017399	-4.605284
GDP2	-2.366050	-4.940799	2.132887	**-3.245235**
GDP3	-2.065947	-4.919831	2.960052	**-3.424929**
Cattle	-4.116887	-6.184015	-2.907455	-6.227270
Poultry	-1.689677	-5.395638	-0.124324	-5.447971
Goats	-0.720306	-6.444463	-0.840245	-6.039038
Swine	-1.487096	-5.672667	-1.814677	-5.582306
Sheep	-1.743484	-6.828675	-1.733438	-6.908150
Total	-2.685059	-4.650738	-2.823076	-4.591154
ImpCattleHead	-1.858607	-10.713480	-1.679028	-10.774490
ImpCattleMton	-2.783741	-7.213526	-1.533211	-7.280541
ImpPoultryHead	-2.255139	-7.660805	-0.720922	-7.697976
ImpPoultryMton	0.684884	-6.530885	2.709770	-7.091140
ImpGoatsHead	-3.247306	-7.213978	-2.267425	-7.314052
ImpGoatsMton	0.228967	-7.627652	1.971721	-6.480453
ImpSwineHead	-0.328413	-6.889195	1.439868	-6.075784
ImpSwineMton	-0.768460	-8.244184	1.280081	-7.332591
ImpSheepHead	-3.208320	-4.180630	-2.232012	-6.342614
ImpSheepMton	-2.283190	**-3.310774**	-1.134381	**-3.371529**
ImpTotalHead	-0.327501	-7.810878	1.832752	-6.481347
ImpTotalMton	-1.153507	-8.012642	0.688923	-7.577519
1% critical value	-4.211868	-4.192337	-3.592462	-3.596616

We used the same algorithm to determine the new structure breaks[7]. Results for years obtained, and from those which are significant, are shown in Table 6.

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[7] Note that because we have divided the series by another non stationary series the structural breakpoints may change.

Table 6 – Year(s) of the structure break(s) for each *per capita* series.

Series	Years (before Chow Test)	Years (after Chow Test)
GDP	1982	1982
GDP^2	1988, 1999	1988, 1999
GDP^3	1988, 1999	1988, 1998
Cattle	1974	-
Goats	1995	1995
Poultry	1974, 1976	1974, 1976
Sheep	1970	-
Swine	1979, 1984	1979, 1984
Total	1975, 1983	1975
ImpCattleHead	1991	1991
ImpCattleMton	1979	1979
ImpPoultryHead	1996	1996
ImpPoultryMton	1988	1988
ImpGoatsHead	1987	1987
ImpGoatsMton	1996	1996
ImpSwineHead	1994	1994
ImpSwineMton	1989	1989
ImpSheepHead	1998	1998
ImpSheepMton	1989	1989
ImpTotalHead	1994	1994
ImpTotalMton	1981	1981

2.2.4.2. Cointegration test

Then, once again, we performed a cointegration test. We also began by estimating a VAR model to determine optimum lag length. We were then able to perform the Johansen test for each model. Results in Table 7 show that there is always at least one case in which a cointegration relation exists. However, it must be noticed that, for example, in the case of Sheep and Swine, if an intercept term and a linear trend are included, there is no cointegration relation. This was considered for estimation purposes.

Table 7 – Number of cointegration relations for each *per capita* series, depending on data trend and test type. Exogenous variables included are GDP, GDP^2 and GDP^3 and those specific to each case.

	Number of Cointegrating Relations				
Data Trend:	None	None	Linear	Linear	Quadratic
Test Type:	No Intercept	Intercept	Intercept	Intercept	Intercept
	No Trend	No Trend	No Trend	Trend	Trend
Cattle	0	1	1	1	1
Goats	1	1	1	1	1
Poultry	1	1	1	1	1
Sheep	0	1	1	0	1
Swine	1	0	1	0	0
Total	1	1	1	1	1

2.2.4.3. Estimation

Finally, we estimated a *per capita* model for total emissions specified as

$$\begin{aligned} Total_t &= C(1)+C(2)t+C(3)D_t+C(4)y_t+C(5)y_t^2+C(6)y_t^3+ \\ &+C(7)\mathrm{ImpTotalHead}+c(8)\mathrm{ImpTotalMton}+\varepsilon_{i,t} \end{aligned} \quad . \qquad (1.3)$$

Results for each animal type are summarized in Table 8. Again, in each case we used an iterative method that eliminated the least significant variables in each iteration, and then re-estimated the model until only 5% significant variables subsided.

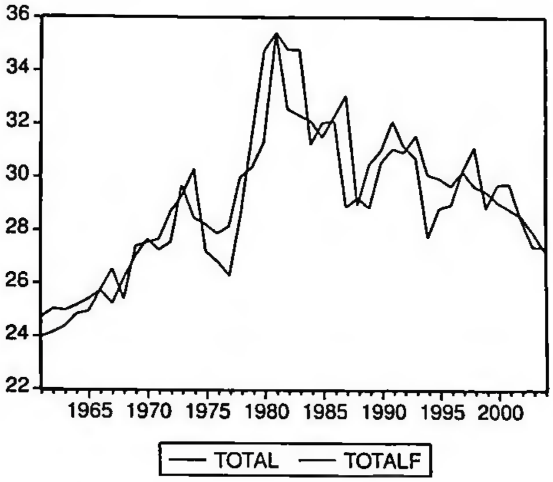
Table 8 – Summary of the estimation results for each type of animal with *per capita* series.

	Cattle	Goats	Poultry	Sheep	Swine	Total
C(1)	6.15E+06	3.23E-01		6.39E+06	4.95E+06	2.39E+06
C(2)	-1.44E-01	-1.54E-02				
C(3)						
C(31)			3.22E+06		6.68E+06	
C(32			-2.37E+06		-3.26E+06	
C(4)	1.05E-03				1.98E-03	
C(41)				5.83E-01		-3.24E+06
C(5)	-1.75E-08	1.82E-08		-9.65E-08	-1.21E-07	1.77E-07
C(51)				7.76E-01	-2.20E+06	-4.80E+06
C(6)		-1.07E-12		7.26E-12		
C(7)				8.66E+06		-1.13E+06
C(71)				-1.66E+06		
C(8)	-1.28E+06	-1.66E+06				-3.53E+06
C(81)						3.71E+06
R-squared	4.74E-01	8.65E-01	4.78E-01	6.83E-01	9.07E-01	7.85E-01
Adjusted R-squared	4.20E-01	8.51E-01	4.66E-01	6.31E-01	8.94E-01	7.50E-01
S.E. of regression	4.00E-01	2.58E-02	6.22E-01	3.67E-01	9.44E-01	1.44E+00
Sum squared resid	6.25E+00	2.61E-02	1.62E+00	4.98E+00	3.39E+00	7.72E+00
Log likelihood	-1.95E+00	1.01E+00	-4.05E+00	-1.45E+00	-5.67E+00	-7.48E+00
Mean dependent var	9.16E+00	4.76E-01	7.83E-01	5.09E+00	1.35E+00	2.50E+00
S.D. dependent var	5.26E-01	6.69E-02	8.51E-01	6.04E-01	2.90E+00	2.89E+00
Akaike info criterion	1.11E+00	-4.37E+00	1.93E+00	9.76E-01	2.85E+00	3.72E+00
Schwarz criterion	1.32E+00	-4.16E+00	2.01E+00	1.26E+00	3.09E+00	4.00E+00
Durbin-Watson stat	9.56E-01	1.70E+00	1.81E+00	9.72E-01	1.75E+00	1.64E+00
EKC?	**Yes**	**No**	**No**	**No**	**Yes**	**No**

There are significant differences from the results using the level series. We can see that the EKC pattern exists for cattle and swine. However, in the case of cattle emissions, the R^2 is low. Results also show that the coefficients for imports are usually negative. The Durbin-Watson statistics shows that there is not serial correlation of residues.

One striking fact is that using *per capita* variables the R^2 is lower than in the levels case, and the adjustment is shown in Figure 2. This may be explained by the fact that there are other variables that explain population that have to be considered now, since population is part of the endogenous variable (emissions divided by population).

Figure 2 – Comparison between original *per capita* data (TOTAL) for total emissions and the estimated *per capita* model (TOTALF).



2.2.5. Discussion

In this section we have tried to assess the possibility of an EKC for CH_4 emissions from animal production in Portugal. We studied five types of animals, as well as an aggregated totals series, an in each case tried to explain its emissions with GDP and imports of the same type. We considered meat imports but not exports, since they are less significant.

If fact, we aimed to determine the historical pattern of meat consumption. CH_4 emissions are used as a proxy, and are necessary to aggregate the production impact of different types of animals, each one with a different emission factor. This analysis could be complemented with the alternative use of the total amount spent by families on each type of meat as the equivalence factor. We should also point out that we considered constant emission factors, which means that there is no technology change in this model. Only consumer choices (first, eating meat or not, and then what kind of meat) are taken into account.

Our results show that there is no EKC for animal production in Portugal. Therefore, we conclude that there is no evidence that livestock emissions will decrease with economic growth. This illustrates the need for intra-sectoral measures to decrease the GHG balance. Since we have correlated emissions and GDP for Portugal, this study is still a very useful tool if we want to anticipate emissions' scenarios in the short term. Given an estimation of future GDP and population, emissions may be quickly estimated using the model we obtained.

The fact that the R^2 of most estimations are very high assures us of our conclusions, but it should be noticed that it may also only translate the fact that we are using a lot of exogenous variables. It is a striking fact that R^2 are lower using *per capita* values, which may translate the fact that population is endogenized in a *per capita* variable, and therefore by doing so we lose some explanatory capability of the exogenous variables, since they almost only respect to emissions.

There are two econometric problems that we acknowledge, but did not address in this work. First, it may be abusive to admit linear structure breaks in highly non-linear series, as GDP^2, GDP^3 and Population. The linear approach to such series may pose a serious limitation to forecast exercises. Second, there is a multicolinearity problem regarding the simultaneous use of GDP, GDP^2 and GDP^3, which are obviously highly correlated. The only way to surpass such problem would be to fit a particular function to the data that would avoid the use of the three series. Giles and Mosk (2005) use a fuzzy set technique that may be a valid solution. Besides, and also regarding the use of these series, they are not I(1), and therefore all estimations regarding both terms must be analysed carefully.

2.3. LULUCF activities and carbon sequestration

We have previously noticed that GHG emissions from the agro-forestry sector are significant, but it remains for us to show why Portugal has elected LULUCF activities in the KP. In fact, there are five major items for GHG balance in LULUCF (IPCC, 1997): livestock entheric fermentation, manure management, rice production, soil management and burning of residues. It is for improvement in soil management that the three LULUCF activities were chosen, namely using practices that promote carbon sequestration. Portugal was one of the very few countries to elect all three of them.

The contribution of forest management is undoubtful. But its potential for GHG reduction is limited to 0.8 Mton CO_2eq by the specifications of the KP. Furthermore, forest management faces the risk of forest fires. Therefore, any room for improvement further than what PNAC (2006) indicates has to be found in grassland and cropland management. The estimated contribution that PNAC assumes for the two items is 0.5 Mton CO_2eq. To go further than PNAC, would be to help Portugal comply with its goal, and there are several possibilities to do so. In order to understand them, we need to first know which systems contribute to each item.

For agricultural land and grasslands, the main mechanism of carbon sequestration is soil organic matter (SOM) accumulation, as will be shown in Chapter 3. Regarding cropland management, minimum tillage practices are known to have a relatively high potential to increase the soils' carbon sink capacity. Freibauer *et al.* (2004) indicate no-tillage techniques as relevant, with a potential of 0.6 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$. This is close to the value found by Six *et al.* (2004) of 0.8 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$. Their value is obtained by statistical treatment of soil organic carbon data. However, these numbers are close to the lower margin of ECCP (2003) (0-3.0 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$). It should be noticed that these values refer only to the use of no-tillage, not to complementary techniques, such as maintaining soil cover with crop residues. If the residues from annual cops are maintained on the field after the harvest, organic matter mineralization (concept defined in Chapter 3) decreases, and soils sequester even more carbon. It is thought that there is already a very significant area of no-tillage that did not exist in 1990, thus justifying Porugal's choice of the item. However, the national information on no-tillage SOM increases is very scarce, and we could not find enough data to devote our attention to it.

Finally, there is grassland management. Even though the carbon balance for all grasslands must be determined, there is a single type of pastures[8] that motivated the choice of the item by Portugal: Sown Biodiverse Permanent Pastures Rich in Legumes (SBPPRL). This system is explained in depth in Chapter 3, but for the moment it suffices to say that Portugal elected this system because, according to the company that commercializes seeds, there are already more than 50 000 ha of SBPPRL in Portugal (David Crespo, personal communication), and each hectare has a very high sequestration potential (as we will show). SBPPRL also have a direct influence in livestock emissions, since they relate to an extensive animal production system (Chapter 3). Finally, there is available data to estimate the carbon balance of the system. For all the reasons stated above, and also for the originality of this system, which is a Portuguese innovation, we decide to devote this dissertation to it.

So if Portugal wants to finance such projects further than what PNAC predicts to be the implementation scenario by 2012, than there are two types of ways in which this may be done: with private funding, or with public funding. Private funds invest in carbon sequestration mainly for voluntary emissions offset. In Portugal, the prime was the contract between EDP and Terraprima, which we will illustrate in Chapter 4. Public funding already occurs via EU agricultural subsidies to all LULUCF activities, but it could occur via PCF specifically for carbon purposes. The PCF could offer contracts to farmers, starting after PNAC's target was fulfilled. This is the option that we will explore in depth in Chapter 4.

2.4. Chapter conclusions

In this chapter, we have set the scope for our work. Portugal's exceeding of the KP maximum allowed emissions led to the adoption of LULUCF activities in the national inventory.

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[8] In this work, we define a "pasture" as a "grassland" with grazing cattle.

Considering LULUCF activities, there are three possibilities: forest management, cropland management and grassland management. In this work, we will not focus on forest management, since its potential is limited by the KP. We will not focus either on cropland, since there is not enough data yet for carbon sequestration induced by no-tillage in Portugal. Therefore, this work focuses on grassland management, and namely SBPPRL. Choosing grasslands has the advantage of relating to livestock production, and hence it allows an integrated view of the agricultural sector in relation to GHG emissions. This is very, since we have determined that there is no reason to believe that livestock emissions will decrease until 2012. We searched for an Environmental Kuznets Curve for livestock production in Portugal and only found it for very specific cases, as for example cattle.

In Chapter 3, we turn to the definition of the potential of such grasslands to sequester carbon. We will determine it by applying econometric models to available data. This is a very important input to Chapter 4, in which we tackle the issue of optimal carbon contracts to offer to farmers, especially focusing on the possibility of the PCF to finance SBPPRL.

3. Characterization of the pasture system

In Chapter 3 we describe the pasture system we intend to study. We compare it with natural grasslands, to justify its choice. Then, we apply econometric methods to soil organic matter data from several locations in Portugal. We build a model to determine the carbon sequestration in each type of grassland. Then, we describe the carbon balance of the pasture system, and link it to the conclusions regarding emissions from livestock production in Chapter 2. Finally, we characterize the main economic incentives and costs that a farmer faces when he decides to install these pastures. All data hailing from the model we build in this chapter is essential to Chapter 4.

3.1. Sown biodiverse permanent pastures rich in legumes

3.1.1. Relation between grassland management and carbon sequestration

The use of grassland management as a carbon sink is well documented in the literature. Several studies have tried to determine a correct number for the carbon sequestration potential via grassland management worldwide. Table 9 is a review of available data.

Freibauer *et al.* (2004) reviewed the potential for European soils to sequester carbon. They also evaluated suitable land for carbon farming. In their survey, they do not refer improved grasslands, but they indicate global grassland potential (with grazing management) as 0.8-2.6 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$. Frank (2002) measured CO_2 flux over a grazed wheatgrass pasture during growing season as 2.18 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$. Higher values were found by Smith (2004) – 4.4-6.2 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$ – and Tschakert (2004) – 5.35 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$. Both studies refer to the conversion of cropland to grassland, but the first study results from a survey, and the second from the application of a biogeochemical model.

As for the effect of increased grazing, Reeder and Schuman (2002) used 12 year data for mixed grass and 56 year data for short grass rangeland to conclude that grazed land has higher soil organic carbon than non-grazed areas. Their conclusions are supported by the bulk of available literature. For example, Freibauer *et al.* (2004) state a value for the increase of carbon sequestration by grazing management of 0.8-2.6 $tonCO_2 \cdot ha^{-1} \cdot year^{-1}$.

