Carbon Management and Scenario Planning at the Landscape Scale with GIS in Tamar Valley catchment, England

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Dedication

This work is dedicated to my heroes, my wonderful parents,

My Father, Moheb

And

My Mother, Shahrokh

Without who caring support, a love of reading and respect for education; it would not have been possible.

Abstract

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It is now widely believed that globally averaged temperatures will rise significantly over the next 100 years as a result of increasing atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide. Responses to the threat of future climate change are both adaptations to new climate conditions, and mitigation of the magnitude of change. Mitigation can be achieved both through reducing emissions of greenhouse gases and by increasing storage of carbon in the earth system. In particular it is thought that there is potential for increased storage of carbon on land in soils and growing vegetation. There is now a need for research on the potential impacts of changing land use on terrestrial carbon storage, in particular as rapid land use and land cover change has taken place in most of regions of world over the past few decades due to accelerated industrialization, urbanization and agricultural practice. This thesis has developed a novel methodology for estimating the impacts of land use and land cover change (LULCC) on terrestrial carbon storage using Geographic Information Systems and Optimization modelling, using a regional case study (the Tamar Valley Catchment, southwest England) and drawing entirely on secondary data sources (current distributions of soils and vegetation). A series of scenarios for future land cover change have been developed, for which carbon storage, GHG and energy emissions amount have been calculated over the short, medium and long term (2020, 2050 and 2080). Results show that in this region, improving permanent grassland and expanding forestry land are the best options for increasing carbon storage in soils and biomass. The model has been validated using sensitivity analysis, which demonstrates that although there is uncertainty within the input parameters, the results remain significant when this is modelled within the linear programme. The methodology proposed here has the potential to make an important contribution to assessing the impacts of policies relating to land use at the preparation and formulation stages, and is applicable in any geographic situation where the appropriate secondary data sources are available.

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Shabnam Delfan Azari Plymouth

Chapter 1

Rationale and Research Aim, Objectives, and Questions

Chapter 1. Rationale and Research Aim, Objectives, and Questions

1.1 Rationale

It is now widely believed that globally averaged temperatures will rise significantly over the next 100 years as a result of increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (Smith et al., 2008; IPCC, 2007a and 2007b). Increased average temperatures are likely to be associated with a variety of other climate changes including variations in the seasonality, amount and intensity of precipitation, and shifting location and strength of wind patterns (Smith et al., 2008). The impacts of future climate change include rising sea levels and effects on water supply, agriculture, infrastructure and human health. Impacts may be both beneficial and detrimental but the net global impact will be negative economically and environmentally (Cantarello et al., 2011; Stern, 2006; King et al., 2004). Responses to the threat of future climate change are both adaptations to new climate conditions, and mitigation of the magnitude of change. Mitigation can be achieved both through reducing emissions of greenhouse gases and by increasing storage of carbon in the earth system (Macleod et al., 2010; Evans and Perschel, 2009). The most successful mitigation strategy will be based on multiple approaches, using as many opportunities for emissions reduction and increased carbon storage as possible. In particular it is thought that there is potential for increased storage of carbon on land in soils and growing vegetation (Obersteiner et al., 2010, Smith et al., 2008; Onno et al., 2008). There is now a need for research on the potential impacts of changing land use on terrestrial carbon storage. Rapid land use and land cover change has taken place in most of regions of world over the past few decades due to accelerated industrialization, urbanization and agricultural practice (Smith et al., 2008; Onno et al., 2008). Rapid industrialization and urbanization has resulted in the loss of a significant amount of agricultural and forestry land (Bedsworth and Hanak 2010; Obersteiner et al., 2010; Smith et al., 2008; King et al., 2004).

This project aims to develop a methodology for evaluating and estimating the impacts of future land use change on terrestrial carbon storage under a range of different scenarios using Geographical Information Systems (GIS) and Optimization modelling. GIS has been widely applied and recognized as a powerful and effective tool in analysing land use and land cover change. The project will use the Tamar valley catchment in southwest England as a case study, to develop a methodology that will be adaptable and applicable in any global context.

1.2 Research Aim

The aim of the project is to develop a method to evaluate the potential impact of changing land use on greenhouse gas emissions, vegetation and soil carbon sequestration and associated activity. The method develops a GIS-based model that can supply quantitative estimates of change carbon for land use planning scenarios as related to climate change impact in the Tamar Valley Catchment, in southwest England, over the 21st century.

1.3 Research Objectives

Future carbon storage on land will depend on a complex range of factors and interactions including the amount of carbon held in different soil, vegetation and land use types, the reaction of these carbon stores to future climate change, and socio-economic drivers of land use change (government policy, food supply, values, planning constraints etc). The main research objectives of this study touch, therefore, on all these topics and are to:

- **Objective 1**
- Develop an integrated spatial planning support system to model land use and land cover change in the Tamar Valley Catchment.

Tasks:

a) Build geo-data base with appropriate data for the research study.
b) Undertake a literature based review of carbon in land use, soils and vegetation.
c) Quantify carbon storage (soils / vegetation / land cover) for the research study area.
d) Quantify GHG emissions for the research study area.
e) Develop statistical relationships between land cover and environmental parameters, including climate and social-economic policy.

- **Objective 2**

- Develop a general methodology and tools for scenario generation and scenario analysis for land cover change in the Tamar Valley Catchment.

  Tasks:

a) Undertake a literature based review of current policy related to land use and land cover within the UK and explicitly the Tamar Valley Catchment.
b) Develop a range of first order, forecasting descriptive quantitative scenarios based on the drivers identified through the literature review.

- **Objective 3**

- Assess the landscape-scale storage and emissions of GHG under the range of different scenarios for different time periods in the 21^{st} century.

  Tasks:

a) Develop a methodology (based in optimisation) for applying land cover changes to each scenario.
b) Quantifying carbon storage/loss under each scenario.
c) Comparison of different scenarios based on outputs of the optimisation approach.

1.4 Project Key Questions

There are a number of key questions related to the overall aim and the specific objectives, which will be answered during the course of the PhD. These are:

1. What is the relationship between land use and carbon emission, sequestration / balance?
2. What land use changes reduce carbon emissions?
3. What are the possible scenarios for agricultural and forestry land use change in the case study area?
4. What are the future strategies of land use changes in climate mitigation?

1.5 Outline of Thesis

This thesis is organised following the defined objectives placed out in Section 1.3. In Chapter 2 a review of literature which is relevant to this research has been provided. Also, in Chapter 2 reference to land use (agriculture and forestry) management, greenhouse gases emission and scenarios definition are presented. The research methodology is presented in Chapter 3. A case study area is placed as a main methodological factor in this research study. Chapter 4 describes the value of carbon and GHG emission in soils and biomass in agriculture and forestry land. Justification and scenarios generation, and sensitivity analyses are presented in Chapter 5. In Chapter 6, the net carbon and emission amounts of different scenarios and the key finding of results analysis are discussed. And finally, a general discussion, conclusion and recommendation of the implementation and formulation of this model in the case study area, and future research need have been defined.

Chapter 2

Literature Review

Chapter 2 Literature Review

2.1 The Nature and Mitigation of Climate Change

2.1.1 Recent Climate Change and Human Activity

Global climate change is a change in the long-term (>30 years) weather patterns that characterize the provinces of the world. The term 'weather' refers to the short-term (daily) changes in temperature, wind, and / or precipitation of a region (Post et al., 1990; Lal, 2008). Climate change is linked to the 'greenhouse effect' which is a warming process that maintains the Earth's atmosphere at a higher temperature than it would be in the absence of greenhouse gases. Greenhouse gases include carbon dioxide (CO_2), Chlorofluorocarbons (CFCs), Methane (CH_4), Nitrous oxide (N_2O), Tropospheric ozone (O_3), and water vapour. In general, fossil fuels are a birthright left to us by the biosphere of the distant past. On an earlier warmer Earth with a high concentration of carbon dioxide (CO_2) in the atmosphere, photosynthetic organisms (algae and higher plants) absorbed the CO_2, and used it to produce profuse organic material, which subsequently formed coal and oil reserves. Carbon, in particular, is a key element in greenhouse gases; its cycle in the Earth system and its change from one form to another is shown in Figure 2.1. Other geochemical element-based cycles include oxygen, nitrogen, phosphorus, sulphur, and iron is also affected by this cycle (Lal, 2008). This diagram also outlines the main forms of carbon and its compounds (Figure 2.1). Over the last 400,000 years the Earth's climate has been unstable, with very significant temperature changes, going from a warm climate to an ice age in as rapidly as a few decades (Figure 2.2). These rapid changes suggest that climate may be quite sensitive to internal or external climate forcing and feedbacks.

Recently human societies are understood to contribute to an enhanced greenhouse effect, and thus climate change, by increasing greenhouse gas (GHG) emissions from fossil fuel use and other sources. Future possible GHG emission trajectories can be explained in both non-participation and participation terms and the costs of decreasing GHG emission (Kern et al., 1998; Smith et al., 2007a). The major emission sources include energy activities and generation, industries, land use, agriculture, and forestry operations (Kern et al., 1998; Smith et al., 2007b).The discovery of fossil fuels and the global industrial revolution that followed changed the atmospheric CO_2 dramatically.

Figure 2.1: Carbon and other GHG cycles in the Earth system (Lal, 2008).

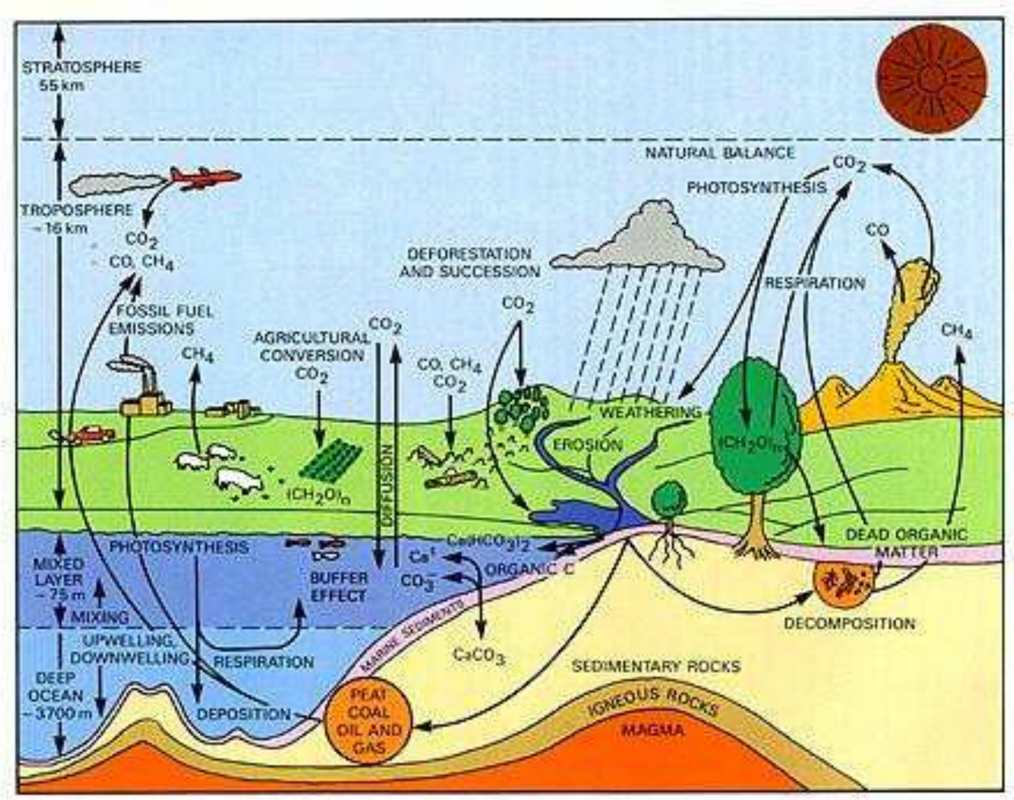
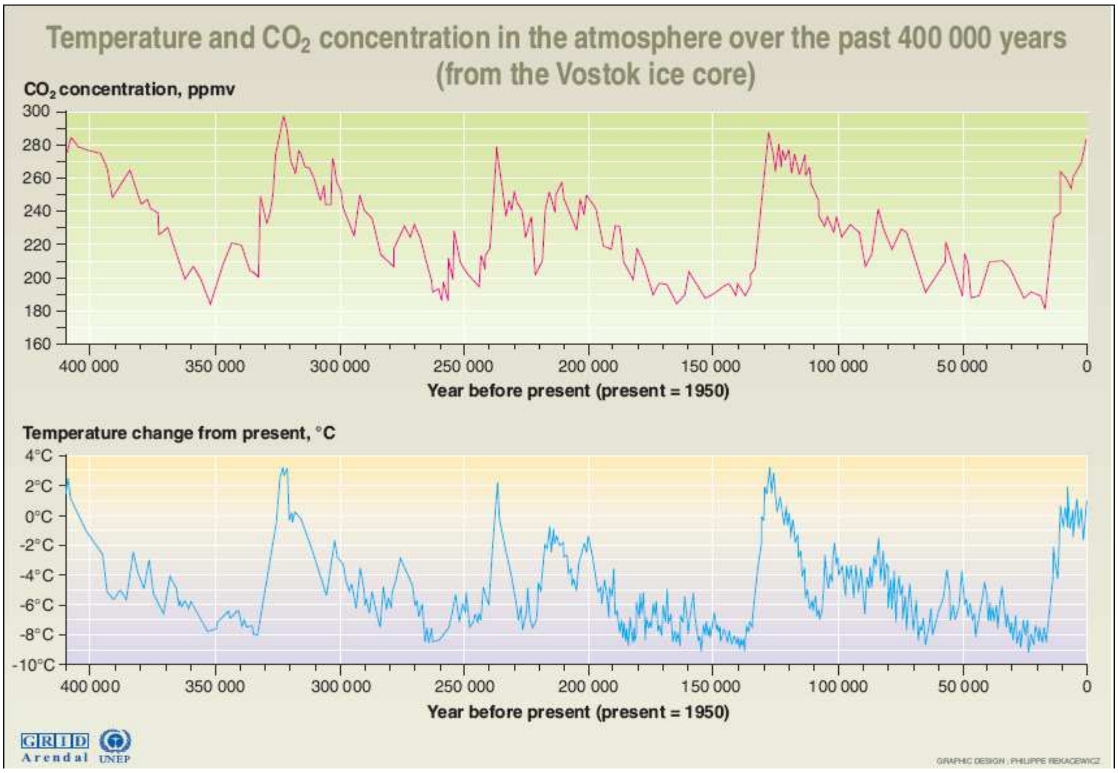


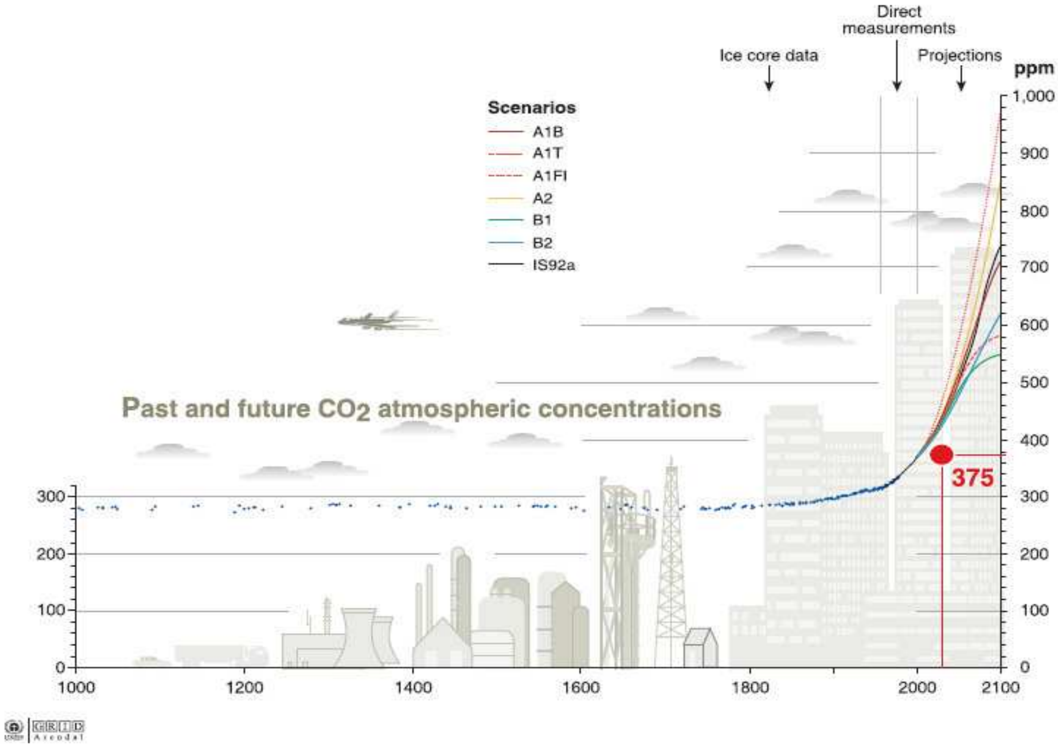
Figure 2.2: Temperature and CO_2 concentration in the atmosphere over the past 400000 years (Petit et al., 1999).



Regardless of the cause of the warming, understanding is sufficient about global climate to forecast that as the temperature increases, the complete global climate system powered by heat energy should also change, even though the extent and direction of the changes are undecided.

The earth has become warmer over the last century. The Intergovernmental Panel on Climate Change (IPCC), a group recognized by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP), reports that the average surface temperature of the earth increased during the twentieth century by about $0.6^{o} \pm 0.2^{o}C$ (The $\pm$ $0.2^{o}C$ means that the increase might be as small as $0.4^{o}C$ or as great as $0.8^{o}C$) (IPCC, 2007b). In fact, the difference between today's standard global temperature and the average global temperature during the last ice age is only about $5^{o}C$, so this small recent increase in temperature is significant. Since pre-industrial times, the atmospheric concentration of greenhouse gases has grown significantly. Carbon dioxide (CO_2) concentration has increased by about 31%, methane concentration by about 150%, and nitrous oxide concentration by about 16% (Wardle et al., 2003). The present level of carbon dioxide concentration (around 375 ppm (parts per million) in 2003 and about 390 ppm in 2011) is the highest for 420,000 years, and probably the highest for the past 20 million years (Figure 2.3).

Figure 2.3: Past and future CO_2 concentrations (IPCC, 2005).



Based on growing evidence, there is high confidence that there will be impacts of future climate change or future impacts of current climate change with consequent effects on hydrological systems, natural systems and biodiversity, agricultural and forestry systems. Rising sea level, increasing runoff and earlier spring peak discharge, warming of lakes and rivers are all likely impacts (Kern et al., 1998 and IPCC, 2007a).

2.1.2 Climate Change and land use in the UK

2.1.2.1 Climate change predictions for 21st century in UK

Many of the scenarios indicate that by the middle of the 21st century global emissions of carbon dioxide may at least start to stabilise, although some predictions note an increase in emissions during all of this century (IPCC, 2007b).

Predictions of future climate change, supported by numerical global climate models, are the most significant outputs of climate science (Demeritt and Langdon, 2004). Recent predictions of future climate change have been produced by the Hadley Centre for several scenarios of future emissions from the IPCC. The main underlying characteristics of the prediction scenarios are summarised in Figures 2.4 and 2.5 and Table 2.1.

Figure 2.4: Anthropogenic carbon dioxide emissions for IPCC scenarios (Met Office Hadley Centre, 2003).

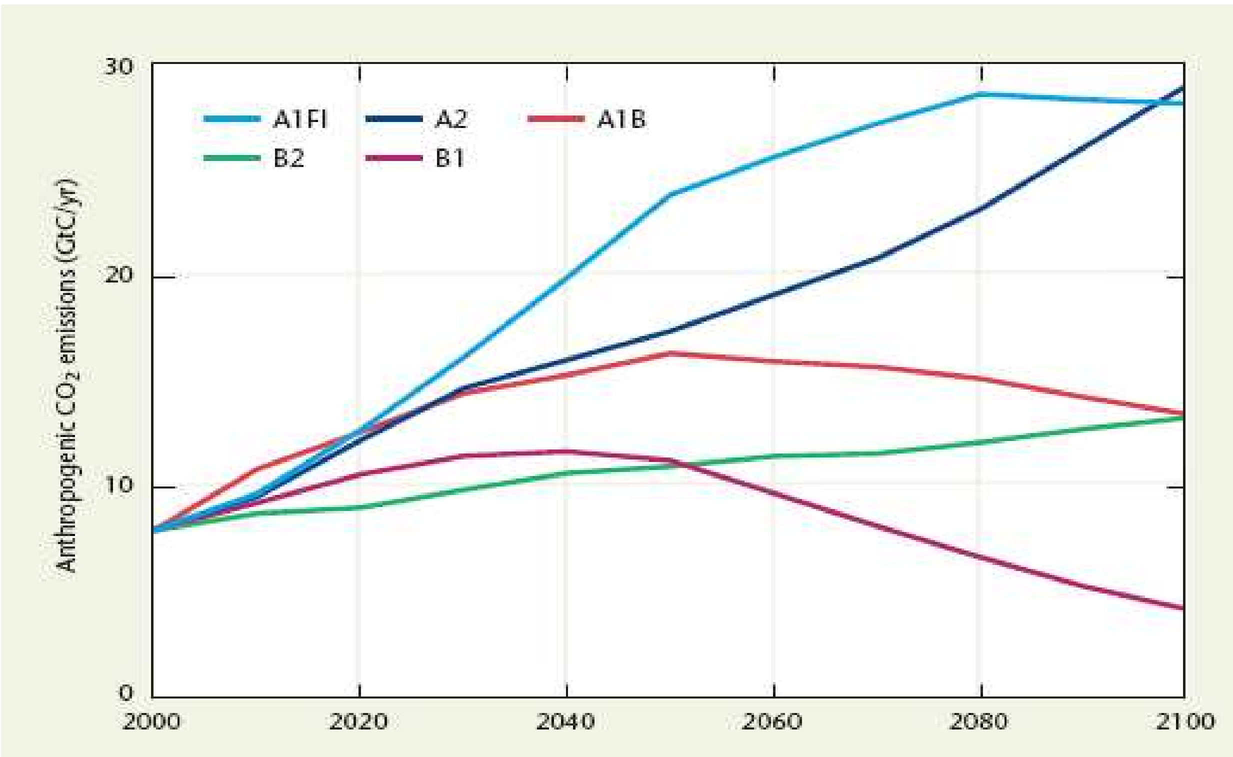


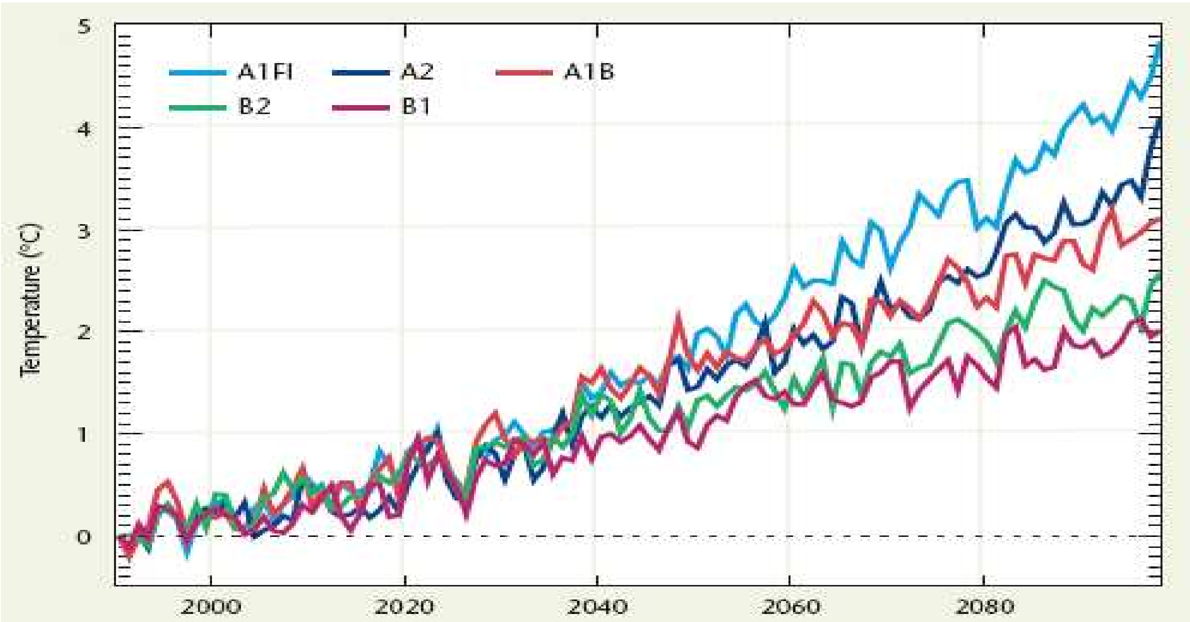
Table 2.1: Assumptions made in the main IPCC emissions scenarios used to derive future emissions of greenhouse gases (Met Office Hadley Centre, 2003).

Name	Economic change between 1990 and 2100 from GNP increase (Trillion US $)	Population by 2100 (Million)	Cumulative CO_2 emissions between 1990 and 2100 (GT/C)
A1F1	505	7140	2190
A2	225	15070	1860
A1B	510	7060	1500
B2	215	10410	1160
B1	310	7050	980

2.1.2.2: Predicted changes in temperature, precipitation, and extreme events

The global mean temperature rise over the 21st century is predicted by the Hadley Centre model to be 4.5°C for the highest emissions (A1F1) and 2 °C for the lower (B1), (Figure 2.5).

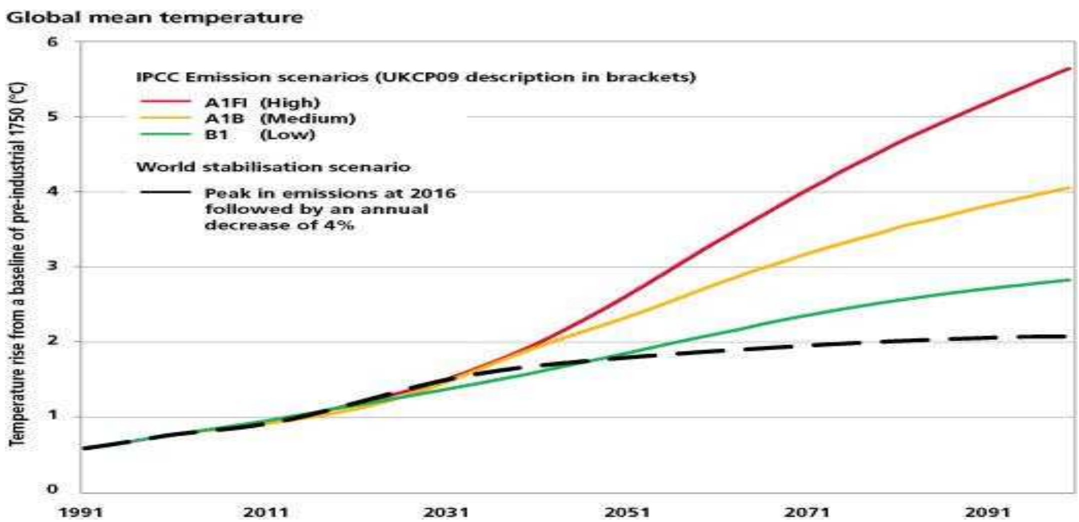
Figure 2.5: Predicted global average temperature due to IPCC emission scenarios (Met Office Hadley Centre, 2003).



A climate prediction index for the UK has been developed by the Met Office Hadley Centre as a means of comparing the performance of models against a range of different indicators such as surface temperature, rainfall and surface pressure using generalised figures.

As global temperature increases, the temperature increases in the UK as well, and the earth's water cycle becomes more intense and rainfall increases. It is well known the temperature and prediction changes during the 21st century will vary from location to location (Hadley Centre, 2003). The UKCIP02 climate change scenarios are supported by a series of climate modelling results by the Hadley Centre, using the HadCM3 climate model (Hulme et al., 2002; Aldy and Stavins., 2007). Daily UKCIP02, 09 and 10-based climate change scenarios for the UK were generated and used to compare different weather extreme events and extreme impacts on land use including intensity and incidence of heat-waves. In the UKCIP09, 10 and 2011, the UK government is strongly committed to determined domestic targets of reducing greenhouse gas emissions in order to play a part in avoiding risky climate change. It is also pushing hard for further international action to reduce emissions. The black, dashed scenario on the graph below (Figure 2.6) represents global emissions if the world community successfully commits to a global deal at international discussions to be held in Copenhagen in 2009 and South Africa climate change summit 2011, using the Committee on Climate Changes most rapid annual reduction rate, which gives the best chance of avoiding dangerous climate change (stabilising world temperatures below a 2ºC increase above pre-industrial levels). The IPCC emission scenarios shown do not include the effect of actions to reduce output of greenhouse gases.

Figure 2.6: Predicted global emissions and temperature due to IPCC emission scenarios in 2009, 2100 (UKCIP, 2009 and 2011).



Despite the intentions of many governments, current global greenhouse gas emissions continue to increase. If we continue on this path it will put us on a trajectory to the medium or high emission scenarios.

As the climate gets warmer, analysis showed that weather extreme statistics related to temperature, such as heat-waves, are likely to increase significantly in extent and frequency.

The rise in UK temperature is predicted to be around 4.5 ^{o}C in 2080. In some areas such as the south west the combined effect of rising temperature and decreasing precipitation is a significant fall in the amount of soil moisture, which may impact on agriculture and food production (Andrews, 2000; Smith et al., 2007a).

2.1.2.3 Responses to Risk

At a specific level, there are a number of possible responses to climate risk in the future of the UK, they can be summarised as follows:

a) Share loss, e.g. insure against business losses from weather events (Aldy et al., 2003; Kaufmann , 2011)
b) Bear loss, e.g. acknowledge that some land will flood during winter.
c) Structural or industrial change, e.g. support building foundations to manage with increased subsidence risk (Hulme et al., 2002; Solomon et al., 2011).
d) Legislation or institutional change, e.g. make stronger planning directions on improvements in flood risk areas (Wear and Bolstad, 1998; Hulme et al., 2002; UKCIP, 2009).
e) Avoid risk, e.g. produce new agricultural crops improved and better suited to the new climate (Hulme et al., 2002; DEFRA, 2008).
f) Research, e.g. use research to better understand the climate risk (Cohen, 2000).
g) Education, e.g. increase public awareness about coping with flooding at home (Prasad et al., 2007; Meehl et al., 2010).

Responses to risk, along with the predicted climate change, offer alternative, but complementary methodologies. In this study a modelling approach will be adopted in order to predict and develop the future climate change phases. It can be considered to fall within the categories of avoiding risk, and undertaking research into the extent of risk.

2.1.2.4 The UK Climate Change Act 2008

Based on a report from the Energy and Climate Change Department, the UK has passed legislation that introduces the world's first long-term legally binding framework to tackle the dangers of climate change. The Climate Change Bill was introduced into Parliament on 14 November 2007 and became law on 26 November 2008. The Climate Change Act creates a new approach to managing and responding to climate change in the UK, by:

- Setting ambitious, legally binding targets
- Taking powers to help meet those targets
- Strengthening the institutional framework
- Enhancing the UK's ability to adapt to the impact of climate change
- Establishing regular and clear accountability to the UK Parliament and to the devolved legislatures (Department of Energy and Climate Change report, 2008).

The target for 2050, which has been introduced by the UK's Climate Change Target, is as follows:

(1) It is the duty of the Secretary of State to ensure that the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline (2) "The 1990 baseline" means the aggregate amount of; (a) net UK emissions of carbon dioxide for that year, and (b) net UK emissions of each of the other targeted greenhouse gases for the year that is the base year for that gas (Department of Energy and Climate Change, 2008 and www.legislation.gov.uk).

2.1.2.5 Impact of Climate Change in the UK

Annual precipitation in the UK is expected to change by less than 10% by 2050; however, this conceals a significant change in seasonal precipitation. Winter precipitation might increase by between 0% and 10% by the 2020s and up to 20% by the 2050s. On the other hand, summer precipitation might reduce by between 0% and 20% by the 2020s and up to 30% by the 2050s (Hulme et al., 2002; DEFRA, 2008). Cloud amounts are supposed to decline considerably overall (between 2% and 6%by the 2050s) with a small increase of up to 2% in winter and a big reduction of up to 10% in summer by the 2050s (Hulme et al., 2002; Post et al., 2009). Overall the relative humidity (the amount of water vapour in the air) is likely to reduce by a small amount in winter (up to -2%) and decline much more in summer (-

2% to -4% by the 2020s and -2% to -8% by the 2050s) as the air temperature is expected to increase (Hulme et al., 2002; Asselt et al., 2004; Keith et al., 2009).

The implications of greenhouse emissions scenarios for future global climate are computed using the HadCM3 global climate model from the Hadley Centre (Hulme et al., 2002; Zeng, 2008; Lal, 2008).

The UK future climate change predictions can be summarised as:

- **The country's climate will become warmer**. Annual temperatures may increase by between 2 and 4.5^{0}C by the 2080s. The degree of warming will vary across the UK and depends on the level of global greenhouse gas emissions. Warming will be maximum in parts of the southeast, where temperatures might rise by up to 5^{0}C in summer by the 2080s (Christensen et al., 2009; UKCIP09 and 2010).
- **High summer temperatures will become more regular and very cold winters will become increasingly unusual**.
- **Winters will become wetter and summers may become drier across all of the UK.** The principal changes will be in the south and east where summer rainfall may decline by up to 50% by the 2080s. Heavy winter rainfall will become more frequent, but the quantity of snow may decline by up to 90% by the 2080s, depending on areas and scenarios (Mike and Tyndall, 2003; Michael et al., 2010).
- **Sea-levels will continue to rise around the UK**. Sea levels could be between 26 and 86cm above the current level in southeast England by the 2080s. At some east coast locations, sea levels that currently have a 2% probability of occurrence in any given year could happen between 10 and 20 times more regularly by the 2080s (Hattenschwiler et al., 1996; Hulme et al., 2002; Onne et al., 2008).
- **The Gulf Stream may weaken in the future**, but it is unlikely to result directly in a cooling of the UK climate within the next 100 years (UKCIP, 2009; Perschel and Evans, 2009).

2. 2: Adaptation and Mitigation

Adaptation to climate change and mitigation of climate change are complementary policies to reduce the impacts of climate change. Adaptation is an automatic or planned response to change that does not minimize the adverse effects and maximize any benefits. It is a means to reduce the impact of climate change without necessarily reducing greenhouse gas emissions. Adaptation is necessary because climate change is already happening, and the long lag times in the climate system make further climate change inevitable (David and Herzog, 2000; Hourcade et al., 2001).

Mitigation is defined as limiting climate change, particularly through reduction of greenhouse gas emissions. Mitigation can be achieved in several general ways including increased energy efficiency, fuel substitution, use of non-fossil-carbon fuels (including nuclear power and renewable), carbon sequestration (or the removal of carbon from the atmospheric system), and associated infrastructure and lifestyle changes. Mitigation, in contrast to adaptation, needs time to take effect due to the lags in the climate system and the time necessary to reduce emissions sufficiently to stabilise climate.

Adaptation and mitigation should therefore be analyzed together in cost-benefit analyses of emission abatement (IPCC 2007a; Audus, 2000). However, adaptation and mitigation are often considered over different temporal scales and this hampers study of the trade-offs between them. An exclusion is facilitative adaptation (Smith et al., 2001), which, like mitigation, requires long-term policies at a high level. Facilitative adaptation is often referred to as enhancing adaptive capacity. Adaptive capacity is the ability of a system to respond to a change (in this case, climate change) and is generally believed to be determined by technological options, economic resources and their distribution, human and social capital, and governance (Smith et al., 2001). Facilitative adaptation is probably a form of planned, anticipatory adaptation but, instead of the central government telling farmers when and what to plant, doctors what pills to prescribe, or households how high to turn on their air conditioners, facilitative adaptation comprises those government actions that allow households, companies and lower authorities to adapt better, that is, to make appropriate planting decisions, medical prescriptions, and air conditioning investments. Facilitative adaptation and mitigation not only both reduce impacts, but they also compete for resources (Audus, 2000; Smith et al., 2001). In general, adaptation and mitigation are substitutes; they are two different ways of reducing climate change damages, and if the costs of adaptation fell, we expect society to do more adaptation and less mitigation. However, in the literature on adaptation and mitigation it is sometimes claimed mitigation and adaptation can be complementary (Freund, 2002; Smith and Conen, 2004).

At the moment, a flurry of consultants and academics are advising governmental and international bodies on what to do about adaptation, classically treating adaptation as something novel. However, adaptation to change is an everyday fact, as is adaptation to weather inconsistency (Fisher et al., 1996; Freund, 2002). Adaptation to climate change has taken place throughout history and pre-history (Hahn and Stavins, 1992; Audus, 2000).

Adaptation with mitigation, has led to demand for an integrated analysis of and policy for mitigation of greenhouse gas (GHG) emission and adaptation to remaining climate change. For example Topp and Doyle (1996) check the impacts literature, attempting to differentiate between adaptation and residual impacts.

Basically, adaptation is incorporated in a “what if “ scenario, such as “what if planting dates are a week earlier than before” (e.g., Puchala, 2005) or “what if we put up dikes everywhere” (e.g., Schils et al., 2005). Adaptation is subjective because there is no assessment of the practicality or attraction of the level and type of adaptation (see, e.g., Smith et al., (2007a); King et al., (2004); Frank, (2002) and Tiedje (1988)). Adaptation and mitigation have some other difficulties as well. The first is a mismatch of scale. Mitigation is primarily a subject of national governments within a framework of international consultations. Adaptation is primarily a remit of local managers of natural resources, and individual households and companies, situated within a district economy and population. Even though individuals will mitigate their emissions, the incentives to achieve this are provided by their governments (Audus, 2000; King et al., 2004).

Adaptation cannot be readily compared to mitigation, because most adaptation is done by different people, at a different spatial and temporal scale than mitigation (Audus, 2000; Freund, 2002). Mitigation may take resources away from adaptation. Emission abatement is a key part of mitigation and has two effects; it reduces the size of the economy, and it reallocates money towards mitigation. As a result, reduced resources are left for adaptation (Audus, 2000; Hourcade et al., 2001).

2.2.1 Mitigation Policies

Policies to mitigate possible damages from global climate change require costs on current production to supply benefits to future production. The effects on global climate of carbon dioxide, methane, and other greenhouse gases that are discharged to the atmosphere are predicted to increase slowly and to continue for many decades (IPCC, 2007b). Policies to mitigate climate change impose costs on the current generation and therefore production in hope of providing benefits to future generations (Groenestein and Faassen, 1996). Therefore, it is easier to evaluate alternative policies for greenhouse gas emissions using for example anticipated-utility-in-advance decision analysis. This approach extends the predicted net-present-value (NPV) model of intertemporal trade-offs to include public options regarding risk and intertemporal equity (Schils et al., 2005).

Although the focus is on global climate change, this analysis can be modified to policy evaluation for other long-term environmental problems, such as storage space of radioactive waste, restoration of sites contaminated with chemical contaminants, and loss of biodiversity (Rosegrant et al., 2001).

A mitigation policy might include various activities, such as:

a) Abatement-preventing emissions of greenhouse gases to reduce climate change.

b) Mitigation and Adaptation-changing technology and performance to decrease the damages connected with climate change.

c) Enhancement and improvement of greenhouse gas sinks, accelerating the absorption of greenhouse gases from the atmosphere, by afforestation for example.

d) Geo-engineering activities to reduce climate change other than limiting net greenhouse gas emissions, such as increasing airborne particulates or deploying tracking mirrors to reflect solar radiation.

2.3 Land use Change as a Method of Climate Change Mitigation

2.3.1 Possibilities and Opportunities for Mitigation through Land Use and Land Use Change and Forestry-(LULUCF)

With the Kyoto protocol, industrialized countries (Annex I countries) are to reduce their greenhouse gas emissions in the period 2008-2012 by approximately 5.2% compared to the 1990 level (IPCC, 2007a). The Kyoto protocol set emissions targets for all greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF6) that can be met by effects and activities in every sector including energy, manufacturing (industrial) processes, agriculture, and waste. Activities from land use, land use change and forestry (LULUCF) can also be used in a limited way to achieve the target (UNFCCC, 2005). The general rules are included in Articles 3.3 and 3.4 of the Kyoto Protocol on land use change and forestry (UNFCCC, 2005).

In the case of LULUCF, one of the main challenges is to produce a sustainable development model that preserves the way-of-life for the population at a general level. It is possible to develop a new relationship with the environment that will guide society to a less carbon intensive level of activities and possible economic and social expansion at the same time (IPCC, 2007a).

Separate rules for greenhouse gas emissions and removals from land use, land-use change and forestry activities have been developed under the Kyoto Protocol, because they have unusual characteristics compared to greenhouse gas emissions from fossil fuels, for the following reasons:

a) LULUCF activities can also remove CO_2 from the atmosphere as well as reducing emissions. This removal can be stored and counts against an emission of the equivalent amount of CO_2, e.g. when the collected biomass is burnt or decomposes (Amadi et al., 2004).
b) Evaluation of LULUCF emissions and removals is more difficult than for fossil fuel emissions but within the range of uncertainty for non-CO_2 greenhouse gases (IPCC, 2001a). Although emissions from fossil fuels can be estimated comparatively precisely from the magnitude of fossil fuels used, the emissions and removals from land use and forestry activities depend on many variables which are harder to measure (Morris et al., 2005; O'Brien et al., 2009).
c) The anthropogenic part of forestry emissions and removals is extremely small compared to the expected turnover of CO_2 in the atmosphere, making it difficult to separate the human induced part from the natural part (IPCC, 2001).
d) The global biosphere's uptake might be affected by climate change and can in a few regions cause significant positive feedbacks (Bailey et al., 2004a).
e) Forestry CO_2 production and removal might happen many years subsequent to a specific human interference while emissions from fossil fuels happen instantly when the fuel is burnt (Day et al., 2002; O'Brien et al., 2009).

2.3.1.1 Greenhouse gas (GHG) profile and purpose of LULUCF activities

For development of the LULUCF framework in the UNFCCC (United Nations Framework Convention on Climate Change), the land use change and forestry can make up four categories (MCT-Minister of Science and Technology/General Coordination on Global Climate Change, 2004):

a) Changes in forests and other woody biomass reserves,
b) Forest adaptation to other uses,
c) Management of abandoned land and,

d) CO_2 emissions and removals from changes to soils.

The UNFCCC outlines five economic sectors that are the sources of anthropogenic greenhouse gases (GHG) in the atmosphere. The LULUCF sector includes no less than five possibilities to decrease net GHG emissions, specifically:

a) Provision of renewable energy.
b) Substitution for more fossil carbon-concentrated product,
c) Decreased production in non-CO_2 gases (e.g.CH_4 from agriculture);
d) Sequestration of carbon through improvement of global C stocks, and
e) Protection of existing C stocks (e.g. through decreased deforestation, devegetation, forest degradation, and land degradation).

Terrestrial environments also supply food, fuel, and shelter, conserve biodiversity and supply other services and environmental advantages (O'Brien et al., 2009 and Macleod et al., 2010).There are three unique characteristics of the LULUCF sector that involve consideration of the background of greenhouse gas mitigation, specifically saturation (which limits biological sequestration potential), non-permanence, and the degree of human control.

The eventual objective of the UNFCCC and all agreements associated with this as far as LULUCF options are concerned, is to generate and encourage actions that (Six et al., 2004).

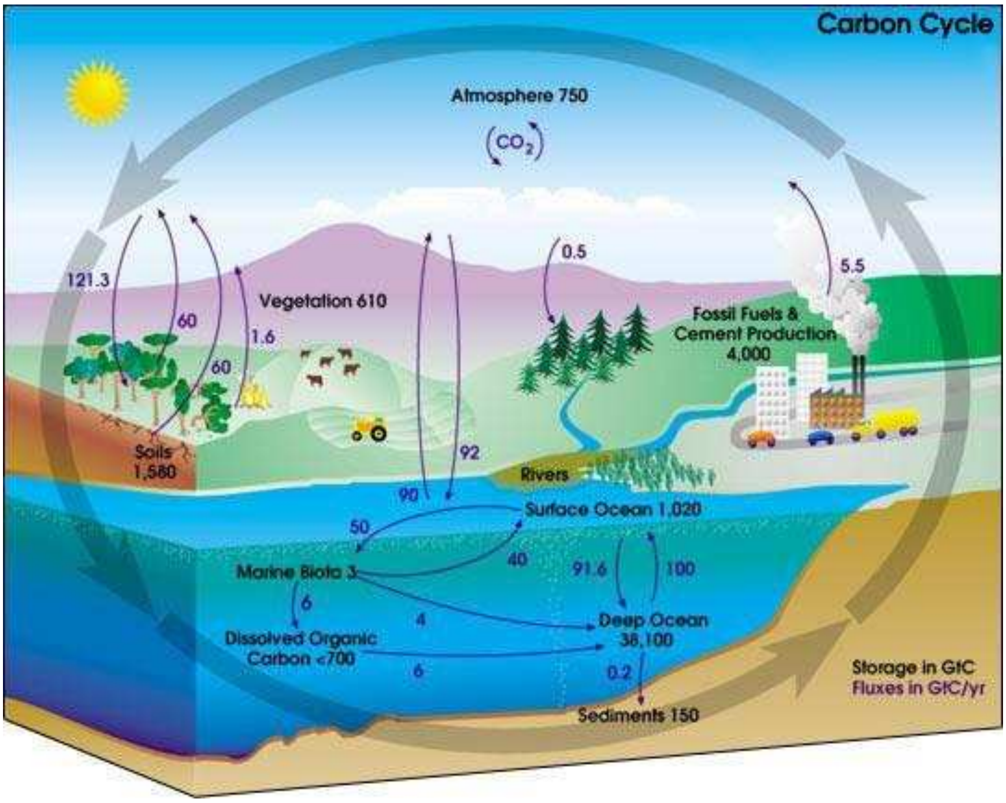
a) Reduce the most important sources of emissions from LULUCF (reduce deforestation, forest degradation, unsustainable logging, etc.).
b) Increase and develop major carbon pools.
c) Encourage the sustainable use of biomass in construction and for energy production.
d) Link emission decrease and sink development activities with adaptation strategies.