Table 9 – Literature review for the potential of cropland and grassland soils to sequester carbon

Land Use	**CO_2 sequestration ($t\ CO_2 \cdot ha^{-1} \cdot yr^{-1}$)**	**Method**	**Reference**
Grassland	0.4-11.1	Survey	Conant *et al.*, 2001
Organic input on arable land	1.0-3.0	Survey	ECCP, 2003
Revegetation of set-aside land and introduction of perennials	2.0-7.0	Survey	ECCP, 2003
Promote organic farming	0-2.0	Survey	ECCP, 2003
Water table in peatland	5.0-15.0	Survey	ECCP, 2003
Temperate grassland	2.8	Flux Measurement	Frank, 2002
Temperate grassland	2.2	Flux Measurement	Frank, 2002
Eliminate bare fallow	0.6-2.8	Survey	Freibauer *et al.*, 2004
Grassland grazing management	0.8-2.6	Survey	Freibauer *et al.*, 2004
Grassland and pastures	0.18-0.37	Survey	Freibauer *et al.*, 2004
Grassland	0.62	Measurement	McLauchlan *et al.*, 2006
Semi-natural grassland	0.7. 0.9. 1.0	Modelling	Sindhoj *et al.*, 2006
Convert cropland to grassland	4.4 – 6.2	Survey	Smith, 2004
Convert cropland to grassland	5.4	Modelling	Tschakert, 2004
Enhancing rotation complexity	0.07 +- 0.04	Survey	West and Post, 2002

3.1.2. Baseline scenario in Portugal

For quite some time now, grasslands in Portugal result from an extensive rotation system where annual crops are grown with conventional tillage systems, involving ploughing and/or harrowing. Crops are sown for one to two years, followed by a number of fallow years, dominated by natural grasslands with low carrying capacity and prone to be invaded by shrubs.

These grasslands exist in soils with low fertility levels (particularly low in organic matter and phosphorus), and as a consequence they carry low animal stocking rates. Farmers often adopt fertilization as a way to compensate the low fertility. According to Van-Camp *et al.*, (2004), 57.1% of the Portuguese soils have low or very low organic matter (between 0.5 and 2.0%), and soil available phosphorus levels are relatively low.

The two major disadvantages of this situation are: (1) if the grassland phase is long, the herbage component is progressively invaded by shrubs, with a corresponding increase in fire risk; (2) if the grassland phase is short and crops are sown using tillage, Soil Organic Matter (SOM) is highly degraded, and erosion risk increases.

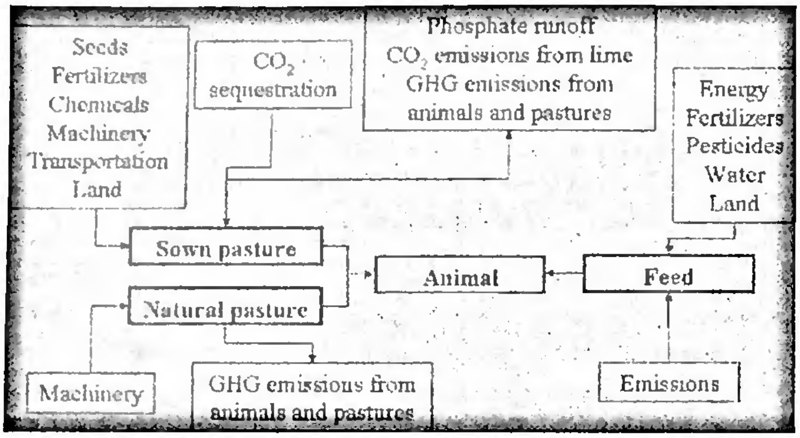
We assume that this was the case in 1990. Since the item "grassland management" of the Kyoto Protocol (KP) involves a *net-net* method, which means that sequestration in 2008-2012 is measured in relation to 1990, the system we propose will substitute this baseline scenario. This guarantees that the introduction of this new system is truly "additional" to the base scenario, which solves one of the main problems associated with carbon sequestration in soils (García-Oliva and Masera, 2004).

3.1.3. The introduction of a new system

As an alternative to this natural grasslands system, in the 70s an improvement was attempted, which consisted in using biodiversity as a defence against the very diverse Mediterranean natural conditions. This system consisted in transforming natural grasslands in "sown biodiverse permanent pastures rich in legumes" (SBPPRL), based on diverse mixtures of about twenty different species. They proved to have widespread economic and environmental effects, resulting in a clear *win-win* policy. They have been installed throughout some regions of the country in the past decade.

SBPPRL require a wider array of inputs than natural grasslands: seeds, fertilizers, and machinery. However, they provide a series of environmental benefits, ranging from prevention of soil erosion to CO_2 sequestration. Major differences between animal production in sown and natural grasslands are shown in Figure 3.

Figure 3 – Life cycles of animal production in natural (baseline scenario) and sown (proposed scenario) grasslands



Differences between baseline and proposed scenarios are summarized in Table 10, which evidences carbon sequestration.

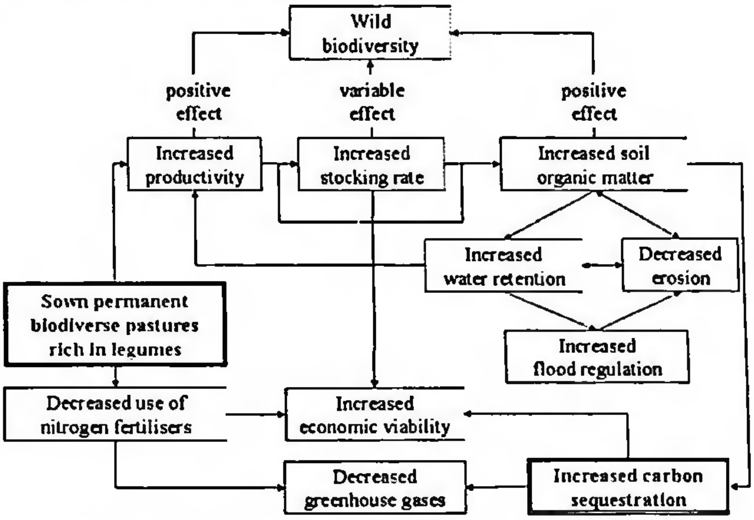
Table 10 - Differences between baseline and proposed scenarios

Baseline Scenario	Proposed Scenario
Degraded natural grasslands / former cropland areas:	**Sown biodiverse permanent grasslands:**
• Net carbon emissions (from animals)	• Carbon sequestration by agricultural soils and improved soil fertility
• Low stocking rate	• Increased stocking rate
• Shrub invasion and fire	• Shrub control and reduced fire risk
• Low inputs and machinery	• Increase in production factors' consumption
• Synthetic nitrogen fertilization	• Nitrogen fixation by legumes
• Erosion and low water cycle regulation	• Benefits in soil and water cycle regulation

3.1.4. From grassland management to carbon sequestration

Figure 4 illustrates the causal scheme that leads from SBPPRL to carbon sequestration. SBPPRL have higher productivity than natural grasslands, and are also richer in number of species. Their high productivity is due to the fact that biodiversity allows the most adapted plants to prosper in each zone. Some common sown species are *Trifolium subterraneum, Trifolium michelianum, Ornithopus spp., Biserrula pelecinus, annual Medicago spp.,* grass species of the genera *Lolium, Dactylis and Phalaris,* but many other species may be chosen according to soil and climate conditions. Often the sown species are accompanied by natural plants such as *Plantago spp., Vulpia spp.* and *Bromus spp*, etc. (Carneiro *et al.*, 2005).

Figure 4 – Causal scheme that leads to carbon sequestration



Increased productivity in SBPPRL allows a sustainable increase in animal carrying capacity. Animals graze the plants, which have an annual life cycle. The plant's root system renews every year, and plant biodiversity implies a high density of roots. Furthermore, a large part of the produced grass (biomass) returns to the soil by leaves' senescence, since without grazing control animals only consume 50% of pasture production. Animals also provide some undigested fibre to the soil.

Therefore, SOM content increases every year by accumulation of roots, and, to lesser degree, aerial biomass residues, and faeces of grazing animals. The basic mechanism consists, then, of atmospheric carbon capture through plant photosynthesis and subsequent soil storage.

SOM increase is also a crucial factor to improve plant nutrients and water holding capacity in the soil, thus increasing plant productivity and reducing water surface runoff, which in turn decreases sediment loss and soil erosion (EEA, 2004).

Decreasing water runoff and soil erosion have positive effects at a larger scope. Sediments, nutrients, organic matter and pesticides carried in water contribute to silting, eutrophication and contamination of surface waters. These effects are known, but their true costs are still hard to estimate. Nitrogen fixation by legumes eliminates nitrogen fertilizer consumption, whose production is highly energy demanding, and therefore responsible for high greenhouse gas emissions. Finally, both increased stocking rate and reduced fertilizer use increase the economic viability of the farms.

It should be noticed that grasslands and agricultural soils do not store carbon indefinitely. As SOM content increases, so does the organic matter mineralization rate, while the soil's storage rate decreases. As storage and mineralization rate become equal, eventually a steady-state is reached. In that steady-state, there is no carbon sequestration, but the system maintains all the other advantages shown in Table 10. Therefore, SBPPRL are relevant to sequester carbon in the short term, and are valuable for other environmental and economic benefits in the long term.

3.1.5. Contributions to the carbon budget

There are mainly three ways in which greenhouse gases (GHG) are either sequestered or avoided by the use of SBPPRL:

- Carbon sequestration by grassland plants, resulting from photosynthesis. Part of this atmospheric CO_2 used for plant growth is introduced in the soil, from root and stem decomposition and dead biomass (such as grass leaves), or from the decomposition of animals' faeces, all of which increase SOM. Article 3.4 of the Kyoto Protocol refers directly to this effect.
- Indirect effects, such as the decrease of the consumption of some key production factors, such as animal feed and fertilizers, and the decrease of forest fire risk (since grazing pressure and higher soil fertility levels favour shrub eradication). In improved grasslands, grazing animals require less feed supplementation during the less productive seasons.

Concentrated feeds are usually based on heavily fertilized crops, and therefore fewer fertilizers are used in the life cycle of the animals' feed. The high energy demanding nitrogen fertilizer is also eliminated or strongly reduced in grasslands itself, mostly due to the capacity of legumes to fix atmospheric N. Indeed, when inoculated with specific *rhizobia*, legumes capture symbiotic atmospheric nitrogen, and therefore no nitrogen fertilization is required. These effects are distributed by the sectors responsible for the emissions in the national emissions accounting. However, since these are indirect effects, we do not use any estimation for net balance calculation purposes.

However, there are three new greenhouse gases sources:

- Emissions due to the increased stocking rate, mainly CH_4 and N_2O from enteric fermentation and faeces. Two scenarios are considered for grasslands used by bovines: in the first one, all animals are newly installed, and, in the second, finishing steers are transferred from intensive to extensive feeding in improved grasslands. These emissions are always credited to the agricultural sector, regardless of optional mechanisms.
- N_2O emissions due to the accumulation of nitrogen by legumes. Soil microbiological activity increases, and so do the nitrogen cycle processes. Therefore, denitrification emissions may be promoted. The corresponding emission factor is highly uncertain, since it depends not only on the number of nitrogen-fixing plants, but also on other plants species that require higher levels of nitrogen, such as grasses or other nitrophilous plants. Climatic factors may also influence N_2O emissions.
- CO_2 emissions due to liming for soil acidity correction.

As noticed, it's important to remark that, for KP accounting purposes, these effects contribute to different items, and only the first one (carbon sequestration by grasslands) corresponds to grassland management. However, in this work, for balance purposes, we study the effects on greenhouse gases of the system as a whole. We begin, in the next section, by quantifying SOM dynamics and its equivalence to CO_2, so that we may them subtract the emissions stated above[9].

3.2. SOM dynamics[10]

As we stated above, SOM increases are the source of soil carbon sequestration (Sollins *et al.*, 1996). At each moment in time, there is a SOM input due to mass stock change in plant roots, which grow using photosynthetic carbon. However, there is also SOM mineralization. Both of these effects are influenced by different factors, like soil type, climatic factors, land occupation and management.

Several authors have related SOM increases with carbon sequestration. Billings *et al.* (2006) studied disturbed fertilized grassland soils, and conclude that their SOM increases represent 13% more carbon than unfertilized ones. However, fertilization-induced SOM increases are associated with labile forms of carbon. In the long term, it's management practices that dictate the soil carbon pool. Other authors, like Leifeld and Kögel-Knabner (2005), point to the fact that SOM dynamics is not independent of soil characteristics, like texture and size distribution.

There is also extensive literature on the role of grasslands in the carbon balance. Guo and Gifford (2002) indicate that soil carbon stocks decline after land use changes from pasture to plantation by 10%. They also decline from the conversion from pasture to crop by 59%. They further indicate that soil carbon stocks increase after land use changes from native forest to pasture by 8% and from crop to pasture by 19%. Martens *et al.* (2004) show that for systems undisturbed for 130 years, pastures' soils retained 25% more carbon than cropped soils.

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[9] It should be noticed that there are flux measurement techniques that determine the carbon balance as a whole. However, such techniques are much more expensive, and they do not allow us to decompose that flux in all the different parts we will describe next.

[10] This section was submitted as a research paper to Global Change Biology in 15/01/2007 (Teixeira et al., 2007a).

Some authors have also tried to model SOM and carbon dynamics. The most typical pattern is a saturating negative exponential. This dynamics is characteristic and supported in most available reviews in the literature, like for example Six *et al.* (2002), or West and Six (2007), who have a systematization of carbon change in soils. Six *et al.* (2004) distinguish several SOM pools, based on their stability, and determine a saturation upper bound for all of them. The need to incorporate the process dynamics is justified by several authors, like Ragot and Schubert (2006).

In our work, we have considered three types of rainfed grasslands, depending on management type: Natural Grasslands (NG), Fertilized Natural Grasslands (FNG), and SBPPRL, which in short we will designate in this chapter by SG, or Sown Grasslands.

As stated before, NG frequently occupy the fallow phase in cereal crop rotations, and there is no particular management practice. In FNG, the recommended fertilization for each soil type was used. However, in both cases, grassland vegetation is spontaneous.

Some early results hinted that in 10 years SG increase SOM from 1 to 3% (Crespo, 2004). This value is confirmed by various experimental results. At Herdade dos Esquerdos, in Vaiamonte (Portalegre, Portugal), following a programme of improved grasslands installation, SOM content across the farm increased from between 0.7% and 1.2% in 1979 to between 1.45% and 4.40% in 2003 (Crespo *et al.*, 2004; Crespo, 2006a, 2006b). This SOM increase is much higher than that of any natural grassland under any form of management.

Our results are based on SOM monitorization in several locations in Portugal. They were obtained during two research projects that occurred previously to the elaboration of the present dissertation: project AGRO 87, “Sown biodiverse permanent pastures rich in legumes – a sustainable option for degraded land use” (Carneiro *et al.*, 2005), and project AGRO 71, “Recovery and improvement of Alentejo’s degraded soils using grasslands”.

3.2.1. *Base data*

We used data from eight farms in Portugal from 2001 to 2005 (Table 11). It is important to notice that these were not isolated test sites, but active pastures in private land currently used by farmers for animal production. Therefore, all values were obtained from farmers' current practices.

Table 11 – Soil characterization in the sites of Projects Agro 87 (farms 1 to 6) and Agro 71 (farms 7 and 8).

Farm No.	Farm	Location	Soil original material	Texture*
1	H. Cabeça Gorda	Vaiamonte	Gneiss	Loam
2	H. Mestre	São Vicente	Limestone	Loamy clay
3	H. Claros Montes	Pavia	Granite	Loamy sand
4	H. Refroias	Cercal	Schist	Loamy sand
5	H. Cinzento e Torre	Coruche	Sandstone	Sand
6	Quinta da França	Covilhã	Granite	Loamy sand
7	H. Monte da Achada	Castro Verde	Schist and Greywacke	Sandy loam
8	H. Corte Carrilho	Mértola	Schist	Loamy sand

*** The "feel" method was used. The textural class is ascertained by rubbing a sample of the soil in a moist to wet condition, between the thumb and fingers.**

In Farm #1 the NG parcel was fertilized in 2002, and so there is only data for SG and FNG. In Farms #7 and #8, which correspond to Project Agro 71, FNG were not studied, and so there is only data for SG and NG.

The soil of each plot in each site was analysed by Laboratório Químico Agrícola Rebelo da Silva (LQARS). First, soil samples were collected from each parcel. Then, the entire sample was spread on a tray and dried overnight, at 35-37°C. The sample was crumbled mechanically and passed through a 2mm stainless steel sieve. The sieved material is the 'fine soil' subject to analysis. The analysis focused on the most important parameters for soil characterization.

3.2.2. *SOM data*

Part of the soil analysis in each site consisted in determining the SOM content. From 2001 to 2004, results were obtained by the wet oxidation method, the digestion of organic carbon by sodium dichromate. A molecular absorption spectrophotometer is used at 640 nm for colorimetric determination. In 2005, a dry combustion method was used. It consists on the determination of total carbon by dry combustion, according to ISO Standard 10694, using a CNS elemental analyzer. Organic carbon is determined indirectly after correction of the total carbon content for the carbonates present in the soil sample. However, an internal study was conducted by LQARS to obtain an equivalence factor between results obtained by both methods, in order to guarantee internal consistency to the results.

Results are shown in Table 12. In Farms #1 to #6, SOM yearly increase ranged from 0.21 to 0.56% for sown grasslands (Carneiro *et al.*, 2005). The minimum value for sown grasslands was obtained in Coruche (Farm #5), where the pasture recovery after the first year establishment was poor. The maximum values were obtained in the more productive gneiss soil in Vaiamonte and the schist soils of Herdade de Refróias. In Herdade de Refróias, SOM at the beginning was already 3%. Farms #7 and #8 increased SOM content by 0.35% and 0.43% per year. Direct comparison with natural (non-fertilized) grasslands at each site shows that increases are usually higher for SG. Furthermore, starting from lower contents of OM in 2001, sown grasslands in 2005 already show higher contents than natural ones.