2.3.2 Agriculture

Figure 2.7 depicts the exchange of carbon, in units of 10^{15} g C yr^{-1}, among the major pools (Thomson et al., 2008; Keith et al., 2009). Carbon dioxide is a critical component in this cycle of carbon, being free in the atmosphere, dissolved in the oceans, integral in plant cells and soil, and locked CO_2 used by plants such as agriculture is important in sequestering and protecting carbon in biomass and from soils into sediments (limestones). On the other hand, locked CO_2 in biomass and soils through sequestration is a key part of this cycle. Agricultural lands are those lands used for agricultural manufacture, consisting of cropland, controlled grassland and staple crops including agro-forestry and bio-energy production. They occupy about 40-50% of the Earth's land surface (FAO, 2005; Wise et al., 2009).

Agriculture accounted for an estimated emission of 5.1 to 6.1 $GtCO_2$-eq/yr in 2005, or 10-12% of total global anthropogenic emissions of greenhouse gases (GHGs). Internationally, agricultural CH_4 and N_2O emissions have increased by around 17% from 1990 to 2005, an average annual emission increase of about 60 $MtCO_2$-eq/yr (IPCC, 2007b).

Figure 2.7: Carbon cycle in land, soil, vegetation, biota and atmosphere (Keith et al., 2009).



As noted in section 2.2, there is a diversity of possible actions for mitigation of GHG emissions in agriculture, involving a combination of carbon sequestration and protection of carbon pools. The most important choices are advanced crop and grazing land management (e.g., improved agronomic performance, nutrient use, tillage, and residue management), restoration of organic soils that are consumed for crop creation and restoration of degraded lands (IPCC, 2007a). Agricultural GHG mitigation choices should be competitive with non-agricultural choices (e.g., energy, transportation, forestry) in achieving long-term (i.e., 2100) climate purposes (IPCC, 2007b).

2.3.2.1 Mitigation technologies and practices

Opportunities for mitigating GHGs in agriculture fall into three categories, supported by international policy:

a. Reducing emissions: Agriculture releases to the atmosphere important quantities of CO_2, CH_4, or N_2O (Cole et al., 1997; IPCC, 2001a; Paustian et al., 2004; and IPCC, 2007a). The fluxes of these gases can be decreased by more efficient organization of carbon and nitrogen flows in agricultural environments (Bouwman, 2001; Gibbons et al., 2006). The approaches that have the greatest potential to reduce emissions depend on local situations, and consequently, are different from region to region (Cole et al., 1997; McKinsey & Company, 2009).

b. Enhancing sequestration: Agricultural ecosystems hold very large carbon reserves (IPCC, 2001a; IPCC, 2007b) in soil organic material. Previously, these systems have lost more than 50 Gt C (Paustian et al., 1998; Lal, 1999, 2004a; Wize et al., 2009), when compared with natural ecosystems but some of this missing carbon can be recovered during mitigation management, thus returning atmospheric CO_2 to the soil. Considerable quantities of vegetative carbon can also be accumulated in agro-forestry systems or other permanent plantings on agricultural lands (Thanet, 2009). Agricultural lands also remove CH_4 from the atmosphere by oxidation (but less than forests; Schneider et al., 2007), but this consequence is small compared with other GHG exchanges (Smith and Conen, 2004; Smith et al., 2007).

c. Avoiding (or displacing) emissions: Crops and residues from agricultural lands can be used as a basis for fuel, either in their original form or after adaptation to fuels such as ethanol or diesel (Schneider and McCarl, 2003; Cannell, 2003; Janssens et al., 2008). These bio-energy feed stocks still discharge CO_2 on combustion, but the carbon is recycled from the atmosphere rather than from fossil carbon (Mutuo et al., 2005; West et al., 2008; Obersteiner et al., 2010).The impacts of the potential mitigation options are reviewed qualitatively in Table 2.2.

Table 2.2: Proposed measures for mitigating greenhouse gas emissions from agricultural ecosystems, their effects on reducing emissions of individual gases where adopted (mitigative effect), and an approximation of systematic confidence that the recommended practice can decrease net emissions at the location of adoption (IPCC, 2007a).

Mitigation[b] (confidence)	**Mitigation Effects[a]**				**Net**
Measure Evidence	**Examples**	**CO_2**	**CH_4**	**N_2O**	**Agreement**
Cropland **	Agronomy	+		+/-	***
Management **	Nutrient management	+		+	***
**	Tillage/residue management	+		+/-	**
*	Water management (Irrigation, drainage)	+/-		+	*
*	Agro-forestry	+		+/-	***
***	Set-aside, land use change	+	+	+	***
Grazing land *	Grazing intensity	+/-	+/-	+/-	*
Management/ *	Increases productivity (e.g., fertilization)	+		+/-	**
Pasture **	Nutrient management	+		+/-	**
improvement *	Fire management	+	+	+/-	*
*	Species introduction (including legumes)	+		+/-	*
Management of ** Organic soils	Avoided drainage of wetlands	+	-	+/-	**
Restoration of ** degraded lands	Erosion control, organic amendments , Nutrient amendments	+		+/-	***
Livestock ***	Improved feeding practices		+	+	***
Management **	Specific agents and dietary additives		+		**
Manure/biosolid **	Improved storage and handing		+	+/-	***
Management *	Anaerobic digestion		+	+/-	***
Bio-energy **	Energy crops,solids,biogas,residues	+	+/-	+/-	***

Notes for Table 2.2:

a + indicates reduced emissions or improved removal (positive mitigative effect);
- indicates increased emissions or concealed removal (negative mitigative effect);
+/- indicates uncertain or variable response.
b + a qualitative estimate of the confidence in the proposed practice for reducing net emissions of greenhouse gases, expressed as CO_2-eq: Agreement refers to the degree of consensus in the literature (the more asterisks, the higher the agreement). Confirmation refers to the relative quantity of data in support of the proposed effect (adapted from Smith et al., 2007a and Cantarello et al., 2010).

2.3.2.2 Estimates of Potential Mitigation Technologies and practices in Agriculture

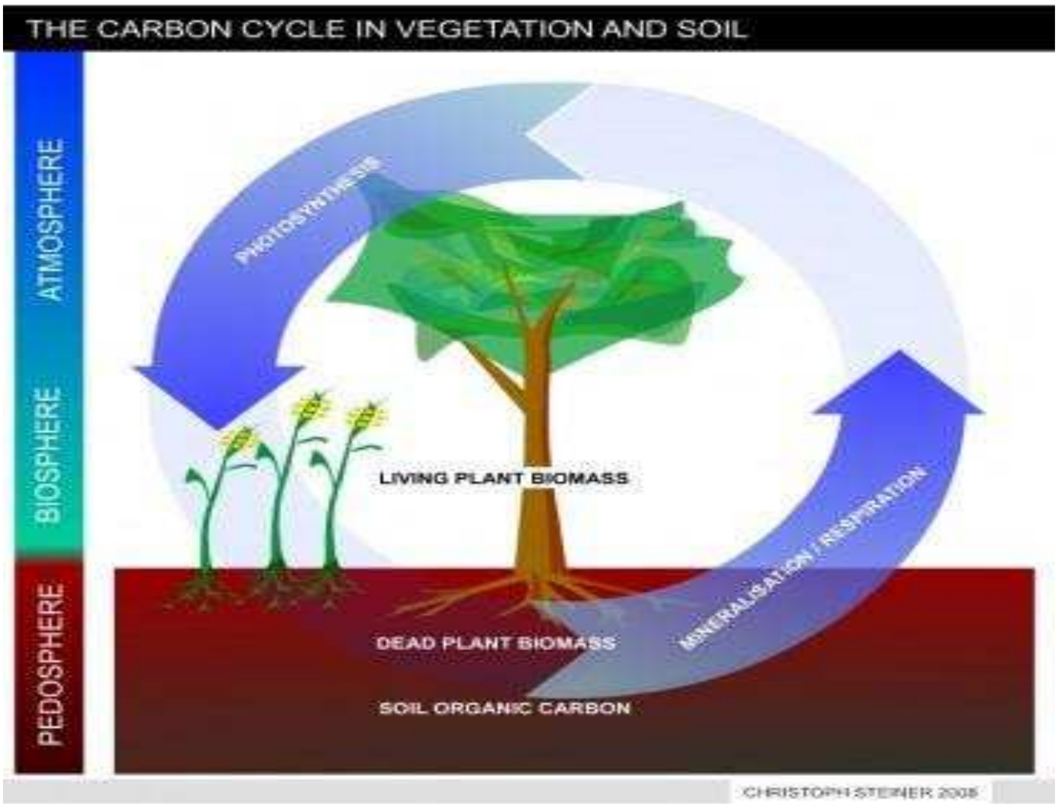
As mitigation practices can cover more than one GHG (Smith et al., 2007a; Smith et al., 2008), it is important to consider the impact of mitigation activities on all GHGs (Robertson et al., 2000; Smith et al., 2001; Gregorich et al., 2005). Mitigation potentials for CO_2 correspond to the net change in soil carbon pools, reflecting the accumulated difference between carbon inputs to the soil after CO_2 uptake by plants and discharge of CO_2 by oxidation in soils. Mitigation potentials for N_2O and CH_4 depend exclusively on emission reductions. Soil carbon changes have been estimated in about 200 studies, and emission ranges for CH_4 and N_2O have been estimated using the DAYCENT and DNDC reproduction models (IPCC, 2006; US-EPA, 2006a; Smith et al., 2007b; Ogle et al., 2004, 2005). In the IPCC third Assessment Report (IPCC, 2001b), estimates of agricultural mitigation potential by 2020 were 350-750 MtC/yr CO_2 (1300-2750 $MtCO_2$/yr).
Smith et al., (2007a) estimated the GHG mitigation potential in agriculture for all GHGs for four IPCC SRES scenarios, at a range of carbon prices, internationally and for all world areas. Using methods similar to McCarl and Scheneider (2001); Smith et al., (2007a), and Smith et al., (2008) used subsidiary abatement cost (SAC) curves specified in US-EPA (2006b) for either area-particular SACs where these were available for a given practice and area, or universal SACs where these were estimated from US-EPA (2006b). Recent bottom-up estimates of agricultural mitigation potential of CH_4 and N_2O from US-EPA (2006b) and DeAngela et al. (2006) have allowed addition of agricultural abatement into top-down global modelling of long-term climate stabilization situation pathways. In the UK, the National Emissions Inventory reported UK agricultural emissions to be 50 $MtCO_2$ in 2005 i.e. 7.6%, of

the 654 MtCO_2 UK total emissions for that year (Committee on Climate Change, 2008, p. 342).

Agriculture contributes almost all of the anthropogenic CH_4 and N_2O emissions (Lovett et al., 2006; Macleod et al., 2010) and rice, nutrient, livestock water and tillage management may facilitate mitigation of these GHGs. For example for mitigation, variables such as increased rates of bio-energy feedbacks, the amount of livestock herds (Finkral et al., 2008), and rates of carbon sequestration in agricultural lands are affected by climate change (Paustian et al., 2004).

2.3.3 Forestry

Figure 2.8 presents a simple version of the carbon cycle in vegetation and soil in a forestry ecosystem (Redrawn from www.ipcc.ch; IPCC, 2007).



Forestry land is an important and main carbon sink, capturing the GHG, especially carbon dioxide, thus reducing emissions. Forest land particularly is important for sequestration and for protection of carbon pools. 'Plants take CO_2 from the atmosphere to manufacture tissue (plant biomass). As long as biomass is growing it accumulates carbon. During decomposition of dead biomass and humus the carbon is released as CO_2. In undisturbed ecosystems the accumulation and release of CO_2 is in equilibrium' (IPCC, 2000a; Cantarello et al., 2011).

The carbon mitigation possible from reducing deforestation, forest management, afforestation, and agro-forestry differs largely by activity, areas, system boundaries and the time over which the options are evaluated. In the short term, the carbon mitigation advantages of reducing deforestation are larger than the advantages of afforestation. That is because deforestation is the single most important source of a net global loss of forest area between 2000 and 2005 of 7.3 million ha/yr (DEFRA, 2008c; Ostle, 2009).

Mitigation options for the forestry sector include expanding carbon preservation in harvested wood products, product substituting, and producing biomass for bio-energy. Biomass from forestry can contribute 12-74 EJ/ yr to energy consumption, with mitigation possible approximately equivalent to 0.4-4.4 $GtCO_2$/yr depending on whether biomass substitutes coal or gas in power plants (IPCC, 2007a). The collective effects of reduced deforestation and degradation, afforestation, forest management, agro-forestry and bio-energy have the potential to increase from the present to 2030 and beyond (IPCC, 2007b; Beach et al., 2008; Ostle, 2009).

Forestry can make a very important contribution to a low-cost global mitigation strategy that supplies synergies with adaptation and sustainable development. However, this opportunity is often lost in the present institutional context and lack of political will to implement and has resulted in only a small portion of this potential being realized at present (IPCC, 2007b; Beach et al., 2008; Macleod et al., 2010).

Forestry mitigation activities can be designed to be compatible with adapting to climate change, maintaining biodiversity, and promoting sustainable development. Comparing environmental and social co-benefits and rates with the carbon advantage will highlight trade-offs and synergies, and help promote sustainable development. However, forestry mitigation activities implemented under the Kyoto Protocol, including Clean Development Mechanism (CDM), have to date been limited. Forestry mitigation options include reducing emissions from deforestation and forest degradation, enhancing the sequestration rate in existing and new forests, providing wood fuels as a replacement for fossil fuels, and substituting wood products for more energy-intensive materials. Forest mitigation strategies should be evaluated inside a framework of sustainable forest management, and with consideration of the climate impacts of changes to other processes such as albedo and the hydrological cycle (Mayers and Bass, 2006; Smith et al., 2008).

The design of the forest sector mitigation portfolio should consider the trade-offs between increasing forest carbon stores and increasing the sustainable rate of produce and transfer of carbon to meet human requirements (Figure 2.9). The selection of forest area mitigation strategies must minimize net GHG emissions all through the forest area and other areas affected by these mitigation activities. For example, preventing all forest harvest would increase forest carbon stocks, but would decrease the quantity of wood and fibre available to meet societal needs. Other energy-concentrated materials, such as concrete, aluminium, steel, and plastics, would be required to replace wood products, resulting in higher GHG emissions (Egan et al., 2007; Bedsworth and Hanak, 2010). Afforestation might affect the net GHG stability in other sectors, if for example, forest expansion reduces agricultural land area and leads to farming practices with higher emissions (e.g., more fertilizer use), adaptation of land for cropland expansion in a different place, or increased imports of agricultural products (McCarl and Schneider, 2001; Cantarello et al., 2011). The choice of system boundaries and time horizons affects the ranking of mitigation activities (Figure 2.10).

The options accessible to reduce emissions at source and/or increase sequestration by sinks in the forest area are grouped into four general categories:

a) Sustaining or increasing the forest area through reduction of deforestation and degradation and through afforestation /reforestation (Asner et al., 2005, US EPA, 2005; Perschel and Evans, 2009).
b) Sustaining or increasing the carbon density in forest areas (tonnes of carbon per ha) by reduction of forestry degradation and during planting, site preparation, tree development, fertilization, uneven-aged site management, or other suitable silviculture methods.
c) Maintaining or increasing the landscape-level carbon mass using forest protection, longer forest rotations, fire management, and protection against insects,
d) Increasing off-site carbon storage in wood products and product and fuel replacement using forest-based biomass to replace products with high fossil fuel consumption, and increasing the use of biomass-obtained energy to replace fossil fuels. So, the main contribution to reducing emissions is to reduce them in other sectors.

Each mitigation activity has a characteristic time sequence of achievements, carbon benefits and costs (Figure 2.10). Relative to a baseline, the main short-term increases are always achieved through mitigation activities aimed at emission avoidance (e.g., decreased deforestation or degradation, fire protection). But once an emission has been avoided, carbon stores on that forest will only be maintained or increased slightly. In contrast, the benefits from afforestation accumulate over years to decades but need up-front action and costs. Most forest management activities aimed at enhancing sinks need up-front investments.

Figure 2.9: Forest mitigation strategies study and their impacts on carbon storage in forest ecosystems and on net GHG productions across all areas (IPCC, 2007a).

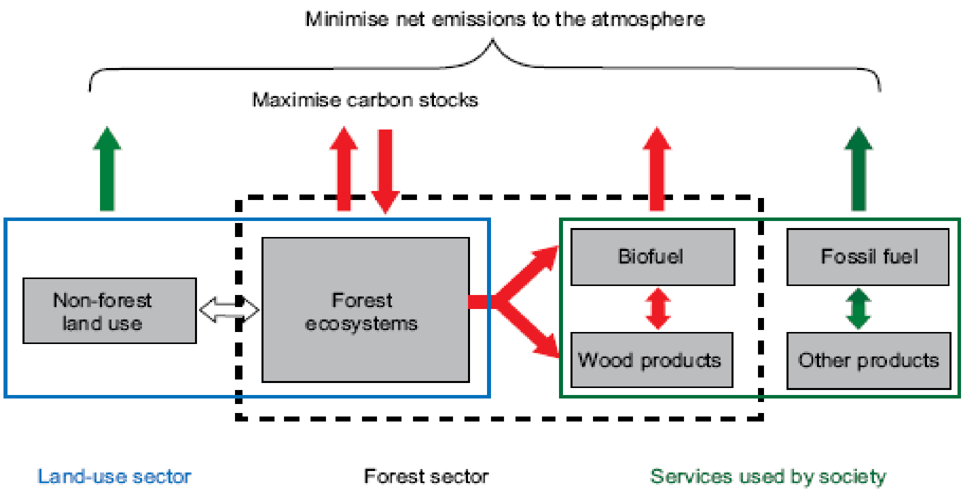
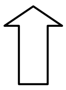
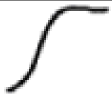
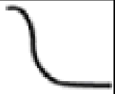
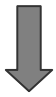
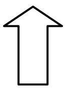
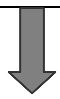


Figure 2.10: Simplified diagram of forest area options type of impact, timing of effects on carbon supplies, and the timing of costs (IPCC, 2007b).

	Mitigation Activities		Type of impact	Timing of carbon change	Timing of Costs
1A	**Increase forest area (e.g. new forests)**				
1B	**Maintain forest area (e.g. prevent deforestation. Land use change)**				
2A	**Increase site-level Carbon density (e.g. intensive management, fertilize)**				
2B	**Maintain site-level Carbon density (e.g. avoid degradation)**				

3A	**Increase landscape-scale carbon stocks (e.g. agriculture, forest)**		⇧		
3B	**Maintain landscape-scale carbon stocks (e.g. suppress disturbances)**		⬇		
4A	**Increase off-site carbon in products (but must also meet 1B, 2B and 3B)**		⇧		
4B	**Increase bio-energy and substitution (but must also meet 1B, 2B and 3B)**		⬇		

Legend

Type of impact	**Timing (change in carbon over time)**	**Timing of cost (dollar over time)**
Enhance sink ⇧	**Delayed**	**Delayed**
Reduce source ⬇	**Immediate**	**Up-front**
	Sustained or Repeatable	**On-going**

Decreased deforestation and degradation is the forest mitigation alternative with the principal and most direct carbon supply impact in the short term per ha and per year globally (Sathaye et al., 2007). Afforestation characteristically leads to an increase in biomass and dead organic material carbon pools, and to a smaller degree, in soil carbon pools (Paul et al., 2003; Smith et al., 2008a). Estimates of future deforestation rates are important inputs in approximations of GHG productions from forest lands and of mitigation advantages. Afforestation and reforestation are the leading mitigation alternatives in specific regions (e.g. Europe). Currently, afforestation and reforestation are included under Article 3.3 and in Articles 6 and 12 (CDM) of the Kyoto Protocol (IPCC, 2002; IPCC, 2007).

Agro-forestry provides an example of a set of innovative practices designed to enhance overall productivity, to increase carbon sequestration, and that can also strengthen the system’s ability to cope with adverse impacts of changing climate conditions (Verchot, et al., 2006). The agro-forestry management systems present important opportunities creating synergies between actions undertaken for mitigation and for adaptation (Albrecht and Kandji, 2003). However, mitigation strategies could also have adverse implications for watersheds in arid and semi-arid regions and biodiversity (Caparros and Jacquemont, 2003; Burgess and Morris, 2009).

Adaptation and mitigation relationships and vulnerability of mitigation choices to climate change are summarized in Table 2.3, which presents four types of mitigation actions.

Table2.3: Adaptation and mitigation implication matrix for forestry (IPCC, 2007a).