Table 12 – Average organic matter values in NG, FNG and SG for the experimental sites (0-10 cm).

Farm No.	Pasture	OM (%)					OM Variation (%/year)
		2001	2002	2003	2004	2005	
1	SG	1.55	-	3.05	3.60	3.80	0.56
1	FNG	1.30	-	2.60	3.40	3.00	0.43
2	SG	1.75	-	2.65	2.70	5.40	0.32
2	FNG	1.95	-	3.00	4.50	3.50	0.39
2	NG	1.95	-	2.70	4.00	4.00	0.51
3	SG	-	0.73	1.20	1.63	1.60	0.29
3	FNG	-	-	1.10	1.40	2.00	0.45
3	NG	-	-	1.10	1.20	1.15	0.02
4	SG	3.40	3.08	5.10	4.60	5.60	0.55
4	FNG	3.80	-	4.70	5.40	5.60	0.45
4	NG	3.80	-	4.70	5.60		0.60
5	SG	0.65	-	1.00	1.28	1.50	0.21
5	FNG	0.55	-	1.10	1.15	1.25	0.18
5	NG	0.55	-	-	0.75	0.55	0.00
6	SG	1.82	-	2.40	2.18	2.70	0.22
6	FNG	1.75	-	2.90	2.70	2.70	0.24
6	NG	1.75	-	3.10	2.40	-	0.22
7	SG	0.55	0.83	1.14	1.60	-	0.35
7	NG	1.10	1.20	1.20	1.33	-	0.08
8	SG	0.80	1.40	1.54	2.08	-	0.43
8	NG	0.84	1.06	1.10	1.45	-	0.20

3.2.3. SOM Model

3.2.3.1. Model A

We used a statistical model to try to identify the SOM dynamics, which was then calibrated using the data shown above. The simplest mass balance for SOM increase is:

$$\frac{dSOM_i(t)}{dt} = K_i - \alpha_i SOM_i(t) , \qquad (2.1)$$

where $SOM_i(t)$ is the SOM content (%) in grassland type $i = \{SG, FNG, NG\}$ at time t, K_i is the organic matter input in each parcel and period, and α_i is the organic matter mineralization rate. Therefore, we consider that SOM accumulation is the balance between uptake and mineralization. Integrating Equation (2.1) between $t - \Delta t$ and t, we obtain:

$$SOM_{i,t} = SOM_{i,t-1}e^{-\alpha_i \Delta t} + \frac{K_i}{\alpha_i}\left(1-e^{-\alpha_i \Delta t}\right). \tag{2.2}$$

Therefore, the general analytical solution to Equation (2.1) has a negative exponential form, which means that there is an upper bound after which further SOM increases are insignificant. West and Six (2007) have a systematization of carbon change in soils that has the same dynamics and varies with the same factors that we present in this paper.

We thus have the general equation and data for SOM content, so we can estimate parameters K_i and α_i. Looking at Table 12, we notice that farms with high initial SOM still increased their SOM content by a relatively high percentage. We hypothesised that this is due to the fact that specific local conditions like soil type or climate favour SOM accumulation. In order to test this hypothesis, we assumed that K_i is composed of a fixed yearly organic matter entry, named K^{*}, which only respects to management type and not local variation, and a variable part, which is a linear function of the initial SOM content:

$$K_i = K_i^{*} + a_i SOM_{i,0}. \tag{2.3}$$

Therefore, we use initial SOM as a proxy for natural conditions of the specific location. Equation (2.2) thus becomes Equation (2.4).

$$SOM_{i,t} = \frac{K_i^{*}}{\alpha_i}\left(1-e^{-\alpha_i}\right) + e^{-\alpha_i} SOM_{i,t-1} + \frac{a_i}{\alpha_i}\left(1-e^{-\alpha_i}\right) SOM_{i,0} \tag{2.4}$$

Then, we estimated as regression in which $SOM_{i,t}$ is the dependent variable, $SOM_{i,t-1}$ and $SOM_{i,0}$ are the independent variables. For each type of grassland i, we pooled all the data available for all locations. From regression results, we obtain terms C_1, C_2 and C_3 in:

$$SOM_{i,t} = C_1 + C_2 \cdot SOM_{i,t-1} + C_3 \cdot SOM_{i,0}. \tag{2.5}$$

From the three equations resulting from Equations (2.4) and (2.5), we obtain the three parameters we wish to know (K_i^*, α_i and a_i) for each type of grassland. Using these parameters, we may predict, for a single land, characterized by an initial SOM, which of the three possibilities guarantees a higher yearly SOM increase.

We also studied if Equation (2.3) is valid, by estimating a model that assumes that $K_i = K_i^*$. In this new model the initial SOM is not a variable, and there are only two parameters of interest. Equation (2.5) thus becomes Equation (2.6). Combining Equation (2.4) (for $a_i = 0$) and Equation (2.6), we retrieve K_i^* and α_i.

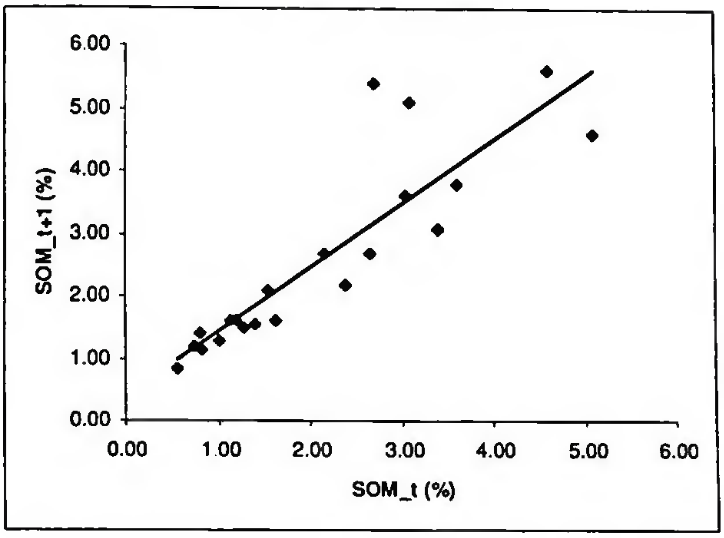
$$SOM_{i,t} = C_1 + C_2 \cdot SOM_{i,t-1} \tag{2.6}$$

Finally, we considered the possibility that SOM increases are linear, which results in a pure auto-regressive model. In this case, we obtain Equation (2.7). Equation (2.7) depicts the possibility that soils would gain organic matter indefinitely and at a constant rate. That rate is 1 – C_2.

$$SOM_{i,t} = C_2 \cdot SOM_{i,t-1} \tag{2.7}$$

In all cases, we used *software* SPSS 15, and performed a least squares estimation with White's heteroskedasticity consistent coefficients covariance (Gujarati, 1995). We chose this correction to cope with the fact that data show an heteroskedastical behaviour, as may be seen visually in Figure 5. SOM variance increases with SOM, since we only used data for the first five years after grassland sowing, and so we have more information for lower SOM values.

Figure 5 – SOM content (%) in SG in years t and t+1. The linear trend is shown.



3.2.3.2. *Model B*

The implication of Model A is that for each type of grassland in each place, all parameters change (i.e., mineralization rate, and SOM input). However, agronomically it is not to be expected that the same soils show such distinct characteristics due to grassland type. So, we built a different model, in which we consider that mineralization rate and soil quality (parameters α and a) are the same for each location in all types of grassland. The only variable parameter is $K_i^{'}$. Equation (2.4) thus becomes:

$$SOM_{i,t} = \frac{K_i^{'}}{\alpha_i}\left(1-e^{-\alpha}\right) + e^{-\alpha}SOM_{i,t-1} + \frac{a}{\alpha}\left(1-e^{-\alpha}\right)SOM_{i,0}. \qquad (2.8)$$

In order to estimate this equation, we followed a different strategy. We consider that the constant term C_1 is the sum of three dummy variables, each one corresponding to each type of grassland. Equation (2.5) thus becomes:

$$SOM_{i,t} = \sum_{i=1}^{3}\theta_i d_i + C_2 \cdot SOM_{i,t-1} + C_3 \cdot SOM_{i,0}. \qquad (2.9)$$

where d_i is a dummy variable for grassland type i, and θ_i is the corresponding coefficient. Therefore, considering two strong restrictions, with a single regression and the same data, we obtain results for the three types of grassland.

3.2.4. Results

3.2.4.1. Model A

Estimation results for the three cases of Model A are shown in Table 13. Regarding Equation (2.5), all coefficients are statistically significant using a 10% p-value limit, except C_3 for SG. For this type of grassland, the model depicted by Equation (2.6) has a better adjustment (higher R^2).

For NG and NFG, the best possible adjustment is given by Equation (2.5). The linear model in Equation (2.7) never yields the best adjustment. However, for NG and NFG, we cannot rule out the linear model as a possibility, since only the auto-regressive coefficient is statistically significant. The explanation for this is simple. An eventual SOM upper bound is only reached after more than five years, and our results do not reflect those years. Therefore, it is natural that only the initial SOM rising effect is well captured by the model, and the first years resemble a linear pattern.

The R^2 is always relatively high, and the Durbin-Watson statistics indicates that there is no serial correlation traces in the residues.

Table 13 – Linear regression for SOM content, using data from all locations for each type of grassland (Model A).

		Equation (2.5)			Equation (2.6)			Equation (2.7)		
		SG	FNG	NG	SG	FNG	NG	SG	FNG	NG
C_1	Coefficient	0.430167	0.465588	-0.268923	0.416540	0.413635	-0.035428	-	-	-
	Probability	0.0223	0.0720	0.0404	0.0330	0.1277	0.7833	-	-	-
C_2	Coefficient	0.778059	0.444116	0.637188	1.021166	0.931852	1.110211	1.165089	1.048660	1,097169
	Probability	0.0179	0.0320	0.0117	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3	Coefficient	0.338319	0.762451	0.799758	-	-	-	-	-	-
	Probability	0.4463	0.0066	0.0175	-	-	-	-	-	-
R-squared		0.783564	0.889565	0.937007	0.889565	0.827191	0.827191	0.751339	0.810923	0.907260
Adjusted R-squared		0.759516	0.865023	0.924409	0.865023	0.809910	0.809910	0.751339	0.810923	0.907260
S.E. of regression		0.743221	0.558002	0.422261	0.558002	0.662196	0 662196	0.755751	0.660430	0.467712
Sum squared resid		9.942807	2.802300	1.783043	2.802300	4.385032	4.385032	1.142319	4.797840	2.625053
Log likelihood		-2.194714	-8.300465	-5.533121	-8 300465	-1.098700	-1.098700	-2.340450	-1.152682	-8.047188
Mean dependent var		2.597540	3.050000	2.018462	2.597540	3.050000	2.018462	2.597540	3.050000	2.018462
S.D. dependent var		1.515567	1.518821	1.535838	1.515567	1.518821	1.535838	1.515567	1.518821	1.535838
Akaike info criterion		2.375918	1.883411	1.312788	2.332193	2.164501	1.543737	2.324238	2.087803	1.391875
Schwarz criterion		2.525136	2.004638	1.443161	2.431672	2.245318	1.630652	2.373978	2.128212	1.435333
Durbin Watson stat		2.655805	1.808969	0.935067	2.701866	2.825345	1.848845	2.566009	3.033768	1.824184

Combining Equation (2.4) with Equation (2.5), we obtain the following equations system:

$$\begin{cases} \alpha_i = -Ln(C_2) \\ K_i' = \dfrac{C_1 \cdot \alpha_i}{1-e^{-\alpha_i}} \\ a_i = \dfrac{C_3 \cdot \alpha_i}{1-e^{-\alpha_i}} \end{cases} \tag{2.10}$$

Using the results in Table 13, and the former equations, we obtain the dynamic parameters shown in Table 14. Table 14 shows that, even though the model in Equation (2.6) is a better adjustment to the data for SG, it yields a physically impossible result, which a negative mineralization rate. Therefore, we chose the model in Equation (2.5) as the best to depict SOM dynamics in all three cases.

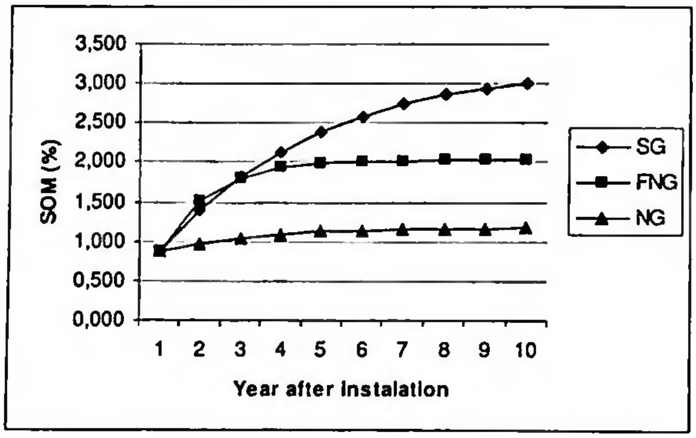
Table 14 – Dynamic parameters for each type of grassland.

	Equation (2.5)			Equation (2.6)		
	SG	FNG	NG	SG	FNG	NG
α	0.251	0.812	0.451	-0.021	0.071	-0.105
K'	0.486	0.680	-0.334	0.412	0.428	-0.034
a	0.383	1.113	0.993	-	-	-

Then, and considering only Equation (2.5), we used the values in Table 14 to predict SOM dynamics in each type of grassland, starting from the same initial level. According to unpublished data from LQARS, in 1999 the national average SOM content was 1.76%. However, most farms studied by the Projects which provided us with all data used are in the region of Alentejo. This is also where more cattle are produced and more degraded grasslands exist. Alentejo has an average soil organic matter content of 1.03%. This value drops to 0,87% if only natural pastures and area under cereal rotation is considered. Therefore, for all calculations, we assumed a baseline scenario with a starting SOM of 0,87%.

Figure 6 shows SOM dynamics in the first 10 years after installing a pasture. In the first year, SOM increases in SG by about 0.60 percentage points, and in the last year by only 0.02 percentage points.

Figure 6 – SOM in each year, as estimated by Model A, starting from 0.87%. In 10 years, SOM is about 2.0% for FNG and 3,0% for SG.



Regression data indicate an average SOM increase for SG of 0.21 percentage points per year during the first 10 years. For NG, the yearly increase is about 0.03 percentage points, and for

FNG 0,12 percentage points. Admitting error normality, the 95% confidence interval of the estimation is $\left[SOM_{i,t}-0.70, SOM_{i,t}+0.70\right]$ for SG, $\left[SOM_{i,t}-0.48, SOM_{i,t}+0.48\right]$ for NFG and $\left[SOM_{i,t}-0.37, SOM_{i,t}+0.37\right]$ for NG.

3.2.4.2. Model B

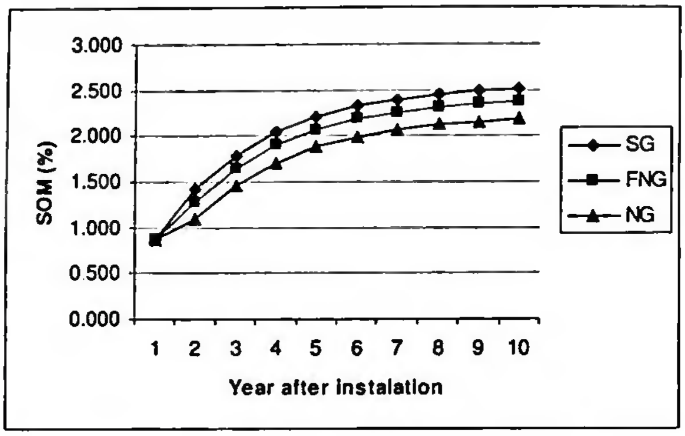
Results for Model B are shown in Table 15. The first particularity about results is that coefficients θ_2 and θ_3 are not statistically significant. This means that it makes a difference whether grasslands are sown or not, but there is no distinction between natural grasslands. The R^2 obtained is close to those from Model A, so it is unclear which one is a better adjustment to the data.

Table 15 – Linear regression for SOM content, using data from all locations for all types of grassland (Model B).

		Equation (9)
θ_1	Coefficient	0.381734
	Probability	0.0036
θ_2	Coefficient	0.23836
	Probability	0.2596
θ_3	Coefficient	0.051564
	Probability	0.7408
C_2	Coefficient	0.674244
	Probability	0.0002
C_3	Coefficient	0.519096
	Probability	0.0435
R-squared		0.854747
Adjusted R-squared		0.840576
S.E. of regression		0.613788
Sum squared resid		1.544614
Log likelihood		-4.017168
Mean dependent var		2.551920
S.D. dependent var		1.537239
Akaike info criterion		1.963986
Schwarz criterion		2.162752
Durbin-Watson stat		2.487599

Figure 7 shows SOM dynamics in the first 10 years after installing a pasture for Model B. It may be seen, in comparison with Figure 6, that Model B estimates a lower upper bound for SG, and higher upper bounds for FNG and NG. Admitting error normality, the 95% confidence interval of the estimation is $\left[SOM_{i,t}-0.58, SOM_{i,t}+0.58\right]$.

Figure 7 – SOM in each year, as estimated by Model B, starting from 0.87%. In 10 years, SOM is about 2.4% for FNG and 2,5% for SG.



Regression data indicate an average SOM increase for SG of 0.16 percentage points per year during the first 10 years. For NG, the yearly increase is about 0.13 percentage points, and for FNG 0,15 percentage points.

It should be noticed that, in this case, we did not consider simplified models, since we also concluded that this was the best choice.

3.2.4.3. *Comparison between estimated and farm data*

Ultimately, a model is useful if it allows us to accurately depict data. In order to verify the adjustment provided by Model A and Model B, and also to compare them, we applied them to each farm. Results are shown in Table 16. Both models provide good adjustments in both farms, but in some specific cases one of them is better than the other. It is unclear which of the two better represents the available data.

Table 16 – Observed and modelled SOM for each farm studied.

Farm No.	Grassland	Observed SOM (%)					Model A SOM (%)					Model B SOM (%)				
		2001	2002	2003	2004	2005	2001	2002	2003	2004	2005	2001	2002	2003	2004	2005
1	SG	1.55		3.05	3.60	3.80	1.55	2.16	2.64	3.01	3.29	1.55	2.23	2.69	3.00	3.21
1	FNG	1.30		2.60	3.40	3.00	1.30	2.03	2.36	2.50	2.57	1.30	1.79	2.12	2.34	2.49
2	SG	1.75		2.65	2.70	5.40	1.75	2.38	2.88	3.26	3.56	1.75	2.47	2.96	3.28	3.50
2	FNG	1.95		3.00	4.50	3.50	1.95	2.82	3.20	3.38	3.45	1.95	2.57	2.98	3.26	3.45
2	NG	1.95		2.70	4.00	4.00	1.95	2.53	2.90	3.14	3.29	1.95	2.38	2.67	2.86	2.99
3	SG		0.73	1.20	1.63	1.60		0.73	1.25	1.65	1.96		0.73	1.26	1.61	1.85
3	FNG			1.10	1.40	2.00			1.10	1.79	2.10			1.10	1.55	1.86
3	NG			1.10	1.20	1.15			1.10	1.31	1.45			1.10	1.36	1.54
4	SG	3.40	3.08	5.10	4.60	5.60	3.40	4.23	4.87	5.37	5.76	3.40	4.44	5.14	5.61	5.93
4	FNG	3.80		4.70	5.40	5.60	3.80	5.05	5.61	5.85	5.96	3.80	4.77	5.43	5.87	6.17
4	NG	3.80		4.70	5.60		3.80	5.19	6.08	6.64	7.00	3.80	4.59	5.12	5.47	5.71
5	SG	0.65		1.00	1.28	1.50	0.65	1.16	1.55	1.86	2.09	0.65	1.16	1.50	1.73	1.89
5	FNG	0.55		1.10	1.15	1.25	0.55	1.13	1.39	1.50	1.55	0.55	0.89	1.13	1.28	1.39
5	NG	0.55			0.75	0.55	0.55	0.52	0.50	0.49	0.48	0.55	0.71	0.81	0.89	0.93
6	SG	1.82		2.40	2.18	2.70	1.82	2.46	2.96	3.35	3.65	1.82	2.55	3.04	3.38	3.60
6	FNG	1.75		2.90	2.70	2.70	1.75	2.58	2.94	3.11	3.18	1.75	2.33	2.72	2.98	3.15
6	NG	1.75		3.10	2.40		1.75	2.25	2.56	2.76	2.89	1.75	2.14	2.40	2.58	2.70
7	SG	0.55	0.83	1.14	1.60		0.55	1.04	1.43	1.73	1.96	0.55	1.04	1.37	1.59	1.74
7	NG	1.10	1.20	1.20	1.33		1.10	1.31	1.45	1.53	1.59	1.10	1.36	1.54	1.66	1.74
8	SG	0.80	1.40	1.54	2.08		0.80	1.32	1.73	2.05	2.29	0.80	1.34	1.70	1.94	2.11
8	NG	0.84	1.06	1.10	1.45		0.84	0.94	1.00	1.04	1.07	0.84	1.05	1.20	1.30	1.36

3.2.5. Conclusion

In this section, we assumed that SOM increases in a saturating exponential pattern. We found statistical evidence that it is the most suited hypothesis for SOM dynamics. Therefore, SOM increases become lower as SOM content approaches a given upper bound. This upper bound depends on grassland type and soil conditions, which we simulate by considering the initial SOM level.

Starting from 0.87% SOM, we found that in 10 years there is an average increase of 0.16 to 0.21 percentage points per year in SG, depending on the statistical model we use. It is unclear which of the model formulations is more correct. Still, increases are always higher than those obtained for NG and FNG. This shows that SG are indeed the type of grassland that maximizes SOM. This, in turn, translates into carbon sequestration. That translation is done in the next section.

3.3. Estimation of carbon sequestration[11]

3.3.1. From SOM increases to carbon sequestration

Using the information in the previous section, we were able to finally determine the potential for SBPPRL to sequester carbon. In order to determine the CO_2 equivalent to SOM increases, we obtained the equivalent to 1% OM in terms of ton $CO_2 \cdot ha^{-1}$. Results are shown in Table 17.

Table 17 – Carbon sequestration equivalent to an increase in SOM content of 1%, considering 10 cm depth

% OM	MBD[12] ($g \cdot cm^{-3}$)	BD[13] ($g \cdot cm^{-3}$)	g(OM[14])$\cdot cm^{-3}$	g(OC[15])$\cdot cm^{-3}$	g(OC)$\cdot cm^{-2}$	tonC$\cdot ha^{-1}$	[16]ton$CO_2 \cdot ha^{-1}$
1	1.25	1.20	0.0120	0.00696	0.0696	6.96	25.5

Results for several depths of topsoil (h_{soil}) are summarized in Table 18. Since 1.25 $g \cdot cm^{-3}$ is the representative mineral bulk density (MBD) value for Portuguese soils, we considered it in all calculations. Assuming increases in the first 10 cm of a soil, an increase in 1% SOM is equivalent to the sequestration of about 25.5 ton$CO_2 \cdot ha^{-1}$.

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[11] This section was submitted as a research paper to Agricultural Systems in 15/11/2007 (Teixeira et al., 2007b).

[12] Based on Rawls and Brakensiek (1985), MBD may vary between 1.20 $g \cdot cm^{-3}$ and 1.69 $g \cdot cm^{-3}$. In our calculations, we also considered the average value of 1.33 $g \cdot cm^{-3}$.

[13] In order to correct the values of the last column, we used the Adams (1973) equation, where BD is soil bulk density ($g \cdot cm^{-3}$), MBD is soil mineral bulk density ($g \cdot cm^{-3}$), and %OM is soil organic matter content (%):

$$BD = \frac{100}{\dfrac{\%OM}{0.244[g.cm^{-3}]} + \dfrac{100 - \%OM}{MBD}}$$

[14] We assumed that OM increases in the 0-10 cm layer of soil. We obtained this column by multiplying the last one by 0.01.

[15] We considered that 58% of organic matter is organic carbon, according to IPCC (1997) and IPCC (2003). Therefore, we obtained this column by multiplying the last one by 0.58.

[16] Given the atomic weight of carbon (former column) and the molecular weight of CO_2, we obtained the final equivalent in ton $CO_2 \cdot ha^{-1}$ (in this column).

Table 18 – Carbon sequestration equivalent to a SOM content increase of 1% depending on soil depth

h_{soil} (cm)	ton $CO_2 \cdot ha^{-1}$ (MBD = 1,25 $g \cdot cm^{-3}$)
10	25.5
20	50.1
30	75.6

Based on these values, we estimated a yearly carbon sequestration of 4.1 to 5.4 ton $CO_2 \cdot ha^{-1} \cdot year^{-1}$, corresponding to our scenarios of 0.16 to 0.21% SOM increase per year in the first 10 cm, which was obtained in the previous section.

3.3.2. Increased emissions from SBPPRL

As stated before, there are three sources of increased GHG emissions due to SBPPRL, namely animal emissions, legumes' emissions and emissions due to limestone application.

3.3.2.1. Animal CH_4 and N_2O emissions

We said earlier that SBPPRL allow an increase in sustainable animal stocking rate. In this section we use beef cattle as an example, and we study three scenarios: (1) there is no change in stocking rate, since current pastures are overused, (2) animals are new to the pasture, and have international provenience, (3) steers are finished in grasslands, instead of common intensive systems.

Scenario (1) – no stocking rate increase

In the first scenario, since natural pastures are not productive enough for the grazing animals, a change to SBPPRL would not imply an increase in stocking rate, and extra emissions would be zero. It would also be the case if breeding cows were not installed newly on the pasture, but transferred from other natural pastures. This is the most favourable hypothesis.

This scenario is plausible, since Table 19 shows that practically all breeding cows in Portugal are subsidized, and so, if animal quotas are maintained, then there can be almost no global stock rate increase. In fact, cattle is precisely one of the types of animal for which an Environmental

Kuznets Curve (EKC) pattern was found in Chapter 2 (using *per capita* emissions). That result may be justified by this information, and also strengthen this scenario.

Table 19 - Registered (INE, 2006) and supported (IFADAP/INGA, 2004) breeding cows in Portugal

Year	Registered animals	Supported animals	% of Supported Animals
1998	341,000	321,948	94.4
1999	342,000	303,700	88.8
2000	342,000	307,093	89.8
2001	351,000	307,731	87.7
2002	359,000	321,978	89.7
2003	371,000	332,243	89.6
2004	384,000	365,050	95.1

Scenario (2) – highest stocking rate increase

As for the second scenario, we start from a degraded grassland with a stocking rate of 0.5 CU, and then introduce 0.5 CU of breeding cows after the grassland is sown. Corresponding emissions would rise by 1.1 ton CO_2 eq·ha^{-1}·year^{-1}, as shown in Table 20.

Table 20 – Emissions from breeding cows in pastures

Gas	Emission factors		Stocking rate	Emissions	
	Enteric fermentation	Faeces		Enteric fermentation	Faeces
	kg·head^{-1}·year^{-1}	kg·head^{-1}·year^{-1}	head·ha^{-1}	kg·ha^{-1}·year^{-1}	kg·ha^{-1}·year^{-1}
CH_4	73[17]	2.156[18]	0.5	36.5	1.078
N_2O	0[19]	1.927[20]	0.5	0	0.964
CO_2eq				766.5	321.478

For Portugal, this is the worst scenario possible of increased animal stocking rate, and it represents only about 20% of total carbon sequestration. Therefore, the global carbon balance would still be very favourable. Considering that meat demand in Portugal does not change by installing SBPPRL, this would represent a transfer: instead of buying meat produced elsewhere, Portugal would produce it locally. Therefore, in terms of global world emissions, they would remain the same.

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[17] Enteric fermentation CH_4 emission factor for breeding cows in grasslands, in 2004.

[18] Faeces CH_4 emission factor for breeding cows in grasslands, in 2004.

[19] IPCC (who establishes the Kyoto accounting method) does not consider N_2O emissions from enteric fermentation).

[20] Faeces N_2O emission factor for breeding cows in grasslands, in 2004.

Scenario (3) – some stocking rate increase

In the third scenario, we assume the transition from a stocking rate of 0.5 CU·ha^{-1}, composed only by breeding cows, to a stocking rate of 1.0 CU·ha^{-1} where for each cow, a steer is being fed and finished during a year (from 6 to 18 months). There are three major effects:

1. Breeding cows' population increases from 0.5 CU·ha^{-1} to 0.625 CU·ha^{-1}.
2. Number of steers being fed in the pasture increases from 0 CU·ha^{-1} to 0.375 CU·ha^{-1}, corresponding to an increase of 0.625 steer·ha^{-1} (since 1 steer represents 0.6 CU).
3. Steers are withdrawn from intensive feeding, and so emissions corresponding to 0.625 steer·ha^{-1} are avoided.

Effects 1, 2 and 3 are quantified in Table 21. Table 21 shows that global balance is 176 kg CO_2eq·ha^{-1} emitted. This value is minor when compared to carbon sequestration by SBPPRL.

Table 21 – Effect on greenhouse gases' emissions of the stocking rate increase

Gas	Effect	Emission factors		Stocking rate	Emissions	
		Enteric fermentation	Faeces/ Manure		Enteric fermentation	Faeces/ Manure
		kg·head^{-1}·year^{-1}	kg·head^{-1}·year^{-1}	head·ha^{-1}	kg·ha^{-1}·year^{-1}	kg·ha^{-1}·year^{-1}
CH_4	1	73	2.156	0.125	9.125	0.270
	2	50.2	0.679	0.625	31.375	0.424
	3	-50.2	-1.156	0.625	-31.375	-0.723
N_2O	1	0	1.927	0.125	0	0.241
	2	0	0.659	0.625	0	0.412
	3	0	-1.122	0.625	0	-0.701
CO_2eq	1			0.125	191.625	80.331
	2			0.625	658.875	136.593
	3			0.625	-658.875	-232.560
Total (kg CO_2eq)					191.625	-15.636

In this case, Portugal would have a benefit from switching from an intensive to an extensive production system. In terms of global effects, since transfers would remain domestic, there would also not be a significant effect.

This third effect is the most plausible for Portugal, and therefore we adopted its results for the rest of the calculations. This is also the most desirable scenario, since it also has the most positive economic effects, and it may even be a conservative one.

3.3.2.2. *Legumes' N_2O emissions*

There are basically two ways in the literature to rapidly calculate nitrogen emissions from legumes. The first uses an emission factor per nitrogen unit fixed. The second uses a factor per production of dry matter.

IPCC (1997) considers an N_2O emission factor from legumes of 0.0125 $kgN_2O\_N{\cdot}kg^{-1}$ fixed N. Carneiro *et al.* (2005) state for several locations values for fixed N ranging from 100 (Coruche) to 300 $kg{\cdot}ha^{-1}$ (Cercal). The average is about 180 $kg{\cdot}ha^{-1}$. Therefore, emissions would be 1.25-3.75 kg $N_2O\text{-}N{\cdot}ha^{-1}$, or 387.5-1,162.5 ton $CO_2eq{\cdot}ha^{-1}$. The average would be about 700 ton $CO_2eq{\cdot}ha^{-1}$

An alternative calculation may be done considering that sown grasslands have higher dry matter (DM) productivity. According to Carneiro *et al.* (2005), productivity varies from 2,000 kg $DM{\cdot}ha^{-1}$ (Coruche, Portugal) to 9,000 kg DM $\cdot ha^{-1}$ (Quinta da França, Portugal). On average, about 60% of such production is due to legumes (Carneiro *et al.*, 2005). Therefore, and considering an emission factor of 0.001 kg $N_2O\_N{\cdot}kg^{-1}$ DM, emissions would range from 1.2 to 5.4 kg $N_2O\text{-}N{\cdot}ha^{-1}$, or 0.3 to 1.5 ton $CO_2eq{\cdot}ha^{-1}$.

Some authors, like Li *et al.* (2005), modelled carbon sequestration enhancement strategies, and found that carbon dynamics influences nitrogen dynamics. They estimate that, when SOM increases, the increase in N_2O emissions diminishes or even eliminates the carbon sequestration. However, empirical studies like Crews and Peoples (2004), Kammann *et al.* (1998), Ledgard (2001) or Rochette and Janzen (2005) state that emission factors are systematically overestimated, and find values close to the lowest extreme of the interval above. These studies refer to mixes of grass and legumes, and therefore are a valid approximation of the system studied here. In equilibrium, it is very likely that fixed nitrogen is fully consumed by grasses.

But even if emissions were of the magnitude of Li's (Li *et al.*, 2005), these emissions may be offset by their alternative. Nitrogen fixed by legumes is a direct substitute of synthetic nitrogen in fertilizers. To achieve close productivities without legumes, pastures would require nitrogen fertilization. The other option would be to use commercial feed for cattle, but then fertilized crop production would be required. Therefore, we may compare the emissions due to biological N fixation to the emissions due to fertilizer production and use (Crews and Peoples, 2003). Cassman *et al.* (2003) note that mineral nitrogen fertilizers are responsible for direct field emissions (N_2O) and indirect emissions due to fossil fuel consumption during their production and application.

Considering the emission factor in IPCC (1997) stated above, each fixed N unit corresponds to 3.88 kg CO_2eq·ha^{-1} emitted. We found on the database of the Life Cycle Assessment software SimaPro 6.0 the CO_2 emissions for which fertilizers are responsible during their production. We found that for each kg of N in the fertilizer urea 3 kg of CO_2eq are emitted, which is about the same as what is emitted by legumes. But for each kg of N in the fertilizer ammonium nitrate, 7.75 kg of CO_2eq are emitted, and this is about the double of the emissions due to biological fixation. Therefore, each unit of nitrogen is used more efficiently if it is biological rather than synthetic.