Mitigation Option	Vulnerability of mitigation option to climate change	Adaptation options	Implications for GHG emissions due to adaptation
A. Increasing or maintaining the forest area [1A, 1B]			
Reducing deforestation and forest degradation	Vulnerable to changes in rainfall, higher temperatures (native forest dieback, pest attack, fire and, droughts)	Fire and management protected area management	No or marginal implications for GHG emissions, positive if the effect of perturbations induced by climate can be reduced
Afforestation/ Reforestation	Vulnerable to changes in rainfall and higher temperatures (increase of forest fires , pests, dieback due to droughts)	Species mix at different scales fire and pest management increase biodiversity in plantations By multi species plantations, Introduction of irrigation and fertilisation Soil conservation	No or marginal implications for GHG emissions, positive if the effect of perturbations induced by climate can be reduced May lead to increase in emissions from soils or use of machinery and fertilizer
B. Changing forest management increasing carbon density at pilot and landscape level [2A, 2B, 3A, 3B]			
Forest management in plantations	Vulnerable in changes in rainfall, and higher temperatures (i.e. managed forest dieback due to pest or droughts)	Pest and forest fire management Adjust rotation periods Species mix at different scales	Marginal implications on GHGs. May lead to increase in emissions from soils or use of machinery or fertilizer use
Forest management in native forest	Vulnerable in changes in rainfall, and higher temperatures (i.e. managed forest dieback due to pest or droughts)	Pest and fire management Species mix at different scales	No or marginal
C. Substitution of energy intensive materials [4A]			
Increasing substitution of fossil energy intensive products by wood products	Stocks in products not vulnerable to climate change		No implications in GHGs emissions
D. Bio-energy [4B]			
Bio-energy production from forestry	An intensively managed plantation from where biomass feedstock comes is vulnerable to pests, drought and fire occurrence, but the activity of substitution is not	Suitable selection of species to cope with changing climate pest and fire management	No implications for GHG emissions except from fertilizer or machinery use

Table 2.3 shows the relationships between mitigation strategies, which themselves are vulnerable to climate change, the adaptations possible to avoid the worst effects and the total effect of mitigation and adaptation on GHG emissions. The table demonstrates the complex relationship between these variables, showing in particular that mitigation may have unpredictable consequences and that several variables, such as carbon sequestration and GHG emissions, should be viewed together.

2.4 Carbon Storage in UK Soils and Vegetation

Estimates of carbon stored in forests and non- forests in Britain have been made by combined studies of ecological surveys of sample areas, and remote sensing maps of land cover (Table 2.4, Milne and Brown, 1997). Carbon storage in forests and non- forests and soil can be appraised in terms of the long-term stability of storage or the short-term rate of storage (Cannell and Milne, 1997; Olsson et al., 2002; Paul et al., 2003; Ogle et al., 2005).

In Britain the estimated total woodland cover in the 1980 was 9.4 percent, with 8.6 percent managed by the Forestry Commission (Durrant, 2000; Dawscon and Smith, 2007). Agricultural land uses are the biggest type of recent land use in the UK. Roughly, about 77% of the total area of the UK has been used for agricultural reasons (DEFRA, 2008c), therefore, about 66 per cent of this being grassland (Mattison et al., 2007). British vegetation is estimated to contain 113.8 MtC, 80 percent of which is in forests and woodlands (91.9 MtC, Cannell and Milne, 1995; Milne et al., 2005). Broadleaved woodlands in Britain have an average of 61.9 tC ha^{-1} and contain 46.8 percent of the total carbon in all vegetation (Cannell and Milne, 1997; Milne et al., 2001, 2005). Carbon stored in plantation forests was approximately 60 Mt C in 1990, about 40 Mt C in the trees and 20 Mt C in litter (Cannell and Thornley, 1998; Milne et al., 2005; Smith et al., 2007a; Smith et al., 2008). The entire carbon pool in plantation forests is estimated to peak at 100 Mt C at around 2020 (Cannell and Thornley, 1998; Anderson et al. 2003; Ball et al. 2008). Moreover, it has been estimated the total carbon in Great Britain is roughly about 113.8 ± 25.6 Tg, or millions of tonnes (Milne et al., 2001, 2005).

In addition, the vegetation in Northern Ireland contains an additional 3.8 – 4.4 Tg (Cruickshank et al., 1998, 2000). Non-forested vegetation such as horticulture and arable crops and grasslands cover contain about a tonne of carbon per hectare (6 percent of the total UK vegetation carbon stock), while heath and bog vegetation contain around 2 tonnes per hectare (14 percent of the UK vegetation carbon stock). Forests and woodland (natural and plantation) account for most UK vegetation carbon stocks, i.e. 80 percent of the vegetation carbon stock in Great Britain and 55 percent in Northern Ireland. Conifer (softwood) species have a lower net carbon density than equivalent-aged broadleaved deciduous (Cannell, 1999; Ostle et al., 2009). Also, according to Dawson and Smith (2007) and Smith et al., (2007a, b) UK forestry and grasslands sequester about 110 ± 4 kg and 240 ± 200 kg of carbon per hectare per year respectively, while croplands lose on average 140 ± 100 kg of carbon per hectare per year.

Soils hold much more carbon than vegetation. In the UK, as in most places in the world, soils contain the largest amount of carbon (Cerri et al., 2004; DEFRA, 2007). This carbon pool can change quickly and changing land use is the main long-term effect on the carbon stored in soils. Soil carbon stored in England is in peats and stagnogley soils and most soil carbon in Scotland is in blanket peats (Milne and Brown, 1997, 2001; Jones et al., 2004, 2005). A major natural carbon pool in the UK is the organic material in peat, totalling about 3000 Mt C for Britain according to Cannell et al., (1995, 1999) or even higher according to Milne and Brown 1997; Milne et al., 2005, (see Table 2.4). Of the 9838 Mt C in UK soils, around 2890 Mt C is in England and Wales and 6948 Mt C is in Scotland, (Table 2.5 and Figure 2.12, Milne and Brown, 1997, 2001; Milne et al., 2005; Dawson and Smith 2007). There have been several studies that estimate the carbon pool in the UK's soils (as cited above). Soil carbon material and allocation across Great Britain has also been explained in aspect by Milne et al., (2005). In another study, the soil carbon stock of Northern Ireland was estimated at 0.4 billion tonnes (Cruickshank et al., 1998; Milne et al., 2005), with 42 percent of this found in peat soils. Bradley et al., (2005) accumulated a carbon and land-use database for the entire UK with soil restrictions and factors (i.e. bulk density, organic carbon and texture) at depths of 0–30cm and 30–100cm which was used to produce a detailed map of estimated UK soil carbon stocks (see Figures 2.11 and 2.12).

Recent research has been done in Southwest England in 2000 which overall estimates the amount of 263 Tg (10^{12}) equivalent of 263 Mt C (Cantarello et al., 2011). This is within range of total carbon amount from 137 to 442 Tg when the minimum and maximum values have been considered, respectively (Cantarello et al., 2011). Carbon density values in vegetation are normally the highest for broadleaved forest, and the least for non-irrigated arable land, while soil carbon (SOC) densities are usually highest for peat bogs and the smallest for non-irrigated arable land (Cantarello et al., 2011).

Table 2.4: Area of vegetation covers groups in Great Britain and linked carbon in vegetation, in 1990 (Milne and Brown, 2001; Milne et al., 2005).

Cover Group	Area (km^2)	Area (% of G.B)	Carbon (Mt) pool	Carbon (% of G.B)
Agricultural	**110,547**	**49.3**	**10.77**	**9.6**
Semi -natural	**66,912**	**29.9**	**11.08**	**9.8**
woodland	**24,965**	**11.1**	**91.97**	**80.1**
Non –vegetated	**21,586**	**9.6**	**0.00**	**0.0**
Total	**224,010**		**113.82**	
Woodland type				
Broadleaf	**9,100**	**4.1**	**53.32**	**47.3**
Conifer	**13,646**	**6.1**	**29.02**	**24.8**
Mixed	**2,220**	**1.0**	**9.62**	**8.5**

Table 2. 5: Total soil carbon in Great Britain (Milne and Brown, 2001; Milne et al., 2005).

	Soil Carbon (Mt)	Soil Carbon (% of G.B. total)
Scotland (peat)	**4523**	**46**
Scotland (non-peat)	**2425**	**25**
Scotland (total)	**6948**	**71**
England and Wales	**2890**	**29**
Great Britain	**9838**	

With references to the data in Tables 2.4 and 2.5; it is important to note that soils are less disturbed than vegetation, so carbon can accumulate in soil more easily than vegetation. So, managing carbon in soils is an integral part of the role of LULUCF in climate change mitigation, especially increasing sequestration, protecting existing carbon pools and eventually developing and increasing the carbon pools.

Figure 2.11: Distribution of soil carbon in Britain based on soil data for Scotland and for England and Wales (Milne and Brown, 1997, 2001).

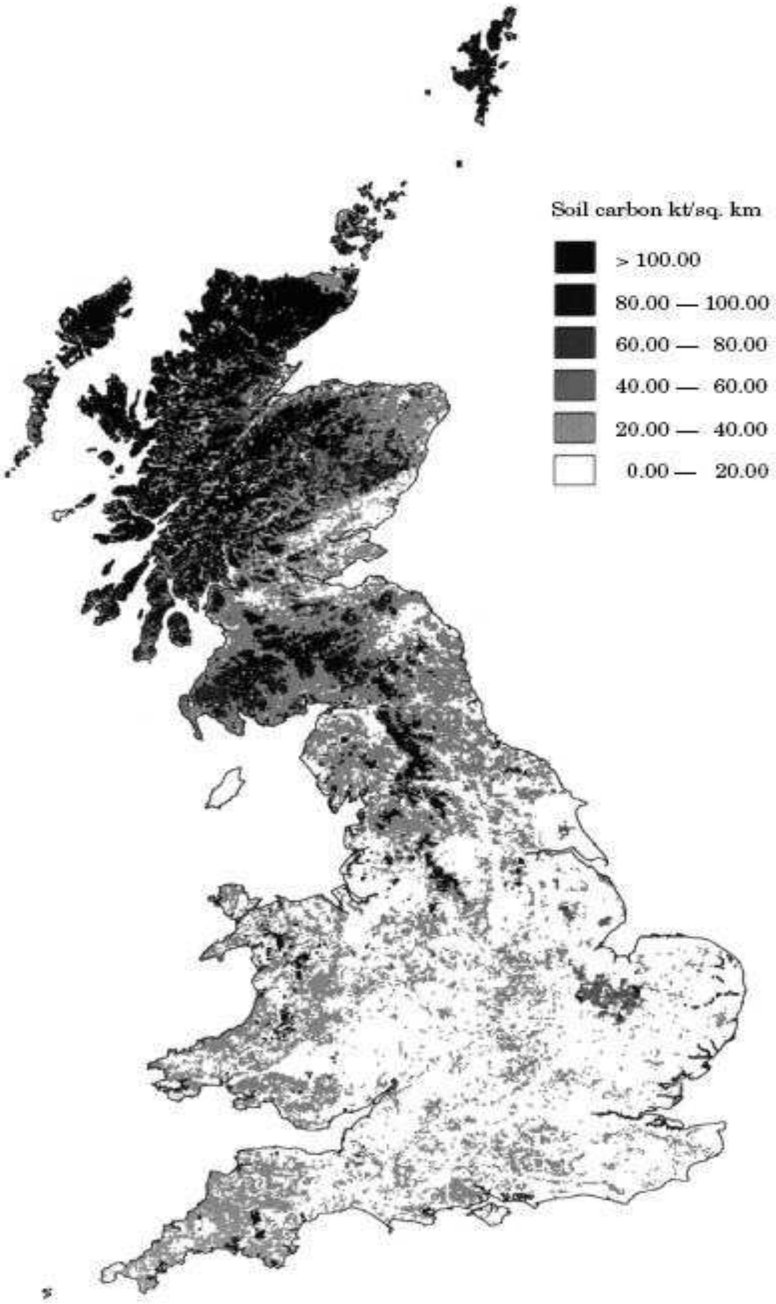
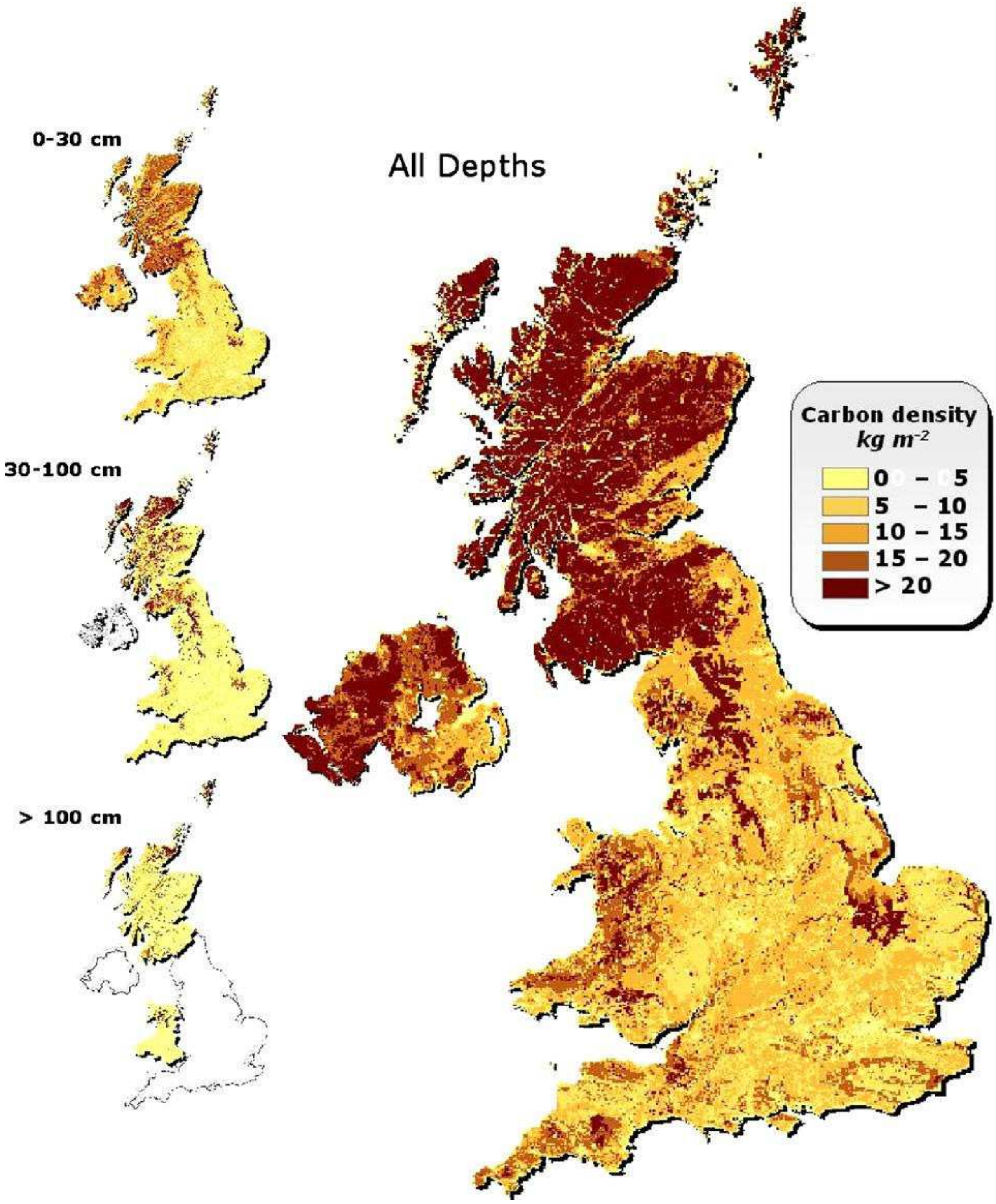


Figure 2.12: Soil carbon map in the UK with carbon density in kg m^{-2} (Cerri et al., 2004; Ostle et al., 2009).



2.4.1 Quantifying Carbon in land use change and carbon storage

A variety of approaches have been taken to estimate the effects of land use change on future carbon storage in soils. This section reviews a series of these approaches taken in different case studies from the literature review.

I) A simulation/modelling-based approach

a) Estimates of soil organic carbon (SOC) stocks and changes in different land uses can help determine susceptibility to land degradation. SOC stocks, and predicted changes by 2040 and beyond, were determined at the national scale using the Global Environment Facility Soil Organic Carbon (GEFSOC) modelling system (Paustian et al., 1997; Pollok, 2008). Local and global C financial plan quantifications require an understanding of SOC dynamics and SOC distribution at a regional level (Paustian et al., 1997; Pike, 2008). Carbon sequestration can be indirectly measured during the modelling of SOC content, which might complement direct measurements (Ardo and Olsson, 2003; Ostle et al., 2009). Modelling helps in identifying regions with a large potential for C sequestration. It also helps in predicting and understanding future changes due to climate change, land use change and different land policy scenarios (Ardo and Olsson, 2003; Ostle et al., 2009; Macleod et al., 2010).

Roth-C (Jenkinson and Rayner, 1977; Lal, 2003, 2004a, and 2009) and Century (Parton et al., 1988; Lal, 2004b) are the most generally used SOC simulation models. They have been validated against a variety of long-term agricultural field trials in a variety of climate zones, including all kinds of regions. Roth-C requires less data input than Century and is, therefore, easier to parameterize. However, Roth-C only models soil processes and, consequently, plant residue C is a required input. Century is an ecosystem model that reproduces biogeochemical changes of C, N, P and S, primary production and water stability on monthly time steps (Parton et al., 1988; Thomson and Oijen, 2007).

Both models have been used in many parts of the world as instruments to predict C stocks and changes (Jenkinson et al., 1999; Hill, 2003; Fallon and Smith, 2002; Ardo and Olsson, 2003; Smart, 2005). Past studies have used different approaches to integrate Century and Roth-C with spatially explicit databases via geographical information systems (GIS). Fallon et al., (1998) and Clair et al., (2008) integrated the Roth-C model with GIS to illustrate the effect on SOM during an afforestation scenario in Hungary. Ardo and Olsson (2003) integrated GIS with the Century model to measure SOC in semi-arid Sudan. Refined estimates of potential SOC sources and sinks, including their difference in space and time, are possible through the connection of dynamic simulation models and spatially explicit data (Ardo and Olsson, 2003). Lal (2002) emphasized that any evaluation of soil C at different scales requires GIS and modelling. Finally, Easter et al., (2007) used the GEFSOC modelling System to make spatially explicit estimates of SOC stocks and changes based on three different methods and two modelling approaches (Century and Roth-C) and the experiential IPCC method (Obersteiner et al., 2010).

b) Participation in carbon (C) markets could provide farmers incentives for improving soil fertility and carbon storage in soil. However carbon traders need assurances that contract levels of C are being achieved. Thus, methods are needed to observe and confirm soil C changes over time and space to determine whether goal levels of C storage are being met. An integrated approach is described in which an Ensemble Kalman Filter (EnKF) is used to assimilate soil carbon measurements into a stochastic soil C model to estimate soil C changes over time and space. The model predictions estimate soil C and changes over time using first decomposition of existing soil C and addition of C from plant residues (Jones et al., 2004). There are three major components in the EnKF: data, models and assimilation / estimation. Data include field measurements of soil C, but it should also include measurement of other variables using field sampling or remote sensing. The model in the EnKF predicts the state of the system, the mass of soil C in each field to a specified depth of soil (kg [C] ha^{-1}), as it changes with time (over year, or years, depending on the case) (Jones et al., 2005).

c) Simulating effects of logging on carbon storage in forest is another method. To investigate the consequences of reductions in logging damage for ecosystem carbon storage, (Tate et al., 1997; Schlamadinger et al., 2007; Thomson and Kolka, 2005) constructed a model to simulate changes in biomass and carbon pools following logging of forests. The relationship between fatal stand damage and ecosystem carbon storage was not linear; biomass recovery following logging was severely limited by 50-60% stand damage. Reduction in fatal damage from 40% to 20% of the residual stand, as was the case with a pilot project in Malaysia, was connected with an increase of 36 Mg C ha^{-1} in mean carbon storage over 60 years. Reduction in damage classification can result in increased carbon preservation in forest biomass (Putz & Pinard, 1993; Woodward et al., 2009).

II) An empirical approach

Alternative methods used in eastern Australia to estimate change in organic carbon in forest plantation soils including soil carbon are:

a) Paired sites: use of paired sites allowing comparisons of soils in plantations with either a previous land use (local vegetation or grazing land), or with successive rotations, or with different species (Ovington, 1953; Hamilton, 1965; Challinor, 1968; Hopmans et al., 1979; Turner and Kelly, 1977, 1985; McIntosh, 1980; Goh and Heng, 1987; Turner and Lambert, 1988; Wardle, 2003; Fargione et al., 2008). Such an approach has been used to successfully measure the consequences of land uses other than forestry (Moody, 1994; DEFRA, 2000).

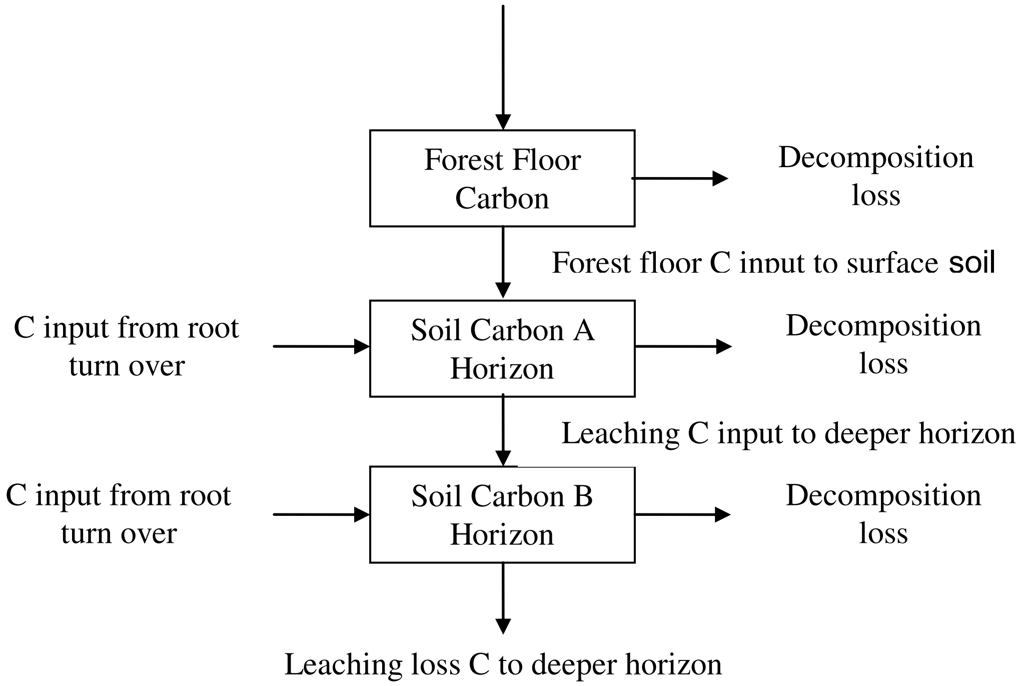
b) Chronosequence studies: such studies use a series of schemes in different aged plantations with presumed similar management regimes and environmental conditions. Where sites from previous land uses are also included, this becomes an extension of the paired plot technique (Hamilton, 1965; P: 1968; Ryan et al., 1981; Gholz et al., 1985; Evans et al., 2006; FAO, 2009).

c) Multiple re-sampling: Re-sampling of the similar soils above an expanded period of time (Gilmore and Boggess, 1976; Smith et al., 2007a).

d) Process and Modelling studies: These studies are related to soil carbon changes, including direct studies on carbon pools or procedures associated with inputs and losses (Ruark and Blake, 1991; Caryle, 1993; Scott et al., 1998; Smith et al., 2007a; Janssen et al., 2008).