3.3.2.3. Emissions due to limestone application

Since some Portuguese soils have high acidity levels, improved plant production requires pH correction by liming. The impact of this operation is direct, during application, and indirect, due to the extraction process.

In this work we did not consider extraction impacts. On the field, there is no soil loss or SOM mineralization in the process, since limestone is applied on the surface (except when the pasture is installed). There are, however, emissions from limestone itself. IPCC (2003) considers a generic emission factor of 12% of all limestone applied (equal to the stoichiometric quantity of CO_2 in $CaCO_3$ or $CaMg(CO_3)_2$, depending on the type of limestone).

Therefore, assuming that during the first ten years 2 tons of limestone are applied every two years (note that this only happens when pH(H_2O) is inferior to 5.3), then 0.44 ton $CO_2 \cdot ha^{-1} \cdot year^{-1}$ are emitted. Note that liming is required in only 20-30% of the soils, so our estimate is conservative.

3.3.3. Global balance

We considered a plausible implementation scenario for SBPPRL of 300,000 ha, in order to check the relevance of this effect. This value was obtained from the Regional Forest Plans in Alto Alentejo, Alentejo Central e Alentejo Litoral, which already recomend the implementation of biodiverse sown rainfed grasslands for their positive environmental effects and as a contribution to an agro-forestry mosaic landscape. Table 22 systematizes the global carbon balance for rainfed grasslands.

Table 22 – Carbon balance for SBPPRL, considering an implementation scenario of 300,000 ha.

	Carbon storage/emission factor		Carbon stored/emitted	
	ton $CO_2 \cdot ha^{-1} \cdot year^{-1}$		ton $CO_2 \cdot year^{-1}$	
	Model A	Model B	Model A	Model B
SBPPRL	5.4	4.1	1 620 000	1 230 000
Animal emissions	-0.2	-0.2	-60 000	-60 000
Nitrogen emissions	-0.3	-0.3	-90 000	-90 000
Liming	-0.4	-0.4	-120 000	-120 000
Total	**4.5**	**3.2**	**1 350 000**	**960 000**

Results obtained by literature survey are systematically below those presented in this paper. But they do not refer to the exact same system we describe in this paper or to the specific climatic conditions of Mediterranean countries. They also name “grasslands” as what we call “degraded natural grasslands”. The motivation behind the implementation of SBPPRL rich in legumes is exactly to enhance the carbon sequestration potential, and therefore it is coherent that our results are higher.

3.4. Estimation of economic drivers

In order to determine the economic incentives to the installation of grasslands, three factors must be considered: net revenue, installation costs, and maintenance costs. In the following analysis, we do not consider external environmental costs. We consider grasslands are installed as feed for grazing cattle, even though other types of animal may also range them.

We present data for both NG and SBPPRL, assuming that the stocking rate in NG is 0.44 CU[21]/ha and in SBPPRL is 1.18 CU/ha (Carneiro *et al.*, 2005). We restrict all calculations to a hectare, since that is the reference for the carbon sequestration factor. Assuming the production of a 12 month old "ready to slay" calf, we use the method developed in Fiúza *et al.* (2007). They developed a setting in which the beef calf is fed only on maternal milk until the age of 7.2 months. Also, the cow gives birth on a yearly basis, so we take into account a year of its life (12/12×1CU). They considered that the calf's emissions are not relevant until after 7.2 months of age, when it grazes for 2.4 months, its diet consisting of 40 % pasture (2.4/12×0.6CU×0.4) and 60 % (2.4/12×0.6CU×0.6) industrially processed feed. From 9.6 until 12 months old (2.4 months), the calf is kept in a stable, fed only on industrially processed feed and silage maize (2.4/12×0.6CU), until taken to the slaughterhouse. Adding up, we have, per year, a CU equivalent of 1.048 for pasture and for the feed a CU equivalent of 0.192. To obtain the equivalent area needs per year per steer for each type of pasture, they divided the CU equivalent for pasture with the average CU/ha. The final values obtained are 1.12 steer.ha^{-1}.yr^{-1} for SBPPRL and 0.42 steer.ha^{-1}.yr^{-1} for NG. Each steer always has the equivalent per year part of the mother's costs and revenue. The following calculations were based on these two values.

3.4.1. Revenue

There are two sources of revenue for farmers:

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[21] CU – Cattle Units, assumed to be equivalent to one adult cow.

- A subsidy for breeding cows of 200 €.cow^{-1}.yr^{-1};

- Revenue from calf sale of about 700 €.steer^{-1}.yr^{-1}.

Assuming the average stocking rate in each type of pasture, we obtain results in Table 23.

Table 23 – Revenue per hectare of both types of pasture.

	Revenue (€.ha^{-1}.yr^{-1})	
	SBPPRL	NG
Cow	224.80	84.00
Steer	786.80	294.00
Total	1011.60	378.00

3.4.2. Installation costs

Since they are fully invested in the first year, we convert implementation costs to constant annuities for the time horizon of the product or service as

$$P=\sum_{t=1}^{T} A\cdot(1+r)^{-t}, \qquad (2.11)$$

where P is the total amount paid in the first year (€), A is the annuity value (€), r is the interest rate (in this case, we assumed it was 1.5%) and T is the time horizon (years). According to Fiúza *et al.* (2007), implementation of sown pastures is considered to be necessary every ten years (at maximum), but NG do not require it. Fencing costs 280 €/ha and lasts for ten years. The steer's mother costs 750€ and we consider it to live and breed for 15 years.

Therefore, using Equation 2.11 and considering the final equivalent stocking rates for each type of pasture, we obtain the results in Table 24.

Table 24 – Annualized implementation costs per hectare of both types of pasture (Fiúza *et al.*, 2007).

	Implementation costs (€.ha^{-1}.yr^{-1})	
	SBPPRL	NG
Fact sheet	40.09	-
Fence	28.19	28.19
Breeding Cow	56.77	21.23
Total	125.05	49.42

3.4.3. *Maintenance costs*

There are mainly three maintenance costs: running costs (fertilization in SBPPRL, tillage for shrub control in NG), feed costs and labour with cattle. All these costs were considered according to Fiúza *et al.* (2007). Values are shown in Table 25.

Table 25 – Annual maintenance costs per hectare of both types of pasture (Fiúza *et al.*, 2007).

	Maintenance costs (€.ha^{-1}.yr^{-1})	
	SBPPRL	NG
Running costs	131.71	54.39
Feed	140.25	52.45
Labour with cattle	90.65	33.90
Total	362.61	140.74

3.4.4. *Public incentives for SBPPRL*

The current Portuguese Rural Development Programme (MADRP, 2007) for the period 2007-2013 stipulate specific amounts to support the installation and maintenance of SBPPRL, but only if they are managed according to two specific agricultural norms: integrated production and organic farming. Base values for the maintenance of natural grasslands and SBPPRL are shown in Table 26.

Table 26 – Public support for the maintenance of natural grasslands and SBPPRL.

Land use	Integrated Production (€.ha^{-1})	Organic farming (€.ha^{-1})	Base area (ha)
Permanent (natural) grassland	106	172	30
SBPPRL	130	210	30

These values should be read as follows: for a farmer with a grassland area inferior to the base area, the indicated values will apply. If a farmer has a superior area that that indicated, the values per hectare drop. The modulation factors are shown in Table 27.

Table 27 – % of total sum attributed to each area class.

Area class, in relation to Base Area (BA)	% of total sum
≤ BA	100
> BA and ≤ 2BA	80
> 2BA and ≤ 5BA	50
> 5BA	20

The major difference in the level of support to both types of grasslands lies in the income loss for the adoption of these systems, in relation to a conventional production method. Difference lies in the need for correct phosphate (P) fertilization, especially in SBPPRL. The value for the first area class under integrated production is consistent with the one we used for running costs (130 €.ha^{-1}.yr^{-1}), which means that public financing was designed to cover running costs.

Public financing was designed in collaboration with PNAC's objectives. This means that grasslands supported by the Rural Development Programme will be fulfilling PNAC's goals. All additional carbon sequestered in grasslands has to be contracted outside from this kind of public financing.

3.5. Chapter conclusions

In this chapter, we have estimated how much CO_2 Portuguese grassland soils, on average, sequester. Adding all the contributions to the carbon balance, we obtain an estimate for the global carbon balance of 3.2-4.5 ton $CO_2eq \cdot ha^{-1} \cdot year^{-1}$ that are sequestered or avoided in SBPPRL. If we consider an implementation scenario of 300,000 ha, then the global effect would be 0.96-1.35 Mton $CO_2eq \cdot year^{-1}$. The predicted Portuguese deficit for the Kyoto goal is 3.73 Mton$CO_2 \cdot year^{-1}$. Therefore, the system we propose would be responsible for the mitigation of about a third of the deficit. The Portuguese Program for Climate Change (PNAC, 2006) has a more conservative estimate for the implementation scenario. It admits a potential of carbon sequestration of 5 ton$CO_2 \cdot ha^{-1} \cdot year^{-1}$ in 70,000 ha for grassland management. This adds up to 0.35 Mton $CO_2eq \cdot year^{-1}$, about 10% of the deficit. This provides a lower and upper bound for the percentage of the deficit that may be reduced via agricultural soils.

We have also built a model that allows us to know how much a farmer may expect to sequester in his grassland soils, if he knows the starting SOM level. We also looked at the costs and incentives he has to adopt the system. This is all the information we need to estimate the optimum price of a carbon contract, i.e., the price to pay farmers for each tonne of CO_2 that minimizes costs and maximizes sequestration.

4. Optimal contract for carbon sequestration in grasslands

In Chapter 4 we start by reviewing the state of the art in contract design for resource conservation contracts with farmers. We explain the difference between "per hectare" contracts and "per objective" contracts. Then, we review the available literature for carbon contracts, including some mathematical formulations for obtaining a market price. This leads us to some difficulties in setting contracts. Finally, we show the example of the first private contract for carbon credits based on grassland management in Portugal, in order to finally reach our main goal, which is a proposal for the optimal contract to offer Portuguese farmers with sown grasslands if the Carbon Fund decides to finance these projects.

4.1. Contracts for carbon sequestration

4.1.1. Designing contracts for resource conservation

In standard economic theory, environmental co-effects of human activities are often considered externalities, in the sense that they are not reflected in commodity prices (Perman *et al.*, 1996). As this effect aggravates, we say that there is a market failure, since the current state of business is incapable of internalizing that impact. There are two main ways usually appointed to cope with this market failure: environmental taxes, and environmental contracts.

An environmental tax is imposed on polluters as a way of internalizing the environmental damage (Perman *et al.*, 1996). The tax will increase production costs, incentivating producers to switch to cleaner techniques, and the collected funds will be used to mitigate the damage effects. But it is a normative regime, and the state is required to regulate and control its operationalizitation. Alternatively, polluters may be given the option to compensate their impacts by participating in other markets created specifically for environmental assets. These markets involve a third party, the suppliers of environmental assets, with who are established contracts for the implementation of measures with positive effects.

The last case constitutes the universe of private resource conservation contracts, either voluntary (for example, biodiversity protection) or mandatory (for example, carbon emissions reduction). But even in this kind of contracts, the state plays a crucial role, since it is usually the source of most funds to such markets. Resource conservation is very dependant of state intervention, since in fact most environmental goods are public and non-exclusive.

It is not a surprise that most resource conservation revolves around agricultural practices and forestry activities. The agro-forestry sector has a very close link to direct environmental effects, and regulates many of the possible ecosystem services, like water cycle regulation, water quality, soil protection, carbon sequestration, air quality, and biodiversity. However, not all transactions involving environmental services from agriculture and forestry are efficient (Gulati and Vercammen, 2006).

The issue of resource conservation contracts has been fairly debated in the economic literature of the last decades. According to Antle *et al.* (2003), there are two types of costs regarding the implementation of contracts for the adoption of good environmental practices. The first type is farm opportunity costs, which includes the cost of the conversion to the required agricultural practice. The second type is contract costs, which include transaction, monitorization costs, and brokerage fees.

There are mainly two mechanisms for the payments to occur: on a "per hectare" base, and on a "per objective" base (Antle *et al.*, 2003). The per hectare scheme consists on a fixed payment for an area where a farmer adopts a land use or management practice leading to environmental benefits. This type of contract is mainly used when there is no specific monitorization method, or it is not possible to correctly assess the result of the adopted practice. The per objective scheme involves a payment based on the accomplishment of environmental objectives, measured in quantitative indicators. For example, for carbon sequestration, this would mean a "per tonne" of CO_2 contract. Every time a farmer would switch its land use or farming practice, he would receive a payment for each unit of carbon incorporated in the soil. Models and field measurements are used to assess the respective sequestration (Antle and McCarl, 2002).

The difference between the two types of contract is that in the first one the farmer receives a payment regardless of the accomplishment of any environmental goal (for example, carbon sequestration). Therefore, the entity that finances the project assumes the risk, and there is only the monitorization cost of assuring that the farmer does indeed adopt the practice contracted. In the second type of contract, only the effective environmental gain is paid for, and it is the farmer who assumes the risk, which also means he has a real incentive to correctly apply management practices. There is, however, a higher cost of monitorization, due to the need of environmental studies (for example, soil analysis for SOM determination). It is thus unclear which of the two types of contract is more efficient, in the sense that more carbon is sequestered by the same total amount paid (Antle and McCarl, 2002).

4.1.2. Designing contracts for carbon sequestration

4.1.2.1. Background

The United States of America did not sign the Kyoto Protocol (KP), but established in 2001 a voluntary initiative that, alongside other measures, included the possibility of carbon sequestration by forests and in grasslands and croplands (Mooney *et al.*, 2002). This initiative is private, consisting on contracts between industries that emit greenhouse gases (GHG) and farmers. But its contribution is not neglectable. Lal *et al.* (1998) indicate that carbon sequestration in agricultural soils could, alone, decrease U.S. emissions by 8%. The credits purchased in this way have prices competitive with those obtained by forest sequestration (Antle *et al.*, 2002).

So, in these resource conservation contracts relating to carbon sequestration, two questions are usually appointed: which economic incentives induce farmers to appoint management techniques that increase soil CO_2?, and would that form of sequestration be economically competitive with other forms of emission reduction (Antle and McCarl, 2002; Marland *et al.*, 2001a)?

Lewandrowski *et al.* (2004) studied which practices would be favoured by farmers for different ranges of incentives in the United States of America. They find that higher payments for each ton of carbon make afforestation the most adopted activity, while for lower payments changes in rotation and tillage practices occur. McCarl and Sands (2007) conclude the same: lower CO_2 prices make cropland and grassland management extremely attractive carbon sinks. They confirm that agricultural sequestration may be an economically effective carbon sink.

However, there are some critics of the use of land use, land use change and forestry (LULUCF) practices for carbon sequestration. Their argument usually revolves around the issue of non-permanence.

4.1.2.2. *The permanence issue*

It is necessary to take into account that some ways to sequester carbon do not necessarily correspond to a permanent decrease. This is the case for carbon storage in masses of water (Herzog *et al.*, 2003), and also for soil carbon sequestration (Blanco and Forner, 2000; Ellis, 2001). The problem is that if there is a reversion of practices, such as the use of tillage for cropland management or deforestation for forest management, sequestered carbon will be emitted again (Antle and McCarl, 2002). Furthermore, soils may be net emitters in certain climatic adverse years. This is usually referred to as "leakage", and Murray *et al.* (2004) estimate that, for forestry activities, it may be as high as 90%.

One way to address this issue was proposed by Blanco and Forner (2000) and Chomitz (2000), who all use the concept of temporary or expiring credits. Temporary credits are basically a way to buy time while cleaner technologies are set in place, keeping all the environmental benefits of permanent sequestration. Many have followed to use this concept. Marland *et al.* (2001b) consider temporary sequestration to be completely different from permanent avoided emissions.

They propose a market for temporary sequestration credits (which is equivalent to a rental market), separate from the carbon emissions credits market. More recently, Maréchal and Hecq (2006) picked up this idea, proposing the issuing of temporary credits from LULUCF activities.

But expiring credits create another market for carbon sequestration, parallel to the market of emissions reduction. Other authors have found other ways to cope with the issue of permanence. The other option is to use an equivalence factor (Kim *et al.*, 2007), which considers that a ton of carbon sequestered during a certain number of years is equivalent to a permanent reduction (Moura-Costa and Wilson, 2000). This is known as the ton-year accounting method, and has spawned several studies which yielded equivalence times from 42 to 150 years (Maréchal and Hecq, 2006). This means that there is a high uncertainty, and that for longer time spans sequestration projects become less interesting.

There are other alternatives, like the average storing capacity method (the main difference is that the variation in carbon stocks is used to generate credits) or liability mechanisms (in which each country would have to compensate LULUCF emissions by a reduction elsewhere), minimum duration or buffer credits (Maréchal and Hecq, 2006), but none of them are consensual or even desirable.

The final option is the determination of an economic equivalence factor. Keller *et al.* (2003) recognize that CO_2 sequestration is not a perfect substitute for the avoidance of CO_2 emissions, but they aim to incorporate and compare both. They define an efficiency factor for CO_2 sequestration as the ratio between economically equivalent avoided and sequestered emissions. They find that afforestation is only about 60% efficient, while sequestration in water masses is about 90% efficient.

4.1.3. Problems with carbon contracts

The major problem with this type of contract is the fact that carbon sequestration may not be as easily measured as an emissions reduction in a point-source, like a factory, or above ground forest biomass (Mooney *et al.*, 2002). Direct measurement, either by flux measurement or soil analysis, is very expensive, and so many times the only possibly way to verify if a farmer does comply with the contract is to observe its practices. However, the only way to relate practices with sequestration is by using fixed sequestration factors, which usually underestimate the potential of soils, and do not consider how well the farmer manages his land. Therefore, the issue of efficiency and trade-off between monitorization costs and net CO_2 sequestration is not linear.

There is also a consequence related with contracts that only target one environmental objective, which is the fact that they ignore co-effects. Sometimes these co-effects are negative, but in the case of carbon sequestration in soils they are usually positive. Land uses and management practices that enhance the soil's carbon pool typically also reduce soil erosion, nutrient leaching and runoff, and increase the soil water retention potential (as shown in the previous chapter). The co-effects are not negligible, but they remain as positive externalities in carbon contracts (Feng *et al.*, 2007).

It is also important to notice that farmers who adopt techniques leading to carbon sequestration may face an important increase in productivity, due to the fact that an increased SOM content improves the soil fertility status (Lal *et al.*, 1998). This is usually a direct effect which, in this type of contracts, becomes a positive externality.

There are mainly two types of contracts available to farmers: private and public contracts. Private contracts occur via voluntary schemes, in which private firms finance carbon sequestration in soils (Antle and McCarl, 2002). The Portuguese state attributed maximum emissions levels for all polluting firms, but sequestration projects do not decrease their normative target. Therefore, private firms finance these projects mainly for image purposes, and in the process they help Portugal achieve their KP target for free. We present one such case in the next section, which is the contract established between EDP and Terraprima. As for public contracts, they refer to economic payments from the government, specifically with the objective of promoting carbon sequestration. One example of such is the Portuguese Carbon Fund (PCF), which we will address further down the chapter.

4.2. Private contracts

In 2006, a contract was established between EDP, the main electricity company in the country, and Terraprima, a small firm with agro-forestry activities in Quinta da França (QF), Portugal. It was the first private contract for carbon sequestration in all LULUCF practices in Portugal (forest, cropland and grassland management). It was also the first private contract in Portugal to finance no-tillage and SBPPRL as carbon sinks. In this contract, EDP will finance in the period 2006-2012 projects regarding forest management, cropland management and grassland management on a partial "per hectare" basis. Terraprima undertakes frequent monitorization of its carbon stocks, and is paid according to the effective fixation.

The yearly payment has two components: a fixed part (F_t) and a variable part (V_t). The fixed part is defined for 2006 and 2007 as $F_t = 45000\,€$, and for 2008 to 2012 as

$$F_t = R_t \times \min\left(c_t, 3000\ \mathrm{tCO_2}\right), \qquad (3.1)$$

where R_t is 15€/tCO$_2$ in 2006, and is actualized in each year by the national consumer price index, and c_t is the amount of fixed carbon in year t.

The variable part is calculated for each year t, according to

$$V_t = y \times \min(x_t, X_t), \qquad (3.2)$$

where y is 6 €/tCO$_2$ when x_t and X_t are inferior to 1500 tCO$_2$, and 7 €/tCO$_2$ otherwise, and x_t is defined as the difference between carbon sequestration in year t and 3000 tCO$_2$, and X_t is

$$X_{2006} = x_{2006}, \qquad (3.3)$$

$$X_t = X_{t-1} - V_{t-1}/y + x_t,\ t > 2006. \qquad (3.4)$$

By definition, if x_t or X_t is negative, then V_t is zero, which means that there is no payment. Prices obtained for the variable part are updated proportionally to the Powernext price variations.

This was the first experience in Portugal of a contract for carbon sequestration in grasslands, which are our case study. Prices and amounts involved in the contract were negotiated between the two firms, even though they reflect the carbon market price fluctuations. However, Terraprima was given a choice to sub-contract part of the carbon sequestration, if Quinta da França was not enough to fulfil the total quantity of contracted CO_2, which were 7 000 tons per year. Terraprima has chosen to do so.

In the case of public contracts, we wish to determine the optimum price and quantity of sequestered carbon based on market considerations that arise from the existence of multiple options and multiple farmers. This is the subject of the next section.

4.3. Public contracts

There are many ways for the national accounting of carbon sequestration in grasslands, and they are derived from calculations in Chapter 3. The basic choice is if Portugal wants to choose "per hectare" or "per tonne" contracts, which depends on whether monitorization costs are high or not. This leads to the definition of three Tiers, each one with a higher precision than the one before:

- **Tier 1** – Use of a national average sequestration factor;
- **Tier 2** – Use of a site-specific sequestration factor;
- **Tier 3** – Active monitorization of soils.

The Tier 1 approach is equivalent to the "per hectare" contract. Since a fixed factor is used, there is a single equivalence between area and carbon sequestered. Furthermore, since that factor is independent of management practices, Portugal would design contracts that would only require monitorization of the installation of pastures. A simple Tier 2 approach does not require carbon monitorization either, since the model we developed only requires the knowledge of organic matter at the year of installation and the year of installation. A Tier 2 contract may be interpreted as "per tonne" or "per hectare", since the models describe how much carbon is sequestered in each year, but that sequestration is also a descriptive function of the hectare in which the pasture is set. Only Tier 3 requires active yearly carbon monitorization, and so only contracts respective of this level are truly "per tonne", since only in this case the management practice will influence the final outcome.

We will study the two likely scenarios for the PCF, which are a Tier 1 scenario, and a combination of Tier 2 and Tier 3, as shown in Table 28.

Table 28 – Definition of the sequestration potential in each year, according to Tier 1 and Tier 2+3 calculations, starting from an initial SOM of 0.87%.

Year	#	Carbon balance (ton.ha^{-1}.yr^{-1})		
		Tier 1	Tiers 2+3	
		Factor	Model A	Model B
2008	1	5.0	15.6	16.1
2009	2	5.0	7.5	6.7
2010	3	5.0	4.5	3.6
2011	4	5.0	3.0	2.1
2012	5	5.0	2.1	1.3

The two scenarios studied may be described as follows:

- **Scenario 1** – Tier 1 scenario, considering a fixed national sequestration factor of 5 ton CO_2.ha^{-1}.yr^{-1}. Contracts established are "per hectare", and then this factor is used to convert data to CO_2 sequestration. The factor is the average value of a linear process of sequestration during the first 10 years.

- **Scenario 2** – Tiers 2+3 scenarios, assuming that sequestration varies with pasture age, computed by Model A and Model B in Chapter 3, which are, respectively,

  $$SOM_t = 0,43 + 0,78 \cdot SOM_{t-1} + 0,34 \cdot SOM_0, \qquad (3.5)$$

  and

  $$SOM_t = 0,38 + 0,67 \cdot SOM_{t-1} + 0,52 \cdot SOM_0. \qquad (3.6)$$

  The values indicated in Table 28 were obtained from an initial SOM of 0.87%. They should be recalculated if initial SOM differs. Contracts are "per tonne", since we consider that in the first year and in the last year there is monitorization of SOM levels with soil samples from each pasture. During the middle years, SOM dynamics is estimated with models 3.5 and 3.6, and payments are adjusted at the end of the contract, when the total carbon sequestered in 5 years is determined.

The justification for these two scenarios is that they compare a "per hectare" with a "per tonne" contract. In order to minimize costs, at best, the "per tonne" contract would only require the determination of the total carbon stock change during the accounting years, which is the change between 2008 and 2012. That is why we consider, in Scenario 2, that there is not a "pure" Tier 3. Using these definitions of two alternative contracts, we will try to determine the demand and supply curves.

4.3.1. *Carbon demand curve*

The part of the Portuguese state is to guarantee that the KP goals are achieved efficiently, in the sense of Antle and Mooney (2002): the government strives to maximize social benefits from carbon sequestration per unit of resource used.

Therefore, considering the state as a buyer of sequestration credits, Portugal will acquire them as long as the final price of each tonne is lower than the reference price. We define the reference price as the lower price between other available domestic projects and the lower possible price for international projects. We assume that, if the grassland carbon price is equal to the reference price, the state will either be indifferent to the choice in project, if the other price refers to a national project, or prefer to finance grassland sequestration, if the alternative is international carbon.

It is also the state who needs to address the permanence issue. Since we are using the PCF as a case study, in this case it is not logic to assume a parallel expiring credits' market. The KP does not discriminate temporary sequestration, and therefore it is almost irrelevant for Portugal how to accomplish the target. However, it is a fact that the use of LULUCF may hold consequences for the future. There is no guarantee that farmers keep maintain their practices after 2012, and so there is a risk of re-emission in the following periods after the KP. Therefore, the state must buy credits from grassland management considering that risk, which brings the need to use an equivalence factor. This is the reason why the state does not finance projects for the reference price.

In order to determine the maximum price that the state would be interested in paying to farmers, we considered the worst case scenario, which is that after the 5 years of payments, all farmers decide to switch practices in such a way that all sequestered carbon is lost. This would mean that the PCF would only be financing temporary sequestration to borrow time. In a future period after the KP expires, the state will either continue to finance farmers to keep SBPPRL, or buy carbon credits, depending on which goals and trade mechanisms are defined for after 2012.

We obtain that price by using the concept of Net Present Value (NPV) (Perman *et al.*, 1996). The NPV of five years of sequestration, plus the updated value of buying an equivalent quantity of credits, must be the same for the state as obtaining the same quantity of credits in the present, instead of financing sequestration. We formulate this problem as

$$p \cdot (1+r)^{-6} \sum_{t=1}^{5} C(t) + p_6 \cdot (1+r)^{-6} \sum_{t=1}^{5} C(t) = p_0 \cdot \sum_{t=1}^{5} C(t), \tag{3.5}$$

where p is the price that the PCF is interested in paying farmers (€/ton CO_2), p_6 is the estimated carbon price in the sixth year (2013), p_0 is the reference price in 2008, $C(t)$ is the amount sequestered in year t (ton CO_2/ha), and r is the discount rate. The choice of discount rate is crucial, as we shall see. Therefore, we used four different values for r, namely 1%, 3%, 5% and 7%. Note that, in Equation (3.5), we are assuming that farmers will only be paid at the end of the KP accounting period (6th year). Using Equation (3.5), we obtain p, since

$$p = \frac{p_0 - p_6 \cdot (1+r)^{-6}}{(1+r)^{-6}}. \tag{3.6}$$

We considered that from 2008 to 2013, the reference price of carbon does not change, and is 20 €/ton. The price is the same for each discount rate, and does not change by using a fixed factor or a model, since it is proportional to sequestered carbon. Results obtained are shown in Table 29. Prices vary from 1.23 to 10.01 €/ton CO_2.

Table 29 – Maximum carbon price, depending on the discount rate.

	Discount rate (*r*)			
	1%	3%	5%	7%
p (€/ton)	1.23	3.88	6.80	10.01

In this case, to the state, every tonne of carbon paid at this price is equally worthwhile, since marginal costs are constant. Therefore, the demand curve[22] would be a horizontal line. Considering that there were no physical constraints, Portugal would be interested in financing sequestration in SBPPRL until the KP deficit was compensated (3.73 Mton CO_2).

However, this simplified situation is not the real one. The number of SBPPRL installed before 2008 is unknown. However, carbon sequestration supported by the PCF has to be additional to

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[22] We define supply curve for carbon sequestration in SBPPRL as a representation of the total carbon sequestered as a function of the payment per tonne.

carbon sequestration considered in PNAC, which is 0.5 Mton for cropland and grassland management. The Portuguese Rural Development Programme predicts a supported area of SBPPRL of 70 000 ha, which we will assume to be the cut-off point, i.e., the point after which all sequestered carbon is additional[23].

However, for a matter of equality and justice, the PCF would predictably have to pay all farmers for the carbon they sequester, regardless of Rural Development support. Such is to say that whichever price is fixed, it will also be paid to the first 70 000 ha, even though their sequestration was already planned and will not be additional.

For simplicity purposes, we consider that those 70 000 ha belong to Alentejo farmers from class 5, which are the most prone to switch systems without any further incentive. Therefore, we must adjust the equilibrium point to cope with this fact. Table 30 shows the quantity of carbon that is not additional to PNAC's objectives, depending on the use of a factor or a model.

Table 30 – Total carbon sequestration which is financed by the PCF but not additional to PNAC's objectives, and calculations of the real price per tonne (p^*) as a function of the total sequestered carbon (C).

	Average sequestration, Alentejo	Area	Not additional carbon	Real price to be paid
	ton CO$_2$.ha^{-1}.yr^{-1}	ha	Mton CO$_2$.yr^{-1}	€.Mton^{-1} CO$_2$.
Factor	5.0	70 000	0.35	$p^* = p\cdot\frac{C-0.35}{C}$
Model A	6.5	70 000	0.46	$p^* = p\cdot\frac{C-0.46}{C}$
Model B	6.0	70 000	0.42	$p^* = p\cdot\frac{C-0.42}{C}$

Since when the PCF pays price p there is a certain quantity of carbon that is not being truly being accounted for Kyoto purposes, a real price must be defined, p^*, which is the maximum price (€) per tonne of carbon that the PCF is willing to spend. This real price is a function of the

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[23] Note that in practice it may not be the case, since the target is common for cropland and grassland management. It is the combination of both that must add up to 0.5 Mton, and so even it may not suffice to achieve the target for the implementation of SBPPRL. We will assume that cropland management achieves its part of the goal.

model used of the total quantity of sequestered carbon. The expressions in Table 30 show that, as C increases, this effect decreases. Therefore, we may plot a demand curve, as shown in Figure 8 for Scenario 1, Figure 9 and Figure 10 for Scenario 2. In our demand curve, the PCF will not be interested in paying for carbon sequestration in SBPPRL until the base sequestration is met. From then on, it will be progressively interested in paying more, since the effect of the first 70 000 ha is diluted in the larger area of interested farmers. The upper limit for the real price is the maximum price, indicated in Table 29. But when the total deficit is met, the PCF will stop financing any project.

Figure 8 – Demand curve for carbon sequestration in SBPPRL, depending on the discount rate and total carbon sequestered, in Scenario 1.

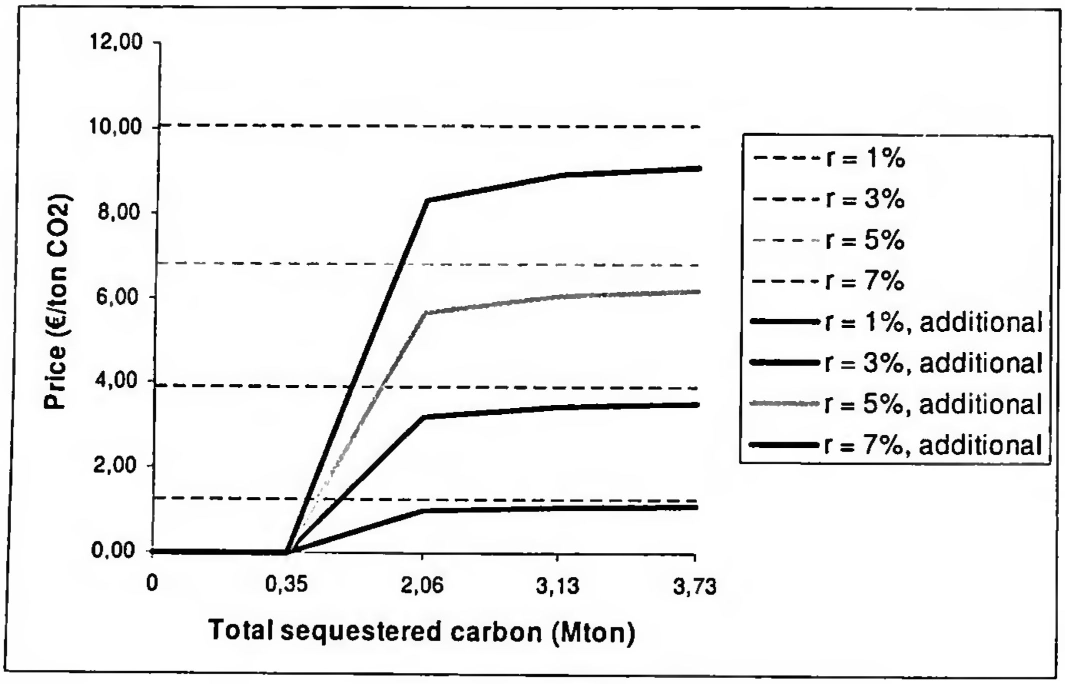


Figure 9 – Demand curve for carbon sequestration in SBPPRL, depending on the discount rate and total carbon sequestered, in Scenario 2 (Model A).