The processes of inputs and losses of organic carbon in plantation soil systems have been presented in the form of a simple schematic model (Figure 2.13). This schematic model considers three carbon pools, specifically the forest floor, a surface (A) soil horizon and a deeper (B) soil horizon. The forest floor is often considered to be a main source of carbon to the mineral soil and the main carbon input to the forest floor is from litter-fall. Inputs to the surface horizon are due to association of carbon from the forest floor and from roots as soluble carbon and similarly, inputs to the deeper horizon are from biological transfers and leaching of soluble carbon from soil and root income (Turner and Lambert, 1988; Bouwman, 2001; Craine et al., 2007; FAO, 2009). Modelling and empirical approaches offer alternative, but complementary methodologies. In this study a modelling approach will be adopted (but using secondary empirical data) in order to create projected future scenarios for land use and land cover changes.

Figure 2.13: Schematic model of processes of inputs and losses of carbon in plantation soil systems (Turner and Lambert, 1988; Bouwman, 2001; Craine et al., 2007; FAO, 2009).



Another approach with carbon saving potential associated is changes to the management of agricultural soils (King et al., 2004). Whatever scale of changes in farming systems are considered such as total system changes (e.g. conversion to organic farming), rotational changes (e.g. including energy crops or increased proportion of grassland), fertilizer changes (e.g. substituting more inorganic with organic nitrogen) or tillage changes (e.g. zero-cultivation) an alteration in energy use will also happen (Leake, 2000; Bullard & Metcalfe, 2001; Woodward et al., 2009).

2.4.2 Quantifying Carbon Storage and Loss from UK soils

There has been a limited amount of work to assess changes in carbon storage and changes in GHG emissions from land use change in the UK. King et al., (2004) suggested a simple additive model of the total net amount of carbon sequestered or saved (TSC) in response to a management change, based upon the changes in four components: (a) soil organic carbon (SOC) changes; (b) the direct energy (DE) changes used on site (energy used to power machinery and operations); (c) indirect energy (IE) change used on site (energy used in the manufacture and supply of fertilizers, agrochemicals, etc., and (d) the emission changes from soils of other greenhouse gases (GG_s) such as N_2O (Bullard & Metcalfe 2001; Mortimer et al., 2002; Dawson and Smith, 2007).

A value for TSC of each hectare of land to which the changes apply is (TSC= SOC + DE + IE+ GG_s). The summation of the components was carried out as part of a geographical information system (GIS) mapping process. The spreadsheets were designed to detail how this value would be applied across each rotation on the seven soil types within each region, such that an annual equivalent value was obtained for each. Saving rates (and ranges) per unit area of land to which the management changes were applied are given in Table 2.6, expressed as the equivalent amount of carbon release for each mole of CO_2 (Dawson and Smith, 2007).

In King's study, changes from arable management and managed grassland to woodland were applied to 11% of the agricultural area, the difference being between current woodland cover (9% of total land area) and the average for the rest of Europe (15% of total land area). Arable changes and grassland management to willow (for example: Miscanthus spp.- mainly hybrids of viminalis, cinerea, caprea, aurita) and Miscanthus (Miscanthus spp.- mainly giganteus) energy crops were also applied to 11% of agricultural land, as a hypothetical 'maximum' uptake scenario (Bullard & Metcalfe, 2001; Cormack, 2000; King et al., 2004). They were also applied to 125000 ha of arable land to model the current target for energy crop coverage by 2010 (King et al., 2004; Ostle et al., 2009).

Table 2.6: Final carbon sequestration and saving rates (kg ha^{-1} yr^{-1} CO_2-C) applied to each unit of land undergoing change according to the scenarios shown (King et al., 2004; Dawson and Smith, 2007; Ostle et al., 2009).

Change in land use or management	SOC	DE+IE	GG_s	TSC
Arable to permanent woodland	552-828	425	327-609	1304-1862
Arable to willow energy crop	552-828	304	327-609	1183-1741
Arable to Miscanthus energy crop	490-734	275	327-609	1092-1618
Conventional to zero tillage	145-235	22	-181 to -84	-14-173
Conventional to reduced tillage	40	16	0	56
Addition of straw residues	532-717	0	-61 to -17	471-700
Application of additional sewage sludge	610	44	-3	651
Addition of livestock manure to arable land rather than grassland	50-208	13-25	8-25	71-258
Set-aside field margins on arable land	490-734	440	25-46	955-1220
Extensification of converting break crops to grass in rotation	479	136	0-172	615-787
Extensification with outdoor pig breeding on grass in rotation	479	136	0-2	615-617
Conversion to stockless organic management	479	238	7-13	724-730
Conversion to organic management with livestock	479	296	7-10	782-785
Grassland to permanent woodland	0	1963	2354	4317
Grassland to willow energy crop	0	1842	2354	4196
Grassland to Miscanthus energy crop	0	1813	2354	4167
Change to clover based pastures	0	196	-33	163
Conversion of conventional to organic dairy management system	0	1749	533	2282

The anticipated net annual additional carbon change in each of the eight Government Office Regions for the carbon sequestration and CO_2 emission saving in England as calculated by King et al. (2004), Dawson and Smith, (2007) and Ostle et al. (2009) is given in Table 2.6 and see Table 2.8 and 2.9. The main contribution to carbon sequestration / saving would come from turning over a larger proportion of land to set-aside as permanent conservation orientated margins around fields (about 0.8 Mt C yr^{-1} for England).

In addition, ensuring that a quantity of cereal straw equivalent to current production was returned to the land would sequester about 0.3 Mt C yr^{-1}, as would a return to grass leys in rotations. By applying livestock manure to arable land rather than grassland other useful contributions to carbon sequestration could be made / saving (0.2 Mt C) and changing tillage practice away from plough based systems to shallow tine systems (0.2 Mt C) (Table 2.7).

Table 2.7: Anticipated total net annual carbon equivalent sequestration and saving (kt C yr^{-1}) for land use and management changes to arable land and managed grassland in England (King et al., 2004).

Change in land use or management	Government Office Region								
	North East	North West	York& Humber	Eastern	South East	West Midland	East Midland	South West	Total
Arable to permanent woodland	190	277	361	578	553	463	515	705	3644
Arable to willow energy crop	16	17	36	69	60	42	55	54	349
Arable to Miscanthus energy crop	15	16	34	66	56	40	52	50	329
Grassland to permanent woodland	284	405	553	791	680	552	671	843	4780
Grassland to willow energy crop	52	39	141	277	186	128	211	147	1181
Grassland to Miscanthus energy crop	50	37	138	275	182	126	208	143	1158
Conventional to zero tillage	8	2	-0.85	17	13	5	7	12	63
Conventional to reduced tillage	7	2	21	51	28	20	38	15	182
Additional of straw residues	12	4	34	83	50	33	61	28	306
Extensification of converting break crops to grass in rotation	0	0	18	40	177	10	46	0	292
Change to clover based pastures	24	13	75	158	98	67	118	72	626
Conversion of conventional to organic dairy management system	12	13	32	59	42	32	47	41	279
Conversion to stockless organic management	1	0.5	3	7	4	3	5	3	28

The conclusion from Table 2.7 is that the potential for real carbon sequestration to soil by agricultural management changes is very limited under English conditions (King et al., 2004). In some cases sequestration and saving can be negated over time by changes in the emission of other greenhouse gases and energy use (exchange to organic systems in arable and the extensification of pigs after 25 years in Table 2.8 and 2.9).

It is also clear that large saving in the national inventory of greenhouse gas emissions will only come from wholesale land use change as single measures (e.g. to woodland, energy crops and a return to temporary grass leys in arable rotations). However, some of the arable management changes are not mutually exclusive and can be run together. Two points are worth noting considering these mechanisms in the context of meeting Britain's commitments under the Kyoto Protocol. The first is that the initial commitment period is only for five years (2008-2012) for which emissions are compared to 1999 levels (Sleutel et al., 2003; Thomson and Oijen, 2007). This means that the five-year values from Table 2.6 can be used, which include a higher SOC component than the long term 25-years scenario-128 Kt SOC-C yr^{-1} compared with 51 Kt SOC-C yr^{-1} for the above arable scenario. The second point is that changes in the SOC component after a land management change are actually a minor contribution to almost all changes- for example 21.27 Mt C within a total of 31.44 Mt C over 25 years for the arable scenario above (Sleutel et al., 2003; Thomson and Oijen, 2007).

Table 2.8: Final carbon sequestration (Mt CO_2-C) possible for England according to the scenarios in land management change over the timescale. Sequestration to SOC is given by the values in parentheses (Sleutel et al., 2003, King et al., 2004; Dawson and Smith, 2007).

Change in management	After 1 year	After 5 years	After 25 years
Arable to woodland	3.65(0.07)	18.24(0.34)	90.16(0.69)
Arable to willow energy crop	0.36(0.07)	1.75(0.35)	7.71(0.69)
Arable to Miscanthus energy crop	0.33(0.06)	1.64(0.31)	7.30(0.61)
Conventional to zero tillage	0.06(0.02)	0.31(0.09)	1.29(0.19)
Conventional to reduced tillage	0.18(<0.01)	0.91(0.02)	4.49(0.04)
Additional of straw residues	0.31(0.06)	1.53(0.31)	6.71(0.62)
Additional of livestock manure to arable	0.18(0.01)	0.90(0.06)	4.33(0.13)
Extensification scenario of break crops to grass	3.22(0.05)	16.12(0.24)	79.91(0.48)
Conversion to stockless organic management	0.03(0.05)	0.14(0.24)	-0.03(0.48)
Conversion to organic management with livestock	<0.01(0.05)	-0.02(0.24)	-0.83(0.48)
Grassland to woodland	4.78(0)	23.88(0)	119.42(0)
Grassland to willow energy crop	1.18(0)	5.91(0)	29.53(0)
Grassland to Miscanthus energy crop	1.16(0)	1.64(0.31)	7.30(0.61)
Change to clover based pastures	0.63(0)	3.13(0)	15.64(0)
Conversion to organic dairy management	0.28(0)	1.40(0)	6.97(0)
Total	17.3	81.95	400.59

Table 2.9: Possible changes in soil carbon storage consequent from land use management change. Positive amount specifies soil carbon increases; negative amount specifies soil carbon losses (Ostle et al., 2009).

Land Use Change	Net Carbon rate and Uncertainty (t C $ha^{-1}yr^{-1}$)
Arable to ley: arable rotation	1.6
Arable to grassland (50 years)	0.3-0.8
Arable to grassland (30 years)	0.6
Arable to grassland (15-25 years)	0.3-1.9±0.6
Arable to grassland short leys (20 years)	0.4
Arable to permanent pasture	0.3
Arable to forestry	0.6+2.8 (C in veg.)
Arable to forestry (115 years)	0.5+1.5 (C in veg.)
Arable to forestry (25 years)	0.3-0.6
Arable to forestry	0.5-1.4
Permanent crops to arable	-0.6 and 1.0-1.7
Grassland-arable (20 years)	-0.9 ± 0.3
Grassland-arable	-1.0 to -1.7
Grassland-afforestation (general-90 years)	1.0 ± 0.02
Moorland- grassland	-0.9 to -1.1
Forst to arable	-0.6
Forest to grassland	-0.1 ± 0.1
Native vegetation-grassland	0.4
Peatland-cultivation	-2.2 to -5.4
Revegetation on abandoned arable	0.3- 0.6
Revegetation on wetlands from arable	2.2- 4.6
Revegetation on wetlands from grassland	0.8-3.9
conservation	>2.2

So, carbon storage in soil management practices presents a significant opportunity to increase and save (protect) the existing carbon pools and sequestration amount. However, although with change in land uses practice the amount of carbon storage and sequestration can be increased, the budget (cost) and preparation of drivers (farmers, policy-maker) for land change management is important (Alo et al., 2008).

There are several recommendations which can be applied as:

In cropland: soil carbon stores can be increased by agronomic practices that enlarge the return of plant biomass carbon to the soil, including, developed produce/ crop selections, expanding crop rotations, in addition of permanent crops (Follett, 2001; Freund, 2002; Lal, 2003; Soussana et al., 2004; Ostle et al., 2009), remains and tillage management to increase soil carbon maintenance and sequestration (Cerri et al., 2004), having a land use change to grassland or forest to increase soil C sequestration (Falloon et al., 2002; Ogle et al., 2004; Ostle et al., 2009).

In grassland: soil carbon stores can be increased by decreased grazing amount (McLauchlan et al., 2006; Craine et al., 2007), increased grassland efficiency (McLauchlan et al., 2006; Ridgwell et al., 2004; Ostle et al., 2009), vegetation species management for improved carbon storage (Fisher et al., 1994), decreased 'lime and N' fertilizer accumulations (Rangel-Holmes et al., 2002), 'managed return of farm waste' to the soil (i.e. farm slurries and waste).

In forest lands: soil carbon storages are optimistically controlled and influenced by 'planting' of inhabitant hardwood species, carbon intendeds place 'preparation' and cropping (Johnson, 1992; Holmes et al., 2002), extensive and greater rotation ages (Schulze et al., 1999; Smith et al., 2007), decreased nitrogen fertiliser application (Harding and Jokela, 2003), decreased liming (Brumme and Beese, 1992; Ridgwell et al., 2004), protection alongside trouble (Magill et al., 2004; Smith et al., 2007), decreased harvest remains exclusion (Reay et al., 2008; Ostle et al., 2009).

The key issue here is changing the land use management to any forestry and permanent grassland over time can significantly save and increase the net carbon value.

The suggested implications for other research could make the following points:

a) King et al. (2004) and Dawson and Smith (2008) provide estimates for the whole country and individual regions based on a set of assumptions that may not apply at the regional/local level.

b) The estimates of change are for one single set of changes – they do not explore a range of scenarios with different assumptions, objectives and motivations (Tilman et al., 2006).

c) The estimates of change are not spatially explicit – there is no consideration of how changes could occur at the local/regional landscape scale. i.e. which specific areas of the landscape would be suitable for change and which would be affected by any particular scenario. There is thus no way to predict what the future landscape might look like, and function under these changes (Soussana et al., 2007).

The main point to note here is that although others have made estimates of Carbon storage and change in Carbon and GHGs in the future; this project makes these unique contributions. Also, this project investigates these particular aspects of carbon sequestration further, thus making an original contribution to knowledge in this field.

2.5 Policy review for Agriculture and Forestry in the UK

2.5.1 Approaches to policy

The most important characteristic of climate change as a policy problem is uncertainty. Agriculture has always been beset by uncertainty. Violent variations in the weather, unpredictable behaviour of market prices, new forms of government interfering, the outbreak of crippling diseases and pests-all these have been familiar but unwelcome complements to the steady regularity of the changing seasons. Few would deny that government action has had important effects for all aspects of agricultural and forestry prospects in recent decades.

What is policy?

Defining policy is not easy. In a memorable phase, a former civil servant once commented that ‘policy is rather like the elephant-you recognise it when you see it but cannot easily define it’ (Cunningham, 1963; Body, 1998; Schneider et al., 2007). The critical point is that policy analysis requires something more than only attending to the detailed content of legislation: ‘Sometimes policy gets written down in an Act of Parliament, or in legislative implements made under an Act. Sometimes it gets itself recorded in a communication or circular. But quite often it emerges from departmental practice in dealing with some particular type of business, or is decided by the way in which Minister or a public authority settles an individual case’ (Schneider et al., 2007). From this emphasis upon the range of means by which policy can be circulated it is a moderately small step to the view that policy is a process. Something that is dynamic and changing rather than a single action, decision or part of legislation. It is this logic of process which characterises the following key definitions:

‘A policy consists of conclusions, decisions and achievements that assign values’ (Smart et al., 2005).

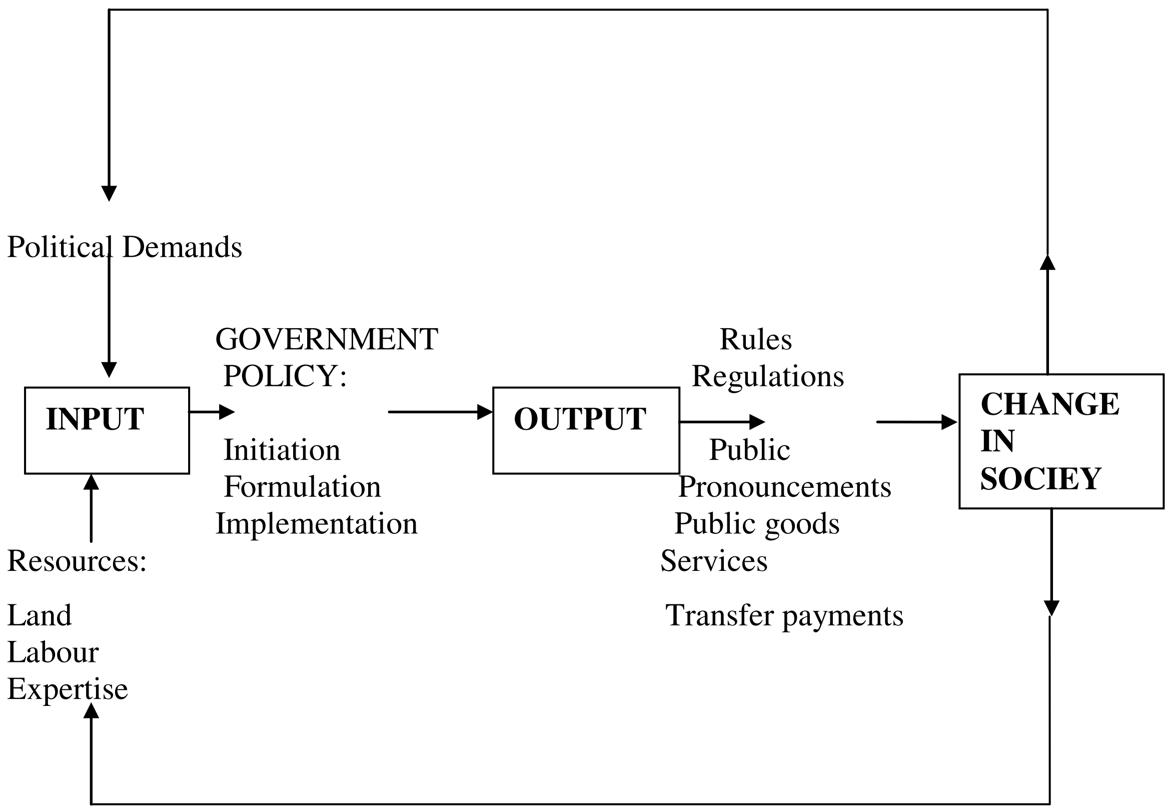
'Policy is a set of interconnected decisions concerning the selection of goals and indicates of achieving them within a specified situation' (Ham and Hill 1993; Lindsay and Bragg, 2004). Thus policy is best seen as a web or network of decisions and actions that take place over a period of time. Ham and Hill (1993); FAO, 2009) suggest that an active understanding of policy leads to five key implications and suggestions about the character of policy, all of which highlight and emphasise the case that to study policy is to study something fairly different to either rule or management. These five points can be summarised as follows:

a) 'A web of decisions may take place over a long period of time, thus expanding far further than any formal original policy-making process (Ham and Hill, 1993).
b) A policy usually involves a series of decisions rather than a single decision (FAO, 2009).
c) A policy might change over time (King et al., 2004).
d) Policy may involve non-decisions as well as decisions, especially if the circumstance for policy changes over time with no consequent fresh decision taking (Smith et al., 2004b).
e) Presentations and performances rather than, or in addition to, official conclusions (decisions) are significant in crucial policy. This may be particularly accurate for recognising the content of policy in the circumstance of acts taken by those responsible for implementing policies rather than formulating them' (Smith et al., 2004a; FAO, 2009).

Model of the policy process:

Figure 2.14 portrays the policy process as a system which has as its input both political demands and resources (Burch, 1979; Jones, 1991; Borjeson, 2006) and as its output different kinds of policy decisions and consequences; the decisions in turn have an impact upon society and consequently influence future inputs (Burgess and Morries, 2009). Thus the process is both continuous and circular. In between the input and output, and within what can loosely be defined as 'government', are three main stages. These are policy initiation, policy formulation and policy implementation (Jones, 1991; Berhout et al., 1998; Stoate et al., 2001). How policy makers within government actually operate these stages of the policy process is itself a complex question. Figure 2.14 illustrates the cyclical and dynamic nature of the policy process (Borjeson, 2006). On the input side are the political demands of society expressed through parties, pressure groups, election results and so forth. These political demands, together with the resources available to government, combine to conclude policy programmes and output. These influence society thus affecting future political demands and, through the economy, the resources available to future governments (Burgess and Morries, 2009).

Figure 2.14: The complexities of this process (policy) in many areas such as land use policy (Burch 1979; Jones, 1991; Borjeson, 2006).



2.5.1.1 The Common Agricultural Policy (CAP)

The principles and instruments of the Common Agricultural Policy were laid down in the Treaty of Rome in 1957 and subsequently at the Stresa conference in July 1958, coming into force from 1962 (Conant et al., 2001; FAO, 2008, 2009 and DEFRA, 2010). Article 39 of the Treaty set out the objectives of the CAP as follows:

1. To increase agricultural productivity by promoting technical progress and by ensuring the rational development of agricultural production and the optimum utilization of the factors of production, in particular labour (Conant et al., 2001).
2. To ensure a fair standard of living for the agricultural community, in particular by increasing the individual earnings of persons engaged in agriculture (DEFRA, 2010).
3. To stabilize markets (FAO, 2008).
4. To assure the availability of supplies.
5. To ensure that supplies reach consumers at reasonable prices (FAO 2009).

Three main principles were to shape the future of the Common Agricultural Policy (FAO, 2008; DEFRA, 2010):

- Market Unity (a single market): in other words, there should be common prices across the Community and free trade in agricultural produce amongst the EC member states;
- Community preference: that a system of tariff barriers should be put in place to protect the internal market from the instability in world markets; the policy, and the introduction of the concept of **multi-functionality**.
- Financial solidarity: that three should be a fund set up; this would finance common expenditures in the agricultural domain.