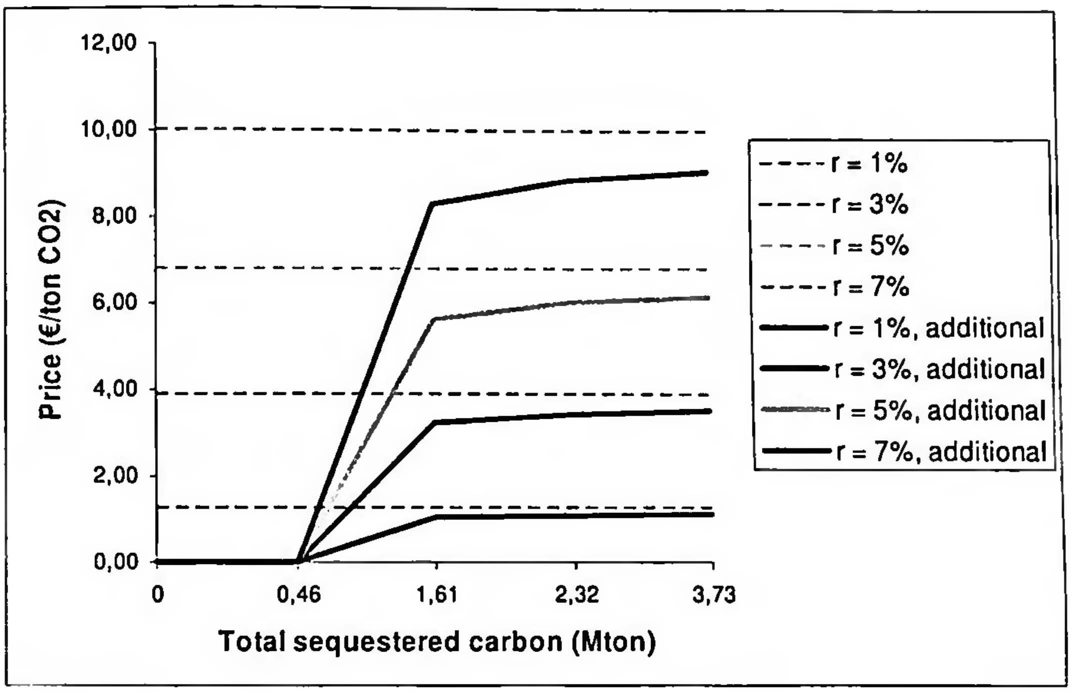
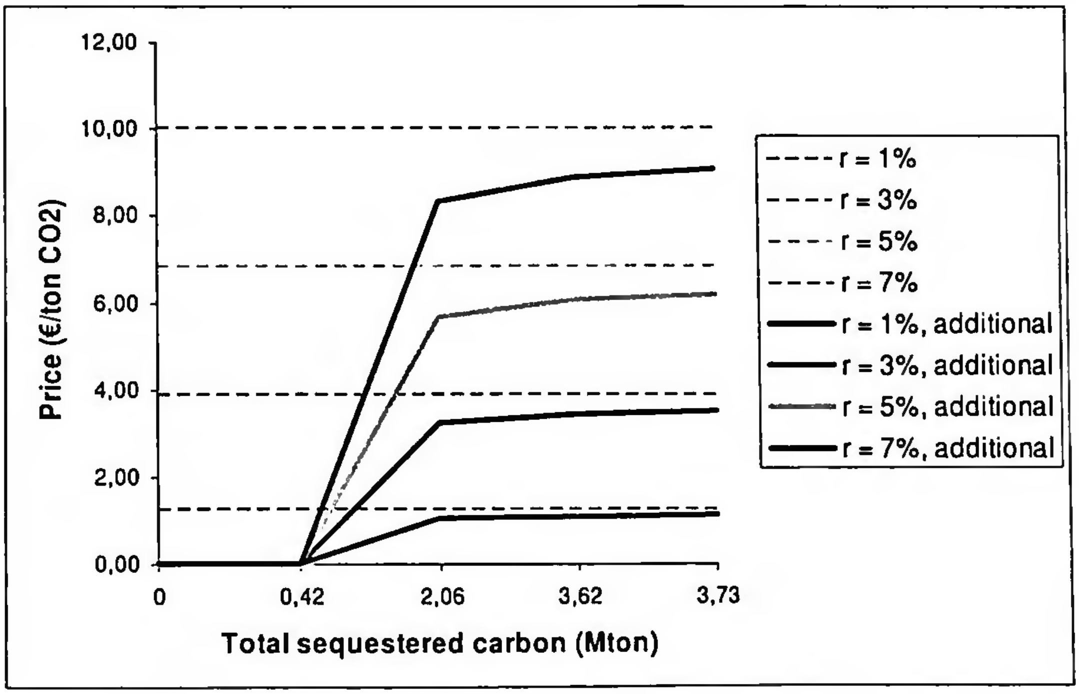


Figure 10 – Demand curve for carbon sequestration in SBPPRL, depending on the discount rate and total carbon sequestered, in Scenario 2 (Model B).



4.3.1. Carbon supply curve

Benítez and Obersteiner (2003) determine a carbon supply curve for Latin America, considering afforestation activities. They determine, for each contracted price of carbon, the total value of sequestration obtainable. Lubowski *et al.* (2001) also estimate econometrically a carbon supply function for land-use changes. Antle and Valdivia (2006) use a model with spatial distribution of opportunity costs, determining the necessary level of incentives for a given practice to be adopted.

We derived our theoretical framework from Antle *et al.* (2007), who based their model in previous ones like Antle *et al.* (2001) and Antle and McCarl (2002). They determined the necessary economic incentives for farmers to switch to carbon sequestration practices. They assumed that producers are rational, profit maximizing agents. As in the demand case, the basic approach is also to use the concept of NPV. A farmer has an option of switching to a carbon sequestration management practice, facing the costs of that switch and the opportunity cost of the highest-returning alternative activity, as well as the state's incentive.

Therefore, the NPV of the activity responsible for carbon sequestration must be higher than the NPV of the alternative, considering farmers' risk aversion, or

$$NPV_{SBPPRL} \geq NPV_{NG} . \tag{3.7}$$

We assume that the alternative is natural grasslands (NG), since those were the only ones that existed in 1990. We could alternatively use fertilized grasslands, but there is no information regarding their adoption by farmers throughout the years. Equation (3.7) means that

$$E\left[NR_{SBPPRL}\right] + g_{SBPPRL} - A_{SBPPRL} - TC_{SBPPRL} \geq NR_{NG} - A_{NG} . \tag{3.8}$$

Therefore, the sum of the estimated net revenue (NR) and public support for carbon sequestration in SBPPRL (g), minus the annualized adoption costs (A) and transaction costs

(TC), must be equal to the difference between net revenue and adoption costs of NG. Rearranging Equation (3.7), we obtain

$$g_{SBPPRL} \geq \left(NR_{NG} - E\left[NR_{SBPPRL}\right]\right) + \left(A_{SBPPRL} - A_{NG}\right) + TC_{SBPPRL}. \tag{3.8}$$

In a per tonne contract, and even as a result of the use of a sequestration factor in a per hectare contract, g is the product of the carbon price (p) and the quantity of carbon sequestered (C). This means that

$$g_{SBPPRL} = p \cdot \left(C_{SBPPRL} - C_{NG}\right), \tag{3.9}$$

and so Equation (3.8) becomes

$$p \geq \frac{\left(NR_{NG} - E\left[NR_{SBPPRL}\right]\right) + \left(A_{SBPPRL} - A_{NG}\right) + TC_{SBPPRL}}{\left(C_{SBPPRL} - C_{NG}\right)}. \tag{3.10}$$

This is the expression that allows us to evaluate the price farmers are open to receive per tonne of carbon to adopt SBPPRL instead of NG. Next, we present an evaluation of each term in this equation.

4.3.1.1. Net revenue

When a per hectare contract is established using Tier 1, the spatial heterogeneity of the carbon sequestration potential is not considered, and so there would be no factor of differentiation between region or class of farmer. However, it is not plausible that all farmers would adopt the SBPPRL system for the same price. Even when different potentials for carbon sequestration are considered, there is another factor at stake, which is the openness of farmers to adopt a new agricultural system. Farmers are usually risk averse, and prefer to keep its current practice even when explained how the system works, its advantages and disadvantages. This means that the adoption of SBPPRL would require a higher incentive to compensate the risk aversion of farmers.

We considered that risk aversion is an unknown, decreasing function with the educational level of farmers. This corresponds to an empirical observation that highly educated farmers are more capable to critically interpret data on a given system and make the economically rational decision. Non-educated farmers are prone to maintain traditional agricultural practices, which corresponds, on the one hand, to a form of social inertia, and, on the other hand, to a lack of learning skills.

Since we do not know the risk aversion function of each farmer, we defined five groups, according to the educational level. To each of the five groups, we attributed a mind set on SBPPRL, and from that we inferred the probability for each type of farmer to adopt SBPPRL. That equivalence is shown in Table 31.

Table 31 – Predicted farmer opinions on SBPPRL, and corresponding probability to adopt the system if proved that it is preferable to the alternative, depending on the education level.

Class #	Education level	Opinion on SBPPRL	Coefficient of certainty that switching from NG to SBPPRL corresponds to the calculated income (α)
1	Cannot read or write	"I will stick to what I know"	0%
2	Can read and write	"I would only switch to SBPPRL if I was sure they worked"	20%
3	Basic education	"They may or may not work, I do not know"	40%
4	Secondary education	"They could probably work"	60%
5	Higher education	"SBPPRL are better, but sometimes their installation fails"	80%

Therefore, the estimated net revenue of SBPPRL is

$$E\left[NR_{SBPPRL}\right] = \alpha NR_{SBPPRL} + \left(1-\alpha\right) NR_{NG} . \tag{3.11}$$

Using values in Table 23, we obtain the estimations of net revenue in Table 32.

Table 32 – Expected net revenue from SBPPRL, depending on the educational level of farmers in as described by Table 31.

Class #	$E\left[NR_{SBPPRL}\right]$ (€.ha^{-1}.yr^{-1})
1	378.00
2	504.72
3	631.44
4	758.16
5	884.88

In order to associate each probability with each fraction of farmers, we used data from INE (2007), as shown in Table 33. Regionalization is required for Tier 2 models, since SOM increases also depend on local conditions. For Tier 1, only the national distribution is important, since a national average factor is used. In our calculations, we will only include three regions: Beira Interior (BI), Ribatejo e Oeste (RO) and Alentejo (ALE). Since we only had SOM data for these three regions, they are the only ones represented by the models obtained in Chapter 3. Furthermore, it is recognized that most extensive livestock production occurs in these regions. Therefore, they will probably be the zones where most SBPPRL will be installed. They are already the zones where more SBPPRL are installed at the present time.

Table 33 – Number of farmers in Portugal per region and per education level.

Regions	Education level											
	None				Basic education		Secondary education		Higher education		Total	
	Cannot read or write		Can read and write									
	Nr.	%	Nr.	%	Nr.	%	Nr.	%	Nr.	%	Nr.	%
BI	5 760	16.3	6 603	18.7	17 591	49.7	2 298	6.5	3 125	8.8	35 376	100
RO	4 407	10.4	4 279	10.1	24 832	58.8	3 337	7.9	5 401	12.8	42 256	100
ALE	5 457	19.6	3 170	11.4	12 087	43.4	1 899	6.8	5 246	18.8	27 859	100

4.3.1.2. Adoption costs

Adoption costs are the costs faced by the farmer due to the adoption of one grassland system instead of the other. They are, on the one hand, annualized installation costs (Table 24) and, on the other hand, maintenance costs (Table 25).

4.3.1.3. Transaction costs

Assuming that the PCF would not be interested to make contracts with specific individual farmers one at a time, but instead with associations of farmers, and that all contracts would be equal, we assume that the cost of the elaboration of the contract for carbon sequestration in SBPPRL is neglectable. Therefore, the only cost involved would be SOM monitorization. This cost only exists in Scenario 2, since in Scenario 1 the only control is the verification of the adopted practice, which we consider neglectable.

Under our Tier 2+3 assumption, there is soil sampling and SOM determination in laboratory in the first and last years, in order to determine the carbon stock at the beginning and at the end. The following values were obtained from LQARS (personal communication) for the contract of Terraprima.

First, there are costs with the technicians who collect samples. Since we assume that the PCF would make agreements with associations of farmers, then those local associations would be responsible to correctly collect soil samples and send them to the reference laboratory, LQARS in Lisbon. We estimate the labour cost based on costs from the contract in QF, were about 600 € were paid for collecting samples in about 400 ha, or 1.5 €.ha^{-1}.

Then, there are laboratory costs, which vary with the number of soil samples. The number of required soil samples is a dependent on the specific site conditions, but as an approximation we used the case of QF. In QF, 118 soil samples were collected in an approximated area of 400 ha. This corresponds to 0.295 samples.ha^{-1}. The total cost was 885 €, or about 2.2 €.ha^{-1}.

These two terms are subjected to a 21% tax. Finally, there are material costs, estimated as 20 € in QF, or 0.05 €.ha^{-1}.

Therefore, we obtain a function to define the monitorizatrion costs, which is

$$M = (0.05+\xi)\cdot L+(1+0.21)\cdot(1.5+2.2)\cdot L, \tag{3.11}$$

where M is the total cost of each year of monitorization, L is the monitorized area and ξ is a term reflecting the transportation costs of technicians and the shipment costs of sending the samples to Lisbon. Since we do not have enough information to estimate this parameter, we will consider it zero. Therefore, the cost to monitorize a hectare is about 4.5 €.

4.3.1.4. Total carbon sequestered

Sequestered carbon will be a function of the total area available for conversion, and, in Scenario 2, the initial SOM level. This combination of effects will be responsible for the spatial differentiation we will show next.

First, as we described at the beginning of Chapter 3, NG are usually fallow years from cropland land, or degraded marginal grassland areas. However, cropland rotations are not suited candidates to adopt SBPPRL for the specific purpose of the PCF, since that would require the whole orientation of the farm to switch. In this case, we devoted our attention to the case of explorations with livestock production as the primary source of income, and determined the incentives for switching from NG to SBPPRL. We obtained the total available area under such conditions from INE (2007). Then, we used the same unpublished data from LQARS that we referred to in Chapter 3 to characterize the initial SOM levels in these areas of permanent NG. All values are shown in Table 34.

Table 34 – Area of permanent pastures and SOM levels (%) in 1999 in Beira Interior (BI), Ribatejo e Oeste (RO) and Alentejo (ALE), according to INE (2007) and LQARS, respectively.

Zone	Area (ha)	SOM (%)
BI	188 981	2.95
RO	154 433	2.95
ALE	1 017 826	0.87

In Scenario 1, the initial SOM is not important, and so there is always a 5 ton $CO_2.ha^{-1}.yr^{-1}$ regardless of the location. The potential total carbon sequestration in five years is 34.0 Mton $CO_2.yr^{-1}$. In Scenario 2, Table 28 has to be calculated again for each region, and becomes Table 35. In this case, the total average sequestration potential is 50.6 Mton $CO_2.yr^{-1}$ for Model A and 44.8 Mton $CO_2.yr^{-1}$ for Model B.

Table 35 – Definition of the sequestration potential in each year, according to Tier 1 and Tier 2+3 calculations, for the three regions considered.

Year	#	Carbon balance ($ton.ha^{-1}.yr^{-1}$)						
		Tier 1	Tiers 2+3					
		Factor	BI		RO		ALE	
			Model A	Model B	Model A	Model B	Model A	Model B
2008	1	5.0	15.6	16.1	15.6	16.1	15.6	16.1
2009	2	5.0	12.2	10.8	12.2	10.8	7.5	6.7
2010	3	5.0	9.5	7.2	9.5	7.2	4.5	3.6
2011	4	5.0	7.4	4.8	7.4	4.8	3.0	2.1
2012	5	5.0	5.8	3.2	5.8	3.2	2.1	1.3

4.3.1.5. The supply curve

We can now join all the information above, and design the unrestricted supply curve. This curve is obtained by using Equation (3.9). Table 36 shows the systematization of data and the case variability, which is twofold: from the expected revenue of SBPPRL, and from the sequestration value. It may be seen in Table 36 that farmers from classes 4 and 5, which are the ones who attribute a higher probability to the benefits of SBPPRL, as would be expected, do not require any incentive to switch practices (minimum prices required per tonne are negative). Therefore, there are a certain number of farmers who accept whichever price is offered. It may also be seen that higher prices are required for farmers to accept contracts established on the basis of a fixed factor ("per hectare" contracts). This reflects the lack of control over practices that such an approach has.

Table 36 – Results obtained for each threshold price p by using Equation (3.9).

Zone	Farmer class	NR_{NG}	$E[NR_{SBPPRL}]$	A_{SBPPRL}	A_{NG}	TC_{SBPPRL}	C_{SBPPRL}			C_{NG}	$p \geq$		
							Fact.	Mod. A	Mod. B		Fact.	Mod. A	Mod. B
		€.ha^{-1}.yr^{-1}					ton CO$_2$.ha^{-1}.yr^{-1}				€.ton^{-1} CO$_2$.yr^{-1}		
BI	1	378.00	378.00	487.66	190.16	4.53	5.0	10.1	8.4	0	59.50	29.95	35.86
	2	378.00	482.24	487.66	190.16	4.53	5.0	10.1	8.4	0	38.65	19.62	23.48
	3	378.00	586.48	487.66	190.16	4.53	5.0	10.1	8.4	0	17.81	9.28	11.11
	4	378.00	690.72	487.66	190.16	4.53	5.0	10.1	8.4	0	-3.04	-1.06	-1.27
	5	378.00	794.96	487.66	190.16	4.53	5.0	10.1	8.4	0	-23.89	-11.40	-13.64
RO	1	378.00	378.00	487.66	190.16	4.53	5.0	10.1	8.4	0	59.50	29.95	35.86
	2	378.00	482.24	487.66	190.16	4.53	5.0	10.1	8.4	0	38.65	19.62	23.48
	3	378.00	586.48	487.66	190.16	4.53	5.0	10.1	8.4	0	17.81	9.28	11.11
	4	378.00	690.72	487.66	190.16	4.53	5.0	10.1	8.4	0	-3.04	-1.06	-1.27
	5	378.00	794.96	487.66	190.16	4.53	5.0	10.1	8.4	0	-23.89	-11.40	-13.64
ALE	1	378.00	378.00	487.66	190.16	4.53	5.0	6.5	6.0	0	59.50	46.20	50.75
	2	378.00	482.24	487.66	190.16	4.53	5.0	6.5	6.0	0	38.65	30.25	33.24
	3	378.00	586.48	487.66	190.16	4.53	5.0	6.5	6.0	0	17.81	14.31	15.72
	4	378.00	690.72	487.66	190.16	4.53	5.0	6.5	6.0	0	-3.04	-1.63	-1.80
	5	378.00	794.96	487.66	190.16	4.53	5.0	6.5	6.0	0	-23.89	-17.58	-19.31

These threshold prices represent leaps after which the area of interested farmers increases. This means that the supply curve is not continuous. We may find for each minimum price and for each of the two Scenarios the area and total sequestration obtained, as shown in Table 37.

Table 37 – Carbon sequestration, per minimum price, and corresponding area, for each combination of region and farmer class.

Zone	Farmer Class	Area	Factor		Model A		Model B	
			$p \geq$	CO_2	$p \geq$	CO_2	$p \geq$	CO_2
		ha	€.ton^{-1} CO_2.yr^{-1}	Mton.yr^{-1}	€.ton^{-1} CO_2.yr^{-1}	Mton.yr^{-1}	€.ton^{-1} CO_2.yr^{-1}	Mton.yr^{-1}
BI	1	30 804	59.50	0.15	29.95	0.31	35.86	0.26
	2	35 339	38.65	0.18	19.62	0.36	23.48	0.30
	3	93 924	17.81	0.47	9.28	0.95	11.11	0.79
	4	12 284	-3.04	0.06	-1.06	0.12	-1.27	0.10
	5	16 630	-23.89	0.08	-11.40	0.17	-13.64	0.14
RO	1	16 061	59.50	0.08	29.95	0.16	35.86	0.14
	2	15 598	38.65	0.08	19.62	0.16	23.48	0.13
	3	90 807	17.81	0.45	9.28	0.92	11.11	0.76
	4	12 200	-3.04	0.06	-1.06	0.12	-1.27	0.10
	5	19 767	-23.89	0.10	-11.40	0.20	-13.64	0.17
ALE	1	199 494	59.50	1.00	46.20	1.30	50.75	1.19
	2	116 032	38.65	0.58	30.25	0.76	33.24	0.69
	3	441 736	17.81	2.21	14.31	2.89	15.72	2.63
	4	69 212	-3.04	0.35	-1.63	0.45	-1.80	0.41
	5	191 351	-23.89	0.96	-17.58	1.25	-19.31	1.14

From Table 37, we may build a cumulative table for each Scenario and model, as shown in Table 38. The values from those tables are the carbon supply curves (which, to avoid repetition, are shown in the next sub-section). It may be seen that much more carbon may be potentially stored using Tiers 2+3 (Scenario 2) than using Tier 1 (Scenario 1). Each tonne of carbon is also cheaper for the PCF using Scenario 2. Therefore, active monitorization proves to be cost-efficient.

Table 38 – Total carbon sequestration, per minimum price, and corresponding area, for each scenario and method used.

$p \geq$	Area	Total CO_2
€.ton^{-1} CO_2.yr^{-1}	ha	Mton.yr^{-1}
Scenario 1 - Factor		
0.00	321445	1.61
17.81	947912	3.13
38.65	1114881	3.97
59.50	1361240	5.20
Scenario 2 - Model A		
0.00	321445	2.32
9.28	506175	4.18
14.31	947912	7.07
19.62	998849	7.58
29.95	1045714	8.05
30.25	1161746	8.81
46.20	1361240	10.12
Scenario 2 - Model B		
0.00	321445	2.06
11.11	506175	3.62
15.72	947912	6.25
23.48	998849	6.68
33.24	1114881	7.37
35.86	1161746	7.76
50.75	1361240	8.95

4.3.2. Market equilibrium

The market equilibrium, which is where supply and demand are equal, is characterized by an equilibrium price and a carbon quantity sequestered. The intersection between supply and demand curves for different interest rates and in each of the two Scenarios and three models used are shown in Figure 11, Figure 12 and Figure 13. The demand curves are the increasing curves, while the supply curves are the vertical lines. This means that that price is demand-driven, while quantity is supply-driven.

Figure 11 – Market equilibrium for carbon sequestration in SBPPRL, considering a "per hectare" contract with a fixed national factor for carbon sequestration.

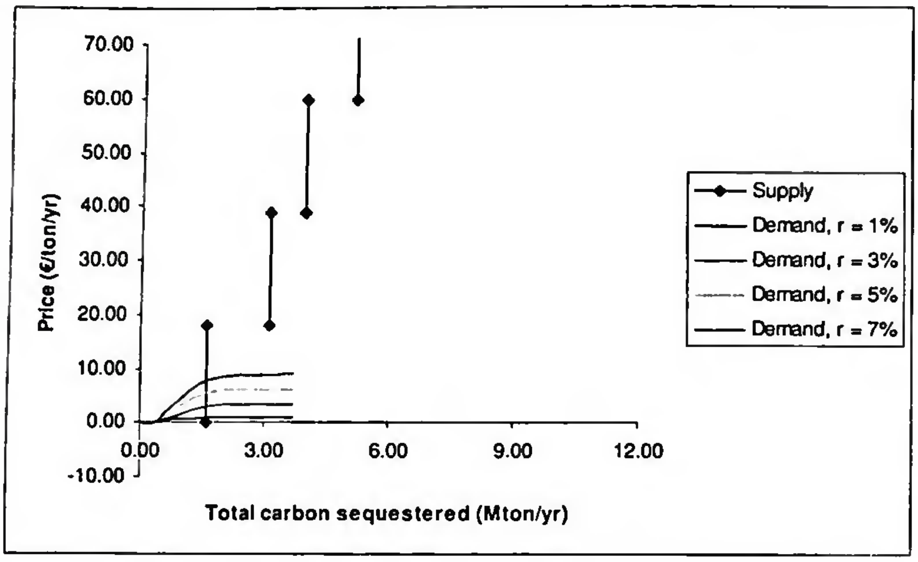


Figure 12 – Market equilibrium for carbon sequestration in SBPPRL, considering a "per tonne" contract with carbon sequestration determined by Model A from Chapter 3.

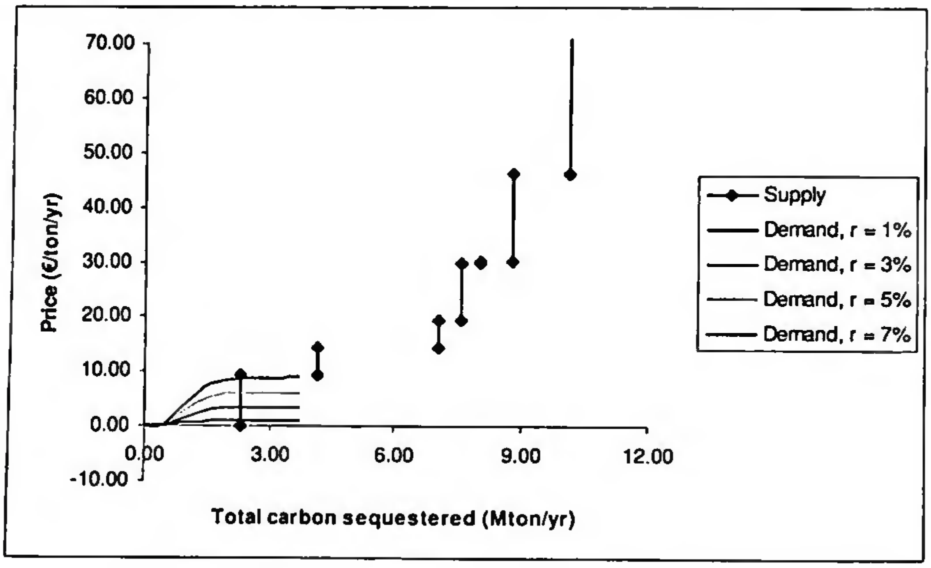
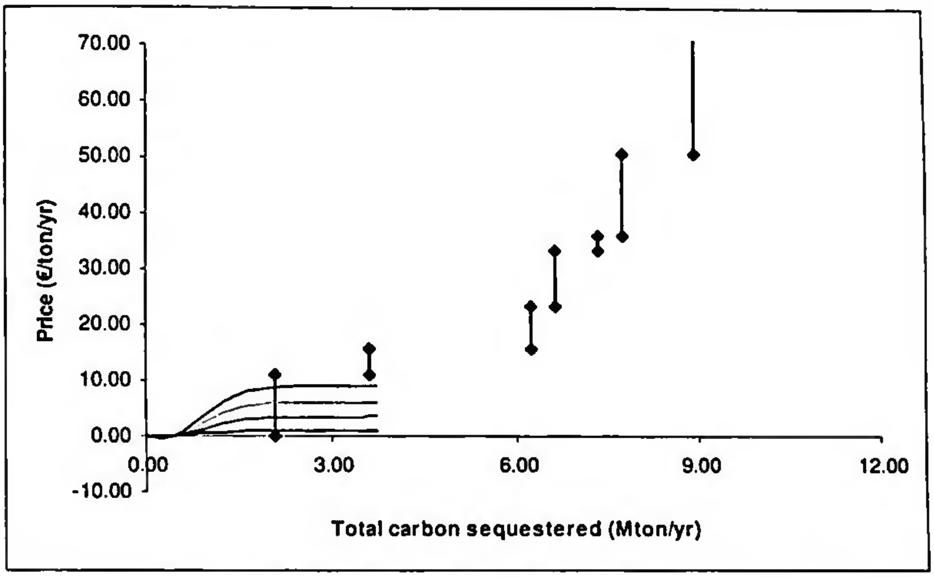


Figure 13 – Market equilibrium for carbon sequestration in SBPPRL, considering a "per tonne" contract with carbon sequestration determined by Model B from Chapter 3.



We thus obtain our final result, as shown in Table 39. In a "per hectare" contract, the PCF would be willing to pay a value of 4.80-39.20 € per hectare, and obtain an additional quantity of 1.26 Mton CO_2. In a "per tonne" contract, that value would be 1.02-8.50 € per tonne of sequestered carbon, and a quantity of 1.65-1.86 Mton CO_2.

Table 39 – Real price per tonne, total area o SBPPRL and additional sequestration obtained.

Scenario	p^*				Area	Total sequestration	Additional sequestration
	€.ton^{-1} CO_2						
	r = 1%	r = 3%	r = 5%	r = 7%	ha	Mton CO_2.yr^{-1}	
Factor	0.96	3.04	5.32	7.84	321445	1.61	1.26
Model A	1.04	3.30	5.78	8.50	321445	2.32	1.86
Model B	1.02	3.22	5.65	8.31	321445	2.06	1.65

4.4. Chapter conclusions

In this chapter we studied the issue of resource conservation contracts, namely contracts for carbon sequestration in SBPPRL. We referred the case of the private contract established between EDP and Terraprima, and introduced the possibility of the PCF to incentive farmers to adopt this system. We defined two scenarios; in the first one, a "per hectar" contract is established, without need for SOM monitorization, since an average national factor is used. In the second one, a "per tonne" contract is established, and SOM is determined in the first and last years.

In all calculations, we used the concept of NPV. Fist, we determined the demand curve, which is a horizontal line that translated the fact that the Portuguese state will finance every tonne of sequestered carbon in pastures for the same price, as long as it is lower than the alternative. This result is independent of the contract scenario, but is extremely dependent of the discount rate used, due to the fact that carbon sequestration is only temporary. Then, we determined the supply curve, by including farmer expectations in a microeconomic model of land use choice. We found more carbon may be potentially stored using the second scenario, which is also the scenario in which each tonne of carbon is cheaper for the PCF. This means that active monitorization is cost-efficient.

We thus obtain market equilibrium prices. In a "per hectare" contract, the PCF would be willing to pay a value of 4.80-39.20 € per hectare, and obtain an additional quantity of 1.26 Mton CO_2. In a "per tonne" contract, that value would be 1.02-8.50 € per tonne of sequestered carbon, and a quantity of 1.65-1.86 Mton CO_2.

5. Conclusions

The anthropogenic sources of large scale climate change are now widely recognized. The United Nations Framework Convention on Climate Change intended to promote the regulation of the level of greenhouse gas emissions (GHG), which led to the Kyoto Protocol (KP). The KP is the international agreement in which signatory countries made a commitment to decrease their global emissions. The European Union (EU) negotiated as a unit, and only afterwards emissions' quotas were distributed among its member states. Portugal was allowed an increase in its emissions of 27% in relation to 1990.

However, that limit was already met, and a significant deficit is previewed for the accounting period of 2008-2012. Therefore, Portugal found several additional measures to overcome the deficit. Among them was the decision to account for "grassland management", two of the optional items under Article 3.4 of the KP.

This work was divided in three parts. In the first part (Chapter 2), we showed that agriculture is responsible for high GHG emissions, mainly due to animal production. We found no statistical evidence that animal GHG emissions will decrease with continued economic growth.

In the second part (Chapter 3), we proposed a system, consisting of sown biodiverse permanent pastures rich in legumes (SBPPRL), which solves this problem in a double way. First, because livestock in pastures are responsible for less emissions, since there is not the formation of manure in stables. Second, because SBPPRL sequester CO_2. We quantified this effect, as well as the economic incentives for farmers to adopt this system. Adding all the contributions to the carbon balance, we obtained an estimate for the global carbon balance of 3.2-4.5 ton $CO_2eq \cdot ha^{-1} \cdot year^{-1}$ that are sequestered or avoided in SBPPRL. These values were obtained from two dynamic soil organic matter (SOM) models, which allow each farmer to know how much carbon his soil will sequester if he knows the initial fertility state.

Finally, in the third part (Chapter 4), we tackled the issue of private and public resource conservation contracts, applying it to possible funds for carbon sequestration in grasslands. We determined the demand curve, which is extremely dependent of the discount rate used, due to the fact that carbon sequestration is only temporary. Then, we determined the supply curve, and found that each tonne of carbon is cheaper for the PCF if soil carbon monitorization is used, instead of a national average factor. We obtained, as a market equilibrium price for "per hectare" contracts, a range of 4.80-39.20 € per hectare, which would yield an additional quantity of 1.26 Mton CO_2 sequestered. We also obtained the market price in "per tonne" contracts, which is 1.02-8.50 € per tonne of sequestered carbon, and a quantity of 1.65-1.86 Mton CO_2.

There were some methodological advances of this work. We present a multidisciplinary work, integrating ecological models with econometric estimation. In the first part, we applied the Kuznets hypothesis to animal emissions in Portugal. Relating economic growth and environmental variables is a useful way to build future scenarios on how the state of the environment will evolve. In the second part, we estimated the carbon sequestration potential for different types of grasslands, and specifically SBPPRL, applying econometric methods to biophysical processes. Finally, in the last part, we build supply and demand curves for carbon sequestration in SBPPRL, in order to determine a market price. We used the concept of NPV, and included farmer expectations in a highly used microeconomic model of land use choice. The number of carbon funds has been increasing, and so the development of this method may have great practical relevance, especially in the context of the Portuguese Carbon Fund (PCF).

The main limitations to our work were the lack of biophysical and economic data. The model for carbon sequestration is very simple, since it only depends on SOM content in the previous year and in the year the grassland was installed. In the future, more climatic and fertility parameters must be introduced. As further work, the construction of an accurate model for SBPPRL is essential. We also miss some field costs, namely for monitorization. This is a burden from using an innovative system, since the lack of experience translates in lack of data.

In the design of the supply curve, we did not consider that farmers discount the payment that they only receive after the contract expires. Our introduction of expectations in the model of land use choice is also based on a coefficient arbitrarily determined that is only a function of literacy. This may not depict very accurately how expectations vary among farmers.

In sum, we tried to contribute with this work to better understand the sink potential of grassland management in Portugal, which is one of mechanisms that will help to reach the national Kyoto goals. We also tried to explore ways in which Portugal may enhance the contribution of SBPPRL to the national carbon budget by offering contracts to farmers for the adoption of this system. This would mean that farmers would receive remuneration for a public service, carbon sequestration, in their land. This internalization of an (positive) externality is one of the cornerstones in Ecological Economics.

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