2.5.2 Future Land Use Policy and Trends in the UK

Land-use, land-use change and forestry (LULUCF) contribute to uncompleted anthropogenic climate change (Meyer and Turner, 1992; Dale, 1997; Watson et al., 2000; Holmes and Keiller, 2002), and have accordingly received increasing research concentration over the last decade (White et al., 2000; Magill et al., 2004; Soussana et al., 2007; Smith, 2008; Ridgwell et al., 2009).

From the 1930s until the mid-1980s, UK policy encouraged increases in agricultural land use. Since the early 1990s policies have required at the same time to make UK internationally competitive and make progress towards ecological sustainability. These policies, apparent in the Common Agricultural Policy (CAP) (DEFRA, 2007) described earlier, direct the way forward for the future (Soussana et al., 2007).

The UK has been planning in a different way in land use policy compared to other regions and especially Europe. This is the subject of discussion in the UK as Smart et al. (2005) note:

a) 'Land use decisions are plan-led rather than plan-based' (FAO, 2007a);
b) Central government has a main role in decisions originally taken by local government (DEFRA, 2008);
c) Regional plans are organised by an elected level of government only in Scotland, Wales and Northern Ireland, but not in England (DEFRA, 2010).

The roles of government and local government have been identified before (see section 2.5.2). So, the key question can be how the approach of forecasting the policy for the next 50 years should be determined.

Policy and legislation are hardly ever believed as subjects that can be forecasted over long timescales: the short-term nature of the political procedure means that direct programmes and priorities tend to change every few years. The formation of community policy is 'a matter of human agency, both of societies and individuals' (Schneider and Ingram, 1999; Lindsay and Bragg, 2004), and is subject to the usual cycles of the political procedure and development within the western democratic and independent institution. Nevertheless, it is likely to expand reasonable, plausible and considered future policy trajectories by accepting an institutional and systemic approach to the analysis and forecast of policy development, based upon a recognising of key drivers for policymaking, noticeable outlines of policy design, implementation and performance and expansion, and wider consideration of institutional civilizations, and the changing styles and obligations of rural governance. Unlike governments, which change relatively regularly, these underlying outlines are likely to continue throughout several decades, and can therefore be a possibly more reliable indicator of future policy coverage and potential gaps (Janet, 2011). The crucial issues of future policy are thus a complex mix of institutional, societal and individual drivers and inter-associations in the policymaking ground (Thomson and Oijen, 2007), rather than a set of changeable 'external' to this mix, such as climate change or global decline/recession. External elements like these frequently supply the challenges around which policies develop and combine, and it is therefore the mix of 'external' and 'internal' issues that decide what they attain (Janet, 2011). The key issue is the strategic role that regional government can play in land use planning in the UK (Ball et al., 2008).

It is historically noted that government involvements are within forestry, agricultural lands and environment policy. A broad collection of authoritarian and economic involvements influence community view in terms of equity and economics, social (organization substances and rural area advantages are there to be enjoyed) and also environmental reflections. Recognising these views agree with policies to be reflective of societal visions within the restrictions and limitations of EU and UK policy structures (DEFRA, 2008c; Burritt et al., 2011). There are four key issues which as a significantly important to be noted here:

a) Farmers are valued;
b) Farming is significant;
c) In general the public consider economic support for farmers probably will be authorize;
d) Balancing environmental results is an increasing priority (DEFRA, 2008a).

The land use key policy and governmental influences on past UK land use and present has been noted. These drivers have been discovered (policy-makers, governors, farmers) from other work in this area (e.g. King et al., 2004; Smith et al., 2007a), and incorporate those set up in past decades, as discussed above, in addition to new concerns and developments deriving from much more current external events. The more traditionally 'set up' (and consequently much accepted) aspects include: spatial planning; EU forest, agriculture and rural development policy and related global operational (contract) agreements; and environmental legislation. Those which have appeared recently and also have important rural land use policy implications, would include climate change and land use policy (Nieto et al., 2010; Janet, 2011).

2.6 Land Use Change Scenarios

2.6.1 Scenario and scenario-based planning

Scenario planning is a method for understanding about **uncertain** futures and learning what we know and do not know about the future. Several definitions of scenario exist in the literature, some of which are included in this section:

(i) Scenarios are hypothetical progressions of events created for the reason of focusing concentration on fundamental procedures and aims (Doulgeris et al., 2011).

(ii) Scenarios are typical descriptions of alternative pictures of the future, produced from rational maps or models that reproduce different perspectives on past, present and future progress (Nieto et al., 2010).

(iii) Scenarios are focused and highlight explanations of fundamentally and basically different prospects and potentials presented in logical and rational script-like or narrative description approach (Cantarello et al., 2011).

(iv) Scenarios are stories or 'snapshots' of what might be in order to gain information about the future. They focus on the analysis of uncertainties, drivers of change and causal relationships associated with a potential decision. Scenarios thus encourage critical thinking about risks and systems relationships (Shabtay et al., 2011).

(v) Scenarios are plausible future based on "if-then" assertions If the specified conditions are met, then future land-use and land-cover will be realized in a particular way (McKibbin and Wilcoxen, 2002).

(vi) Scenarios are descriptions of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play (UNEP 2002; DEFRA, 2007).

(vii) Rotmans (1998) and Cantarello et al. (2011) expand this basic definition by highlighting a few key points in more detail. These key points include:

First, a scenario consists of not only the end-state (a future image or vision) but also the path by which this is achieved. Thus it should be seen as a dynamic story and not simply a static snapshot of some future point in time. Scenario development begins with What if ….? ; In the latter How could…?

Second, the set of assumptions make up only part of a complete scenario. This could be problematic when these assumptions are taken from other scenarios. An answer to the question of the extent to which specific actions are included in a scenario is also important. These actions divide in to two groups, some are intended to cope with the situation portrayed in the scenario; others could fundamentally alter the nature of the scenario.

Third, a scenario can be derived and expressed in various forms such as narrative text, images (qualitative scenarios), tables, charts of data and maps (quantitative scenario).

Finally, the most important thing is to note that scenarios are not meant to be predictive.

Couclelis (2005) describes important differences in interpretation of different scenarios as: "Some view scenarios as describing future end states, others as constructing dynamic courses of events leading to such future". She uses the term of 'first-order scenarios' for description of possible futures outside the purview of the planning system, and 'second-order scenarios' for alternative courses of action within the purview of the planning system. For land-use planners and modellers this two-tier view of the future (first-order scenarios as 'scenario', and second-order scenarios as 'alternative plan or strategy') implies an approach such as that illustrated schematically in Figure 2.15, whereby a range of alternative land-use plans are tested against a small number of different scenarios. In this context, a major role of PSS (Plan Support System) would thus be to facilitate the development of land-use models that can be adapted to the different boundary conditions implied by the variety of scenarios considered (Couclelis, 2005).

Figure 2.15: Embedding planning strategies within scenarios (Couclelis, 2005).

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Plan **A**				
Plan **B**				
Plan **C**				

Different subdivisions of scenarios are described in the literature. One subdivision is to distinguish between descriptive and normative scenarios. Descriptive scenarios sketch an ordered set of possible events irrespective of their desirability or undesirability, while normative scenarios take values and interests into account (Venkataraman et al., 2005; Burritt et al., 2011).

Quantitative scenarios are usually computed by formalized computer models and provide numerical information in the form of tables, graphs and maps (Lindsay et al., 2004).

Forecasting or exploratory scenarios are forward-directed, explore alternative developments, starting from the current situation with or without expected/desired policy efforts (Tilman et al., 2006).

Independent of their type, all scenarios require a coherent set of assumptions for the driving forces of future land-use/cover. The driving forces typically used by scenario developers include demographic changes, economic growth and technological development (Lindsay et al., 2004).

Doulgeris et al. (2011) and Shabtay (2011) provide an updated scenario typology based on **14** separate characteristics of scenarios which are aggregated into three overarching themes:

a) **Project goal** which could be stated as 'why?' and addresses a scenario analysis' objectives as well as the subsequent demands on the design of the scenario development process.

b) **Process design** which could be stated as 'how?' and focuses on how scenarios are produced, the degree of qualitative and quantitative data used or the choice for stakeholder workshops, expert interviews or desk research.

c) **Scenario content** which could be stated as 'what?' looks at the composition of developed scenarios and focuses on the nature of variables and dynamics in a scenario and how they interconnect.

Table 2.10 illustrates the different scenarios in each overarching theme based on the characteristics of scenarios.

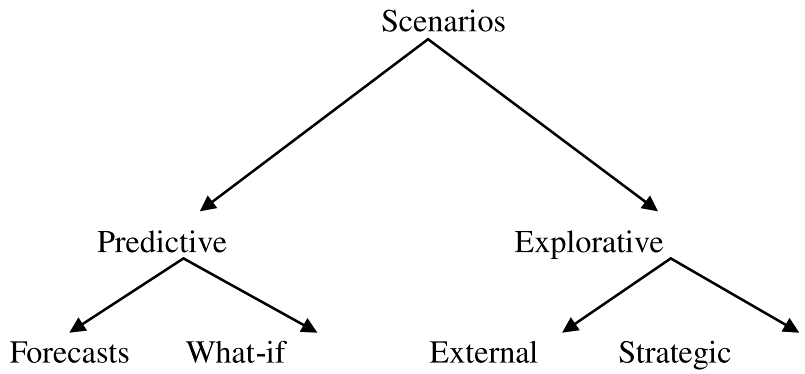
Table 2.10: A scenario typology in detail (Doulgeris et al., 2011; Shabtay, 2011).

Overarching themes	Scenarios	Characteristics
A. Project goal; Exploration and decision support	I.	Inclusion of norms? descriptive and normative
	II.	Vantage point: forecasting and back casting
	III.	Subject: issue-based, area-based, institution-based
	IV.	Time scale: long term and short term
	V.	Spatial scale: global/supranational and national/local
B. Process design: intuitive and formal	VI.	Data: qualitative and quantitative
	VII.	Method of data collection: participatory and desk research
	VIII.	Resources: extensive and limited
	IX.	Institutional conditions: open and constrained
C. Scenario content: Complex and simple	X.	Temporal nature: claim and snapshot
	XI.	Variables: heterogeneous and homogenous
	XII.	Dynamics: peripheral and trend
	XIII.	Level of deviation: alternative and conventional
	XIV.	Level of integration: high and low

Borjeson et al. (2006) suggest a scenario typology with emphasis on how the scenarios are used. Three categories of scenario studies are distinguished in this research which is based on the principal questions a user may have about the future. These are '*What will happen?',* provided by Predictive scenarios, which aim to make it possible to plan and adapt to situations that are expected to occur. They can also be used to make decision-makers aware of problems that are likely to arise if some conditions of the development are fulfilled; 'What *can happen'?* These scenarios are provided by Explorative scenarios, which aim to explore situations or developments that are regarded as possible, usually from a variety of perspectives. A final category of scenario is 'How can a specific target be *reached?',* provided to by normative scenarios, which focus on certain future situations or objectives and how these could be realized.

Figure 2.16 illustrates the scenario typology with two categories and four types which is presented by Borjeson et al., (2006):

Figure 2.16: Scenario typology with two categories and four types (Borjeson et al., 2006).



Borjeson et al. (2006) and Cantarello et al. (2011) also discuss different techniques to generate scenarios. According to this research, there are a number of identifiable tasks to handle in scenario studies including: generating ideas and gathering of data, integration where parts are combined into whole, and checking the consistency of scenarios. Table 2.11 illustrates different techniques in these phases of scenario development based on scenario types (Borjeson et al., 2006; Cantarello et al., 2011).

Table 2.11: Contribution of techniques in the phases of scenario development (Borjeson et al., 2006; Cantarello et al., 2011).

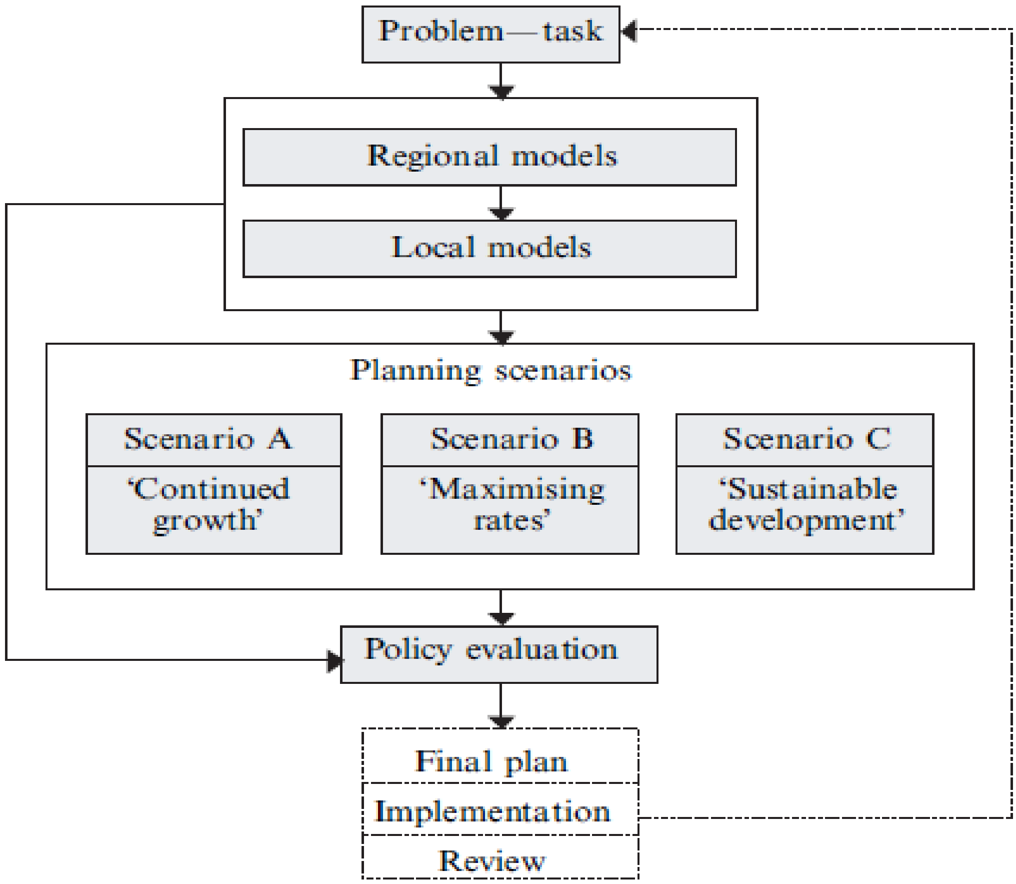
Scenario types	Techniques		
	Generating	Integrating	Consistency
Predictive Forecasts	➢ Surveys ➢ Workshops ➢ Original Delphi method	Time series analysis Explanatory modelling Optimising modelling	
What-if	➢ Surveys ➢ Workshops ➢ Delphi methods	Explanatory modelling Optimising modelling	
Explorative External	➢ Surveys ➢ Workshops ➢ Delphi methods	Explanatory modelling Optimising modelling	Morphologic field analysis Cross impact
Strategic	➢ Surveys ➢ Workshops ➢ Delphi methods	Explanatory modelling Optimising modelling	Morphologic field analysis Cross impact

Aherne et al. (2011) provide a good review of some of the key theoretical and methodological issues that are raised by a backcasting approach and discusses how these are addressed in the Georgia Basin Futures Project (GBFP), a five year participatory integrated assessment project focusing on modelling, scenario analysis and community engagement.

According to this paper, the essential rationale for a backcasting in contrast to forecasting approach is twofold. **First**, our ability to predict the future is strongly constrained because of the future uncertainty, which stems from (i) lack of knowledge about system conditions and underlying dynamics, (ii) the prospects for innovation and surprise, and (iii) the intentional nature of human decision making. **Second**, if the future were predictable, in the cases of long-term societal problems like sustainability, it is important to explore the desirability and feasibility of alternative futures, not simply focus on likelihood. This leads to an approach that is explicitly normative in its approach to the future.

Pettit et al. (2004) and Aherne et al. (2011) report the results of research on developing future scenarios for land-use planning to achieve policy goals. They investigate how demographic (socio-economic) and land-use (physical and environmental) data can be integrated within a decision support framework to formulate and evaluate land-use planning scenarios. Their approach is to take regional forecasts on socio-economic data and to disaggregate these to the land-use level by using spatial planning models (Couclelis, 2005). The main focus is on predicting future land-uses through various scenarios, in order to provide a realistic assessment for future growth planning, and evaluate how well these achieve a variety of policy goals (Borjeson et al., 2006). A case-study approach is undertaken with land-use planning scenarios for a rapidly growing coastal area in Australia, the Shire of Heavy Bay. Three potential urban growth scenarios include: Scenario A ('continued growth') is based on existing socio-economic trends, Scenario B ('maximum rate base') is derived using optimization modelling of land-valuation data, Scenario C ('sustainable development') is derived using a number of social, economic, and environmental factors and assigning weightings of importance to each factor using a multiple criteria analysis approach. Using a GIS, future possible land-use allocations up until 2080 are delineated (Pettit et al., 2004; Aherne et al., 2011). Then the planning scenarios are evaluated by using a goal achievement matrix approach. The integrated decision support framework in this paper is able to incorporate development constraints and controls from a variety of sources, for example that combines both regional growth strategies, local planning schemes and stakeholders, and incorporate these in the formulation of scenarios (Couclelis, 2005; Borjeson et al., 2006). Figure 2.17 illustrates the scenario planning framework in this research.

Figure 2.17: Scenario planning framework (Pettit et al., 2004).



The above descriptions about different types of scenarios and scenario planning modelling approaches offer alternative, but complementary, rigorous, methodologies. The scenario planning used in this thesis can be placed in the context of these typologies. A modelling approach is adopted in order to create descriptive, predictive (Fig 2.16) scenarios for land cover change. The scenarios are first order scenarios (Couclelis, 2005; Borjeson et al., 2006), which are descriptive and qualitative; they are focussed on forecasting and will consider the backcasting less. In fact, this research creates scenarios that highlight explanations of fundamentally different prospects and potentials in available land uses in the Tamar Valley catchment.

2.7 Land use and Landscape Planning System

2.7.1 Planning Support System (PSS)

Several definitions for Planning Support Systems (PSS) have been proposed in the literature. Some described PSS as the collection of digital techniques (such as GIS) which are emerging to support the planning process. This views PSS as an information framework that integrates the full range of current (and future) information technologies useful for planning. Geertman and Stillwell (2004) propose that PSS are a subset of computer-based geo-information instruments, each of which incorporates a unique suite of components that planners can utilize to explore and manage their particular activities. According to this definition, it includes tools to facilitate and support different aspects of the planning process, including problem diagnosis, data collection, mining and extraction, spatial and temporal analysis, data modelling, visualization and display, scenario building and projection, plan formulation and evaluation, report preparation and collaborative decision making (Maguire et al., 2005).

McKibbin and Wilcoxen (2002); Geertman et al. (2004) and Nieto et al. (2010) report an effort to construct an inventory of PSS practices world-wide between 2001, 2004 and 2005. The diversity of PSS which are evaluated in the inventory is apparent in the aims, capabilities, content, structure and technology of the PSS.

In terms of **aim**, some PSS can be characterized as tools dedicated to support specific tasks within the planning process; others have been developed to inform the public about different planning and policy topics in their region or country; and others support specific forms of planning by practitioners such as strategic planning, land-use and infrastructure planning or environmental planning (Tian et al., 2011).

In term of **capabilities**, some PSS are dedicated to support modelling activities for future population distributions or land-use patterns; some provide tools to support the sketching of new spatial structures; and others are designed purely to allow the visualization of potential spatial developments in all kinds of different ways (Lu et al., 2011).

In terms of **content**, PSS is a ‘toolbox’ containing various components including data sets, (meta-) information, storage and query tools, analysis methods, theories, indicators, etc.. Some PSS, however, are much more specialized and contain only very specific software components to perform specific tasks.

In terms of **structure**, some PSS can be considered fully integrated systems in which all components are interconnected closely and others have components that are only loosely connected tools within a container (Geertman et al., 2004).

In terms of **technology**, some PSS are stand-alone programs while others are developed solely for the Intranet or Internet.

This exercise showed some conclusions. The first one is that the numbers of PSS are increasing world-wide but many of them are not mature. A second important conclusion is that experiences with PSS in actual planning practice are very limited. A third conclusion that those systems recorded in the inventory reflect a very wide range of application areas. They also made some recommendations about the future of PSS development and application.

First, PSS should be an integral part of the planning process and context (Aherne et al., 2011).

Second, PSS should meet users and context requirements too, besides the conformation to requirements of the planning process and context (Geertman et al., 2004; Sharifi et al., 2008).

Third, one should be aware of the fact that people address issues from an interdisciplinary perspective. In contrast to science in which the study of reality has been categorized in separated disciplines, laypersons do not tend to think in accordance with distinct disciplines but in terms of integrated systems or parts thereof. PSS that intend to connect to peoples' way of thinking should address issues in an interdisciplinary manner, linking the spatial to the social, and the environmental to the economic and so forth (Laborte et al., 2008).

Fourth, PSS should take seriously its users and leave them with the feeling that they have been taken seriously (Sharifi et al., 2007; Aherne et al., 2011).

Fifth, the user-interface of the PSS should be sensitive to the characteristics of the user, to the kind of information that it communicates to that user, and to the types of intended use that is made of the information provided (Doulgeris et al., 2011).

Sixth, the PSS should be focused in particular on the planning problem at hand. For some strategically oriented planning tasks, this means the incorporation of tools for sketching, modelling and impact analysis. The activities of detecting the most likely future, exploring potential scenarios, and/or designing desirable futures belong to the core of strategic planning tasks (Doulgeris et al., 2011).

Finally, PSS should be appealing; they should fulfil participants' needs and wishes, and allow the participants to enjoy using them too.

2.7.2 Spatial Decision Support Systems (SDSS)

In the last decade a large number of spatial decision support systems have been developed to assist decision makers in the field of spatial planning issues (Agrell et al., 2004; Janssen et al., 2008). A decision support system can be defined as an instrument for finding (sets of) alternative solutions for a decision problem. In terms of spatial planning, it should be able to support the finding of optimal spatial distributions of land-uses (Vescoukis et al., 2011).

To meet a specific objective, it is frequently the case that several criteria need to be evaluated. Such a procedure is called Multi-Criteria Evaluation (Vescoukis et al., 2011). A decision is a choice between alternatives (such as alternative actions, land allocations, etc.). The basis for a decision is known as a criterion. In a Multi-Criteria Evaluation, an attempt is made to combine a set of criteria to achieve a single composite basis for a decision according to a specific objective (Janssen et al., 2008). Through a Multi-Criteria Evaluation, these criteria layers representing suitability may be combined to form a single suitability map from which the final choice will be made (Janssen et al., 2008).

While a variety of standardization and aggregation techniques are important to explore for any multi-criteria problem, they result in images that show the suitability of locations in the entire study area. However, in land use planning, we need to make site selection or land allocation decisions that satisfy **multiple objectives**. The case of conflicting or competing objectives, however, requires some mechanism for choosing between objectives when a location is found highly suitable for more than one. For example, MOLA (Multi-Objective Land Allocation) in the IDRISI package provides a procedure for solving multi-objective land allocation problems for cases with conflicting objectives (Vescoukis et al., 2011). Based on the information from a set of suitability maps, one for each objective, the relative weights to assign to objectives, and the amount of area to be assigned to each, MOLA determines a compromise solution that attempts to maximize the suitability of lands for each objective given the weights assigned (Janssen et al., 2008).

Studies on the application of heuristic algorithms are relatively conceptual and little methodological research exists as to how to use design techniques in actual planning processes, including making reference to the potential of the techniques for using them in a multi-stakeholder setting (Janssen et al., 2008; Vescoukis et al., 2011).

Greeuw et al. (2000) and Janssen et al. (2008) present the result which describes a step-by-step application of heuristic design technique in land-use planning, based on a genetic algorithm approach and specifically developed for use in a prototype SDSS. Genetic algorithm (GA) is a proven optimization technique whose power has been widely verified in different fields. Recently, researchers are trying to apply it to solve more complicated optimization problems (Vescoukis et al., 2011). These researchers address the following requirements for the application of the design technique:

a) The SDSS should facilitate multiple objectives defined in a spatial context, such as spatial relationships across land uses in adjacent areas, in the sense that attribute values associated with one unit may be dependent on activities in neighboring units (Vescoukis et al., 2011).

b) The SDSS should be able to handle a large amount of data while maintaining good communication between the SDSS and the end users (Janssen et al., 2008).

c) The SDSS must be able to accommodate rapid adjustments to land-use plans developed in interactive sessions with the SDSS. This requires short response times from the algorithm, at least during earlier stages of evaluation (Vescoukis et al., 2011; Shabtay et al., 2011).

On a cross-disciplinary project to design a decision support system (DSS) that aims to assist government policy makers in planning the regional agricultural development of the Bungoma region in Kenya (Vescoukis et al., 2011). The DSS is based on the agro-ecological zones (AEZ) model, a previously developed non-interactive optimization model that provides an agro-ecological and economic assessment of various types of land uses, including cash-crops, food production, grazing, forestation and farming (Van et al., 2003; Matthews et al., 2006).

Van et al. (2003), Matthews et al. (2006) and Xiao et al., (2007) performed multi-criteria analysis in the IDRISI GIS package to evaluate development suitability for four land use categories according to appropriately measured and weighted criteria. The four suitability images were then subjected to multi-objective land allocation to demarcate optimum locations for each land use type. The decision-making process entailed execution of seven consecutive steps which are discussed in detail and applied in the case study.

Matthews et al. (2006) report the outcomes of a workshop comparing land-use plans proposed by land-managers or domain experts with those derived using a computer-based decision support system (DSS). The land-use planning DSS (LADSS) integrates four main components, a geographic information system, land-use systems simulation models, impact assessments and land-use planning tools. Since the land-use planning tools are based on multi-objective genetic algorithms (mGAs) it is possible to generate a range of alternative plans that define the structure of the trade-off between the objectives (Xiao et al., 2007).

Given the increasing availability of geographical information systems (GIS), integrating multi-objective spatial decision tools into GIS and other visualization systems is a fruitful direction for future work (Vescoukis et al., 2011; Tian et al., 2011).

2.7.3 Optimization Modeling, Linear Programming

The optimization of land-use structure is the core of optimizing the allocation of land resources, including the optimization of quantity and space (Ma and Nakamori, 2009). Optimization modelling has structured a number of decision methods based on quantity structure optimization such as Multi-objective Optimization, Linear Programming, Multi-criteria Optimization and System Dynamics etc, and spatial optimization methods which include Landscape Ecology and Cellular Automata (CA) models (Xiao et al., 2007; Ma and Nakamori, 2009). However, using traditional methods such as multi-objective programming models used in landscape ecology; this is very difficult to make the space structure and the amount structure united effectively (Ma and Nakamori, 2009; Abdollahi, 2011).

The progress and improvement of geographic information system (GIS) and computer technology has offered a strong and great technical support for the analysis and investigation of spatial data when making spatial optimization decisions about land-use (Abdollahi, 2011). Combining the mathematical methods of linear programming units with GIS and realizing the reasonable and sensible allocation of land allocation resources both in quantity and space, has become a hotspot to scientists and researchers, and it also promotes and supports the development of scientific research about land-use (Bonilla et al., 2010; Bek and Stanislav , 2011).

The relationship between the land and the activity in optimization models can be linear and non-linear. Nowadays, there are different types of models which are mainly used for optimization modelling such as; General Algebra Modelling System (GAMS), Multi-objective Genetic Algorithm (MOGA) and Multi objective Cellular Automata (MOCA). Although the genetic algorithm has strong capability for global optimization, it involves complicated map spot coding, which makes the program difficult to realize, and it does not have a strong capability of spatial correlation (Khare and Singh, 2011). The multi-objective cellular automaton model performs timing simulation based on the results of multi-objective optimization, which can not realize trans-space search (Voinov et al., 2002; Li et al., 2011;

Mizgier et al., 2012). As a result, the General Algebra Modelling System (GAMS) is mainly tool used for optimizing.

In the case of this modelling (Optimization), the variations of constraints and purposes in the model input (control) are performed automatically, as well as the procedure of the output. The heart of this procedure is the algorithm of numerical optimization that makes the decision on how to define and analyze the outputs and scenarios based on the available and accessible information about the results of previous model runs (Ma and Nakamori, 2009; Bonilla et al., 2010). This optimization process connects the scenarios, the simulation procedure and the performance and presentation standard and criterion. 'Algorithms of optimization are capable of performing a systematic search in the space of control variables to find an input vector which controls the systems in the desired way, specified by the goal function' (Voinov et al., 2000; Bek and Jezek, 2011; Singh et al., 2011).

In most cases to measure the outcome and result of a scenario in terms of economic, environmental, social aspects, more than one output and parameter variable needs to be considered. To evaluate different scenarios, output variables need to be integrated into a scalar value (or to analyze and examine a multidimensional decision problem). This function that can be chosen to integrate or combine several results or output variables is identified as an objective function or 'performance criterion' and is a mathematical formalisation of the situation of the system that should be maximized or minimized to reach the desired state (Seppelt and Voino, 2002). The scope of ecosystem and land management problems ranges from forest management and timber harvest (Loehle, 2000; Seppelt and Voino, 2002) to agricultural problems (Markides et al., 2011) to general and specific issues of land use change (Voinov et al., 2002; Li et al., 2011), and to habitat suitability (Bonilla et al., 2010). The models used differ in terms of mathematical structure. Modelling varies from combined and aggregated dynamic models based on variation or deviation equations of exponential growth (Bonilla et al., 2010) to complex models based on systems of non-linear differential (derived function) equations (Voinov et al., 2002; Abdollahi, 2011).

In relation to these research reviews, in this thesis it has been evaluated that the appropriate combination of methods, in relation to the research aim, is Optimization modelling (Linear Programming). A Spatial Decision Support System (SDSS) is used to relate the aspatial model results to a realistic distribution of land cover in the landscape; the two approaches are therefore complementary in examining the feasibility of different options for increasing carbon sequestration through land use change. Planning support systems provides a conceptual context within which the data sets necessary for this work can be integrated.

2.8 Conclusions

This chapter reviews all of the aspects of science and policy that impinge on the PhD thesis. There is a common agreement (between the government and policy-makers) that there is still a need for quantification of the most promising alternatives for landscape change for climate change mitigation. There are a large number of possibilities for changes in land management, but all are subject to environmental, social, political and economic constraints. The analysis in this study provides a pathway for the identification and consideration of scenarios for the future with a realistic range of drivers (environmental, climatic, policy, and socio-economic) and a spatially explicit analysis at the landscape scale. The large number of constraints shows that the development of these changes cannot be isolated. Interventions such as the use of improved crop varieties cannot be made without conceding the social, political and economic context of the total system. A major gap in research at present is the lack of approaches for developing and modelling the impacts of different scenarios with a range of drivers at the landscape scale. Whilst other studies have provided national and regional estimates of total changes (e.g. King et al., 2004; Smith et al., 2008), there is very limited use of spatially explicit landscape change scenarios based on land suitability analysis to explore the potential of a range of options for climate change mitigation at the local and regional level. As has been noted before, carbon storage approach in the land use management and mitigation of GHG emissions of agriculture and forestry lands are the key issue.

Furthermore, it is important to mention that land use change is not only spatially but also temporally dynamic and the balance of positive and negative consequences of any changes may alter over time.

This study thus aims to provide a new spatially- explicit approach to quantifying soil and biomass carbon and greenhouse gas emissions associated with major land uses. It also provides a conceptual framework for scenario development and assessment of spatial models of landscape change over time using GIS modelling. The scenarios that are explored provide a much improved understanding of the implications of potential land use changes for climate change mitigation and impacts on the landscape. In turn it is hoped that these scenarios will provide a basis for demonstrating the potential for climate change mitigation to planners and managers and for evaluating their impacts on the landscape and socio-economics of the region.

Chapter 3

Research Design and Methodology

Chapter 3. Research Design and Methodology

3.1 Outline of Methodological Framework for this Research

This chapter outlines the methodology to estimate change in soil and biomass carbon pools, emission of greenhouse gases and energy use (direct and indirect) due to changes in land use management. The intention is to provide an overview of the methodological approach used in this research. The full detail of the methods for individual aspects of the analysis is provided in the results chapters (address to chapters 4, 5 and 6) as these are more appropriately read in this context and this strategy avoids the need for constant cross reference between chapters.

The study of land use (agriculture and forestry) in chapter 1 concentrated on searching particular policy, demand scenarios and ultimate outcomes, based on an approach that combines and incorporates biophysical, environmental and socio-economic information. The approach is based on knowledge of environmental and biophysical processes implicit in agriculture and forestry, land allocation possibilities, and a GIS and Linear Programming (LP) modelling. In this way, possible alternative future land uses can be determined by recognising value driven; scientifically what are 'feasible' or 'practicable' prospects and including the consideration of economy, carbon amount in agricultural and forestry land, and greenhouse gases and energy emissions objectives in this study. The methodology used in this study includes four main parts: estimating carbon accumulated with land use based activities (carbon quantity), GIS modelling, Linear programming (Optimization modelling) (see chapter 6, section 6.2), and evaluation assessment and presentation of results (including scenario evaluation). Table 3.1 and Figures 3.1, and 3.2 present the components and procedure of the methodology.

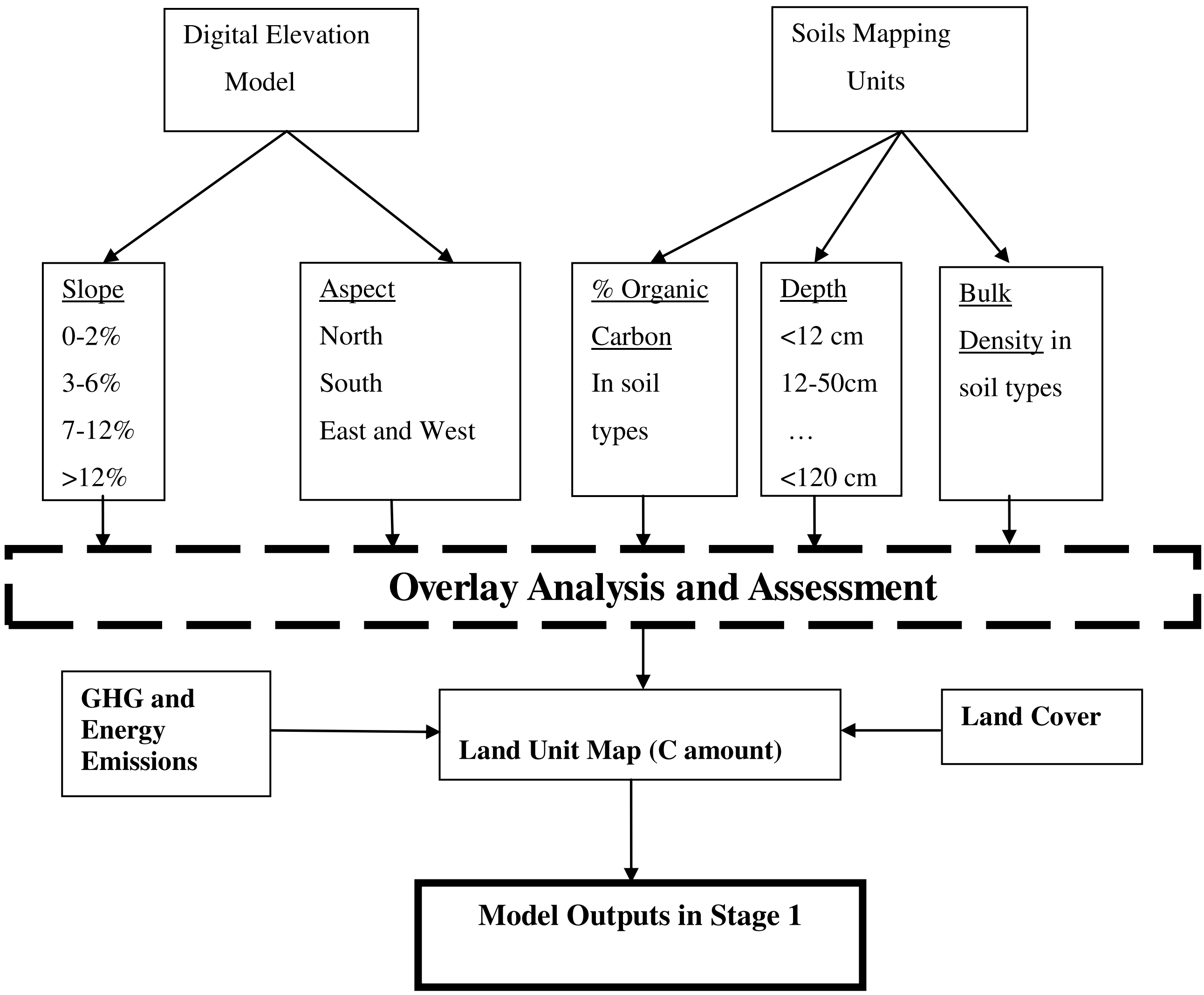
3.1.1 Quantification of Carbon Density (soils, biomass, emissions)

This study adopts GIS technology to construct a multi-criteria carbon storage model, compares the model with the distribution of current land cover and projected land use plans, and prepares a landscape plan for the Tamar valley catchment in Southwest England (Figure 3.1). In this section, first, the carbon storage amount will be constructed from a set of environmental attributes considered most important for forest and agriculture land in this study, and by identifying their spatial distribution in this case area. To estimate total land cover organic carbon content and its distribution within the catchment, spatial analysis will be used. To achieve this, representative measurements of total mass of carbon in the vegetation will be estimated from published carbon density values (Milne and Brown, 1997) and land use classification totals by plotting for each 25m x 25m square the average vegetation carbon density of the land class of the square within the GIS. This will enable calculation of the estimated total carbon distribution in different land classes.

Second, the study will examine the degree to which lands highly-ranked for carbon storage are considered as areas for consideration for land use change in the long-term in Tamar Valley Catchment, and thirdly; an assessment of the overall greenhouse gas balance, estimates of greenhouse gas and energy emissions (direct and indirect) associated with land use and management is required, as well as estimate of carbon stored in soils and vegetation (Figure 3.1).

Figure 3.1: Flow diagram showing the GIS data layers and modelling methods that will be used to create the landscape storage (carbon) map, determine its relation with current land cover, and collect priorities for a land uses and GHG emissions (Developed by Author).

Carbon Calculation and Quantitative Model



3.1.2 GIS and Optimization Modelling in this Study

The GIS and Optimization modelling system intended for this research theoretically and fundamentally is divided into four main key constituents or subsystems (Figure 3.2). The different factors are:

3.1.2.1 Geo-Database Management System: which stores the required data in the necessary format for management and manipulation of data.

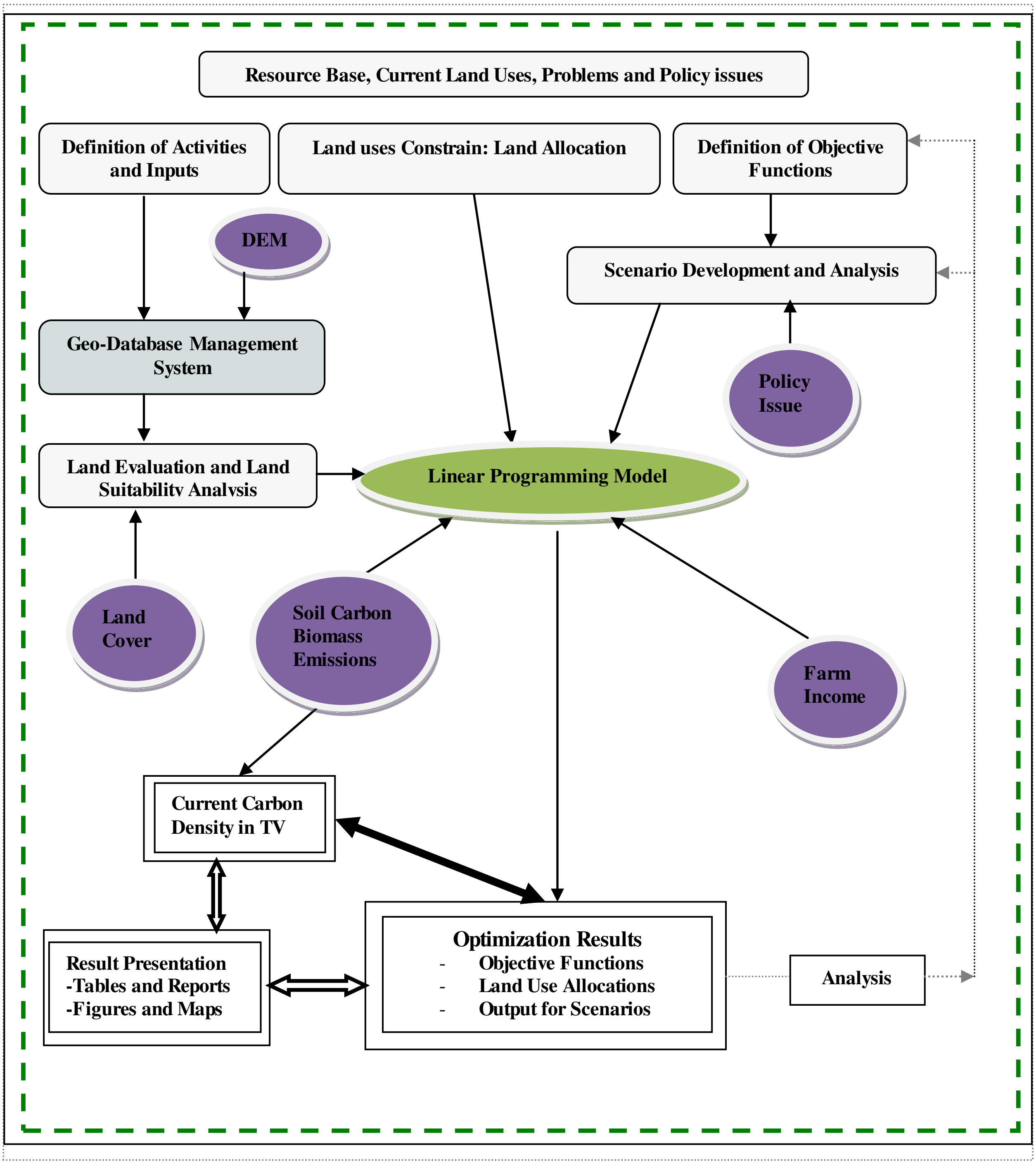
3.1.2.2 Land Suitability Analysis and Assessment Component: Land suitability is an important link form between land use resources appraisal and evaluation of the decision procedure in land-use management and planning. This element plays an important role in land-use management and planning. Land evaluation and suitability assessment for each specified use is the key work of this element.

3.1.2.3 Scenarios Development and analysis (SDA): Scenarios are generated and implemented based on future climate change and a range of possible policies.

3.1.2.4 Development of the linear modelling (LM) approach and calculation of Carbon under different scenarios: This will be used to find the optimal spatial distributions of land-use based on the results of scenarios and data analysis.

The role of this system is to provide a flexible mechanism for communicating between data, models, and knowledge rules in the quantification of carbon and other GHG, energy storage and emissions respectively under possible future land use change. In this study some assumptions are made such as no change in the amount of soil carbon over time; land evaluation process takes into account to control on distribution of land cover. Also, it has been assumed that all agricultural and forestry lands are fulfilled in accordance to the principles of the best management practise and carbon saving intention, presuming suitable and adequate use of inputs, policies and methods.

Figure 3.2: Conceptual Framework of Methodology Employed in the Research.



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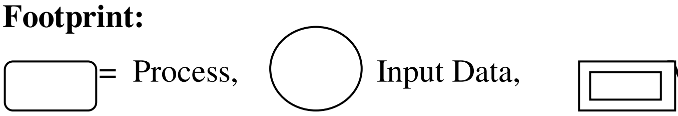

= Process, Input Data, Model Outputs

3.1.2.1 Geo-Database Management System

In land-use management spatial and non-spatial data with different formats and structures are needed. In order to develop the methodological system, there is a need to use a geo-database management system to create the potentialities that are the objectives of this research. The first important capacity, in relation to this requirement, is the integrated abilities and potentials of the system, which means that the different models and modules should combine and work together in an appropriate way and transfer data to each other. The synergistic relationship of the policies and economics in different parts of the system also is another key capacity. The geo-database management system can provide an appropriate and proper data model for managing different data types needed for land-use management and planning, as stated above, and allows the ability and potential for fundamental interaction with different sub systems and models.

The processes of developing the geo-database management system in this research are explained as follows:

a) Identifying and categorizing of data which are required in the land-use scenario generation procedure, as part of the set-up and construction of the system.
b) Evaluating and assessing the purposes of the system which has fundamental interactions with databases in order to evaluate the system for data storage and management.
a) Evaluating and assessing the existing software for an expanded geo-database management system and selecting the one which meets the assessed needs.
b) Designing, aiming and implementing the data model and organisation of the geo-database management system.
c) Generating datasets (Table 3.1) required for the analysis, including details of the types of data available to the geo-database.

Table 3.1: Required datasets for the geo-database in this site study (Met-office, British Geological Survey, 1985, LCM 2000, Soils and their use in Southwest England., 1984, Soils in the British Isles, 1990).

Data Type	Geometry	Resolution	Source
Land cover /Land use	Raster	25m	LCM2000
Soils	Vector	1:25,000	Soil survey of England and Wales
Elevation	Raster	1:25,000	Digital elevation model (DEM)
Aspect	Raster	1:25,000	Digital elevation model (DEM)
Slope	Vector	1:25,000	Digital elevation model (DEM)
Soil Depth	Vector	1:25,000	Soil survey of England and Wales
Soil Bulk Density	Vector	1:25,000	Soil survey of England and Wales
Soil Organic matter	Vector	1:25,000	Soil survey of England and Wales

3.1.2.2 Land Suitability Analysis and Assessment Component (LSA)

This phase of the project will identify criteria and constraints for each specified land-use type and develop spatial models to assess suitability and appropriateness of the study area for different land cover types. These models will be developed and expanded based on Multi-Criteria Analysis/ Evaluation (MCA/E) and the FAO's land elevation (Food and Agricultural Organization) technique and classification, which involves finding out the factors, constraints, limitations and alternatives for each land use. There are two key stages in developing the LSA model:

a) Identification of the environmental, policy and socio-economical factors, which explain current land cover and land use in the study area.
b) Implementing and using the MCA/E suitability models, such as Linear Combination (LC), to produce and generate a final suitability value for each land area type.

3.1.2.3 Scenario Development and Analysis (SDA)

The three main key conceptions of this stage are scenario building, land-use future studies and forecasting of the land-use changes, including future hindrances and uncertainties.

This stage was initiated through a literature review on scenario typologies, evaluation, analysis, the methods of scenarios to handle uncertainty and existing work on land cover change scenarios (Refer to chapter 2). The results of this stage are to identify what types of scenarios can be created for land-use management and how these are applied and to choose the most suitable and appropriate methodological approach. Also to evolve a methodology and implement this for scenario generation, development and scenarios for land cover changes in the Tamar Valley catchment.

The second action is to recognise and define the driving powers for future land cover change and spot the critical policy objectives, ideas and consider the landscape-scale storage and emissions of GHG and energy under the range of different scenarios for different periods in the 21st century for the Tamar Valley catchment area. This methodology will be based on computer implementation to make possible the relation and fundamental interaction of policies and climate change in scenario generation and analysis (refer to Chapter 5).

3.1.2.3 Development of the LM (Linear Modeling) approach and calculation of Carbon under different scenarios

In this section of the methodology approach, the key components are defined as: definition of activities, land assessment and evaluation, and finding of inputs of the activities (refer to Figure 3.2 in this Chapter). The land use activities have been defined on the basis of environmental and available economic-socio information, taking into consideration the current land use situation and crisis recognised.

The linear programming (LP) model (addressed in Chapter 5) employs the linear purposes to connect the land use activities, constraints and objective functions. A complex and adaptable process is used that permits the model to find out the carbon value, GHG and energy emissions, and farm business income. The constraints and limitations of the model are split into land use (resource) constraints. These constraints include the available land allocation. The objective functions are categorised based on land and GHG National Inventory policies and problems defined that could be maximized and minimized in this research. Each of the objective functions is activated as a limit and constraint or non-connecting objective when has not optimized. The scenarios are adjusted and generated by different objective functions with different concern places (see Chapter 5). The objective functions are calculated independently (separately) with the model, and the scenarios in a repetitive process. Firstly, each of the picked objective functions is optimized independently with enforcing constraints under the range of different scenarios, and is then assessed. With considering this optimization model, in relation with the farm income, the results have been produced (Chapter 5 and 6). In the end, the total outputs are presented in different tables, maps, and figures.

3.2 Study Area

3.2.1 General description of the catchment: geology, climate, and land use

3.2.1.1 Location and site description

The Tamar Valley catchment is located in the counties of Devon and Cornwall in southwest England (Figure 3.3). The Southwest is the largest region in England in terms of area, and extends from the counties of Gloucestershire, Avon, Wiltshire, Dorset, Somerset, to Devon and Cornwall (Figure 3.4).The region is nearly 400 km from end to end, covers almost 24,000 km^2 and has a coastline about 1,100 km long. The small native population is enhanced by growing numbers of retired people and, particularly in Devon and Cornwall, by large numbers of seasonal visitors attracted by the mild climate, beautiful coastline and unspoiled countryside. The northern part has a population distribution more similar to the neighbouring Midlands, with Bristol and Swindon as its main centres.

Figure 3.3: Location of the Tamar Valley Catchment (Tamar AONB, British Geological Survey, 1985).

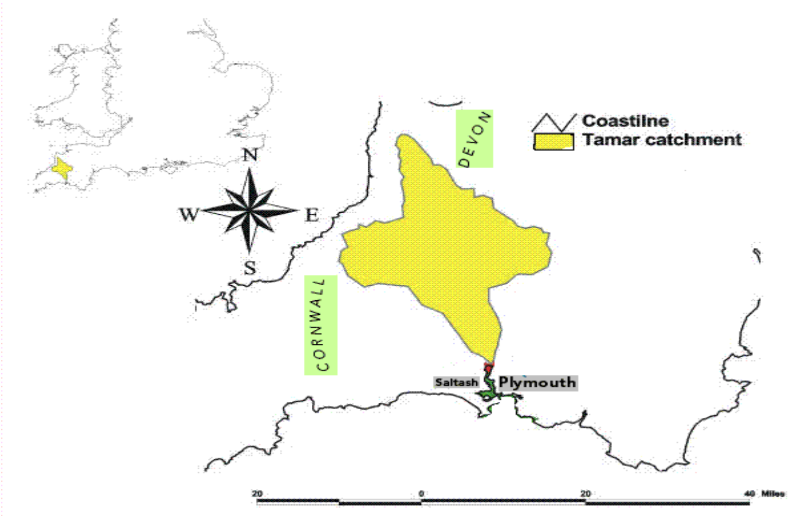
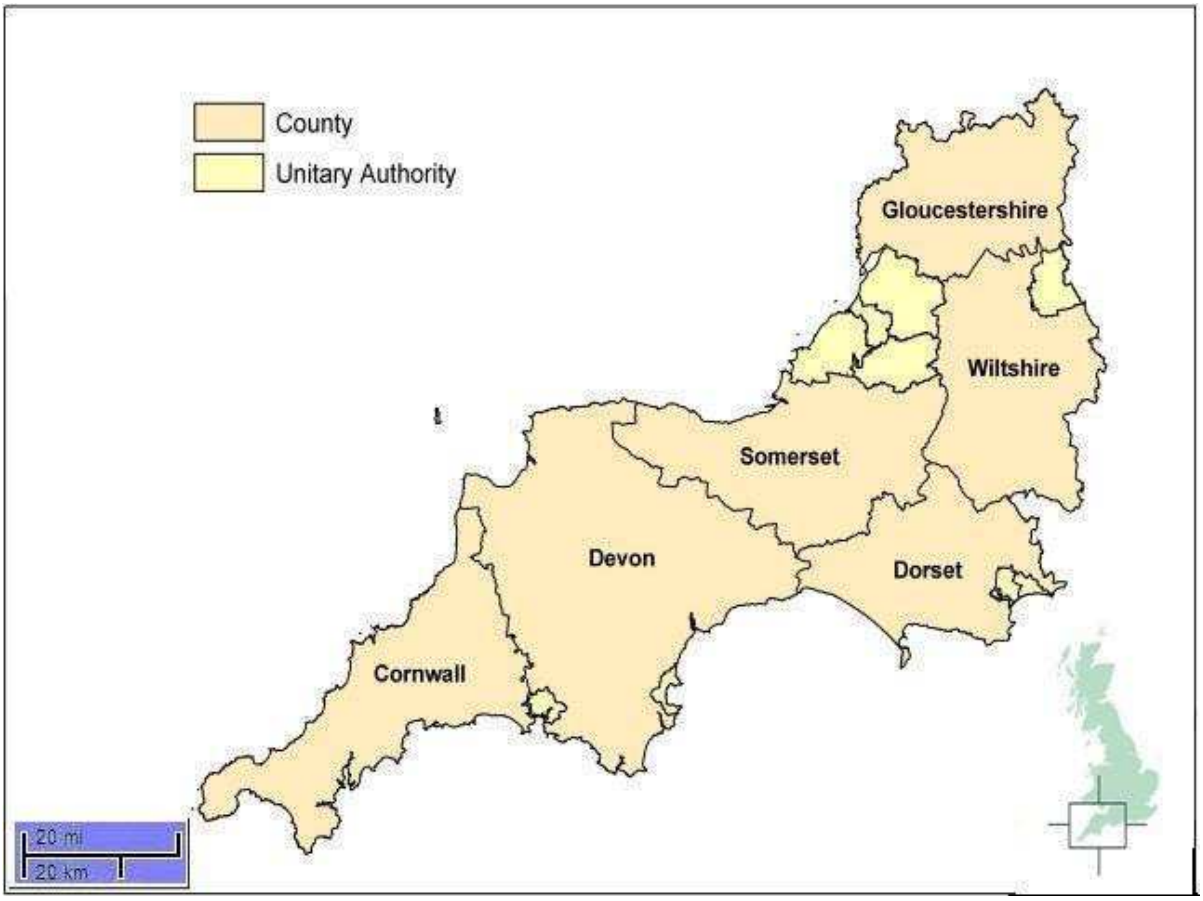


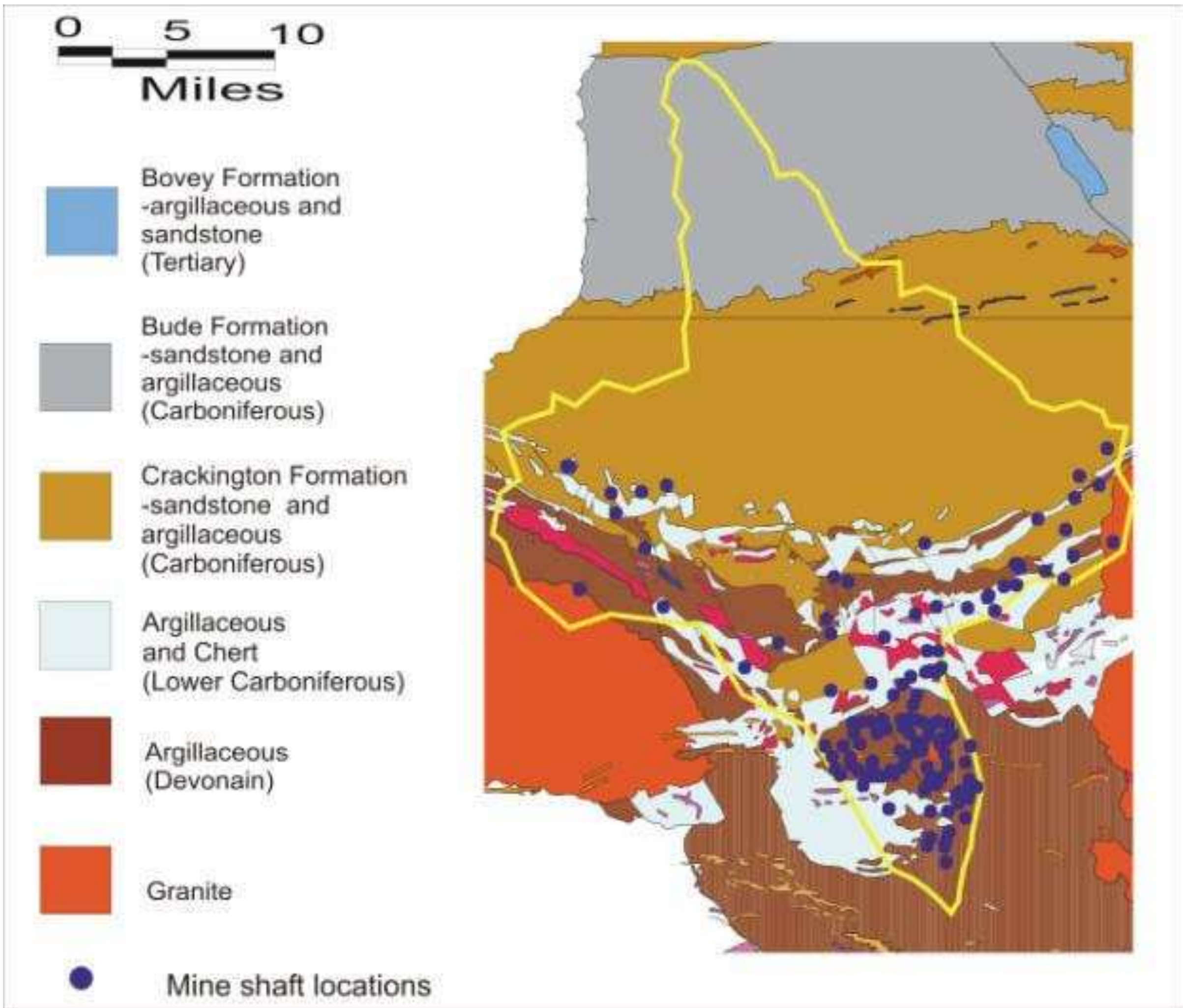
Figure 3.4: The region of Southwest England (Tamar AONB, British Geological Survey, 1985).



3.2.2 Tamar Valley Catchment; Geology, Topography and Climate

Bedrock geology in the north of the catchment is predominantly interbedded sandstones and argillaceous (fine-grained) sedimentary rocks from the Carboniferous period (Figure 3.4). Further south, the Lower Carboniferous rocks are dominated by fine-grained sedimentary sequences and chert (crystalline silica). Outcrops of granite occur on the eastern (Dartmoor) and western (Bodmin Moor) sides of the catchment, and are also interspersed with outcrops of Lower Carboniferous and Devonian slates. Given the distribution of historical metalliferous mine shafts (Figure 3.5), mineralisation throughout the area is most common in the south of the catchment associated with Upper Devonian, Lower Carboniferous lithologies and a range of igneous rocks, from small outcrops to larger outcrops of Dartmoor and Bodmin Moor. The British Geological Survey has carried out previous work investigating mining and mineralisation in this area, including Bennett et al. (1980), Jones (1981), Leake (2000), Caparros and Jacquemont (2003) and Jones et al. (2004), as well as geochemical investigations of the Bude and Crackington Formations: Hourcade et al. (2001) and Houghton, (2003). The only significant Quaternary deposits throughout the catchment are alluvial sediments along the larger rivers (not shown on the simplified geology map). The Tamar catchment covers an area of 916.9 square km, with a maximum altitude of 586 metres OD. The north of the catchment has an elevation of around 200 metres, rising to the east (>500 metres on Dartmoor) and to the west (>300 metres on Bodmin Moor); the remainder of the catchment towards the south has elevations of less than 200 metres. Annual average rainfall across the catchment between 1961 and 1990 was 1216 mm (Institute of Hydrology, 1993).

Figure 3.5: Simplified geological map of the Tamar Catchment (British Geological Survey, 1985). Yellow line shows the outline of the Tamar valley catchment.



3.2.3 Soils Description in the Tamar Valley Catchment

The soils of the Tamar catchment are dominantly comprised of typical brown earths (Soil Survey of England and Wales, 1983). These are well-drained, fine loamy soils, prone to slight seasonal waterlogging. The brown earths in the south of the catchment also contain a fine silty fraction. In the north of the region, overlying the Bude Formation, widespread mottled patches of pelo-stagnogley soils are dispersed through the brown earths. These clayey soils are slowly permeable, with seasonal waterlogging. They cover a broad region (6 km in width) covering much of the boundary between the Bude and Crackington Formations (Figure 3.5).

Brown earths cover large parts of the central region of the catchment between the two major granite bodies. Mottled areas of pelo-stagnogley soils occur around Roadford reservoir and further east and this soil type also overlies the course of the River Thrushel. Typical brown alluvial soils overlie the course of the River Tamar in the centre of the catchment. The main soil type overlying the Bodmin Moor Granite is an ironpan stagnopodzol. These soils are gritty, loamy and very acid, with a wet, peaty surface horizon. A thin ironpan is often present. To the north of this area, there are two bands of soil contrasting the typical brown earths.

The band nearest to the granite is composed of a typical brown podzolic soil, while the second band is mainly composed of a ferric stagnopodzol. Both bands trend NW-SE. Over the western edge of the Dartmoor granite, the soils are largely comprised of humic brown podzolic soils, cambic stagnogley soils and ferric stagnopodzols. To the west of the granite, there are patches of cambic stagnogley soils, typical brown podzolic soils, ferric podzols and typical cambiogley soils. Soils in the southern part of the catchment are mostly brown earths, although other soils of limited extent do occur. These include typical brown podzolic soils, which are mainly located around the River Tamar, cambic stagnogley soils and typical alluvial gley soils (Soil Survey of England and Wales, 1983 and Falloon and Smith, 2002).

To estimate total SOC content and its distribution within the Tamar Valley Catchment, spatial analysis will be used. To achieve this, representative measurements of organic carbon for different soil types, bulk density and soil depth will be obtained from published sources (see chapter 4, section 4.2). This will enable calculation of estimated total SOC distribution. The different soil types in this study have been classified as follows (Figure 3.6):

a) **Alun:** Fine loamy brown to dark brown sandy loam topsoil which merges into a yellowish brown or brown sandy loam subsurface horizon. Land use: Permanent grassland;meadow foxtail, perennial ryegrass, fescues, dandelions, buttercups, thistles, clover, and lay’s smoke.
b) **Conway**: silty alluvial gley soils with silty clay loam texture, some loamy alluvial gley soils in alluvium from slates and slaty shales, grey colour. Land use: permanent pasture.
c) **Crowdy 2**: Raw oligo-amorphous and some fibrous peat soils of variable depth with stagnohumic gley soils where the peat is thinner than 40 cm.

   Land use: Rough grazing on perennially waterlogged areas associated with Molinia and Sphagnum.

d) **Denbigh 1**: Typical brown earth, fine loamy over lithoskeletal mudstone and sandstone or slate. Land use: permanent grassland.

e) **Denbigh 2**: Typical brown earth, fine loamy over lithoskeletal mudstone and sandstone or slate. Land use: permanent grassland.

f) **Hafren**: Ferric stagnopodzols. Loamy over lithoskeletal mudstone and sandstone or slate. Land use and vegetation: Rough grazing with Nardus stricta and Agrostis sp.

g) **Hallsworth 1**: Typical brown earth, Coarse loamy over non-calcareous gravely. Land use and vegetation: permanent grassland with Lolium perenne.

h) **Hallsworth 2**: Typical brown earth, Coarse loamy over non-calcareous gravely. Land use and vegetation: permanent grassland with Lolium perenne.

i) **Halstow:** Clay loam plough layer over clay or silty clay, Impeded drainage. Land use: Permanent grass or long ley with occasional cereals are suitable crops or land use.

j) **Hexworthy**: Ironpan stagnopodzols. Loamy over lithoskeletal acid crystalline rock. Land use and vegetation: Coniferous woodland with lodgepole pine and some Sitka spruce.

k) **Laployd**: Humic gley soils, peaty or humose surface horizon, greyish, mottled Bg horizon, gravely loamy textures. Land use: Ash plantation, rough grazing; wet moorland of rush, purple moor-grass and tufted hair-grass with encroaching scrub.

l) **Larkbarrow:** Stony coarse loamy or loamy skeletal ferric podzols in reddish drift (Head) containing sandstone. Land use: Woodland or patches of heathy rough grazing, rocky in places.

m) **Malvern**: stony coarse loamy or loamy skeletal typical brown podzolic soils in drift (Head) from basic or intermediate igneous rocks (dolerite). Land use: Ley and permanent pasture and arable with some woodland on steep slopes.

n) **Manod:** Dark brown, slightly stony clay loam, fine loamy. This has solid or shattered rock within 80 cm depth and is a permeable clay loam with dark topsoil over ochreous subsoil, usually with granular structure. Land use: most of the unit is in grassland as permanent grass, leys, and rough grazings.

o) **Moor Gate**: Humic brown podzolic soils. Coarse loamy over lithoskeletal acid crystalline rock. Land use and vegetation: Unenclosed acid grassland with Bent, Fescue, and bracken.

p) **Moretonhampstead:** very dark brown to dark brown gritty humose sandy loam; slightly stony; moderate fine crumb structure; very friable; high organic matter;

abundant fine fibrous roots. Land use: Permanent grass, rough grazing, acidic grassland with bracken.

q) **Neath**: Typical brown earth, Fine loamy over lithoskeletal sandstone.
Land use: Coniferous wood land.

r) **Nordrach**: Reddish brown to yellowish red silt loam; slightly stony to stoneless with fine slate fragments and very occasional limestone as medium stones; friable; moderate organic matter; abundant roots. Land use: ley grass.

s) **Onecote:** with dark, humose topsoil, clayey cambic stagnohumic gley soil over shale or shale-derived Head. Surface horizons are humose or organic and often accompanied by grey, little mottled subsurface horizons which can be reduced to a thin discontinuous seam by ploughing. Land use: Onecote soils are usually found in Funcus-Molinia moorland and in neglected pastures with little or no cultivation often in places where drainage is especially difficult.

t) **Parc:** Dark humic brown podzolic soils on mudstone, humose topsoil about 25 cm thick over bright ochreous subsoil, passing to loose stony Head or deeply shattered rock. Shale and sandstone and including some similar fine silty soils. Land use and Vegetation: The vegetation, mainly of bent-fescue or bristle-agrostis grassland with patches of gorse and bracken provides rough grazing of very variable value.

u) **Princetown:** Very poorly drained coarse loamy cambic stagnohumic gley soils of the princetown series (abundant), Black amorphous peat, sometimes with a few bleached and grains; stoneless; moderate angular or subangular blocky structure; greasy consistenc when wet. Land use: Open moorland, wet grassland or heath.

v) **Powys:** Shallow soils, brown to dark brown clay loamy or silty clay loam, slightly stony with gravel to medium angular platy slate fragments; slate within 30 cm, fine loamy, moderate fine subangular blocky structure although structures can become weak when heavily stocked; friable consistenc.
Land use: Grassland with some arable.

w) **Sportsmans:** stony coarse loamy or loamy skeletal stagnogley soils with a few stagnopodzols and brown earths in drift (Head) from slates with slaty shales and sandstone s or from schistose rocks. Land use: Enclose from moorland and downland but now mostly ley pasture with some arable and permanent pasture.

x) **Teme:** Deep permeable fine silty typical brown alluvial and fine silty gley soils. Land use: permanent grassland; perennial ryegrass, meadow foxtail, buttercups, chickweed and cow parsley.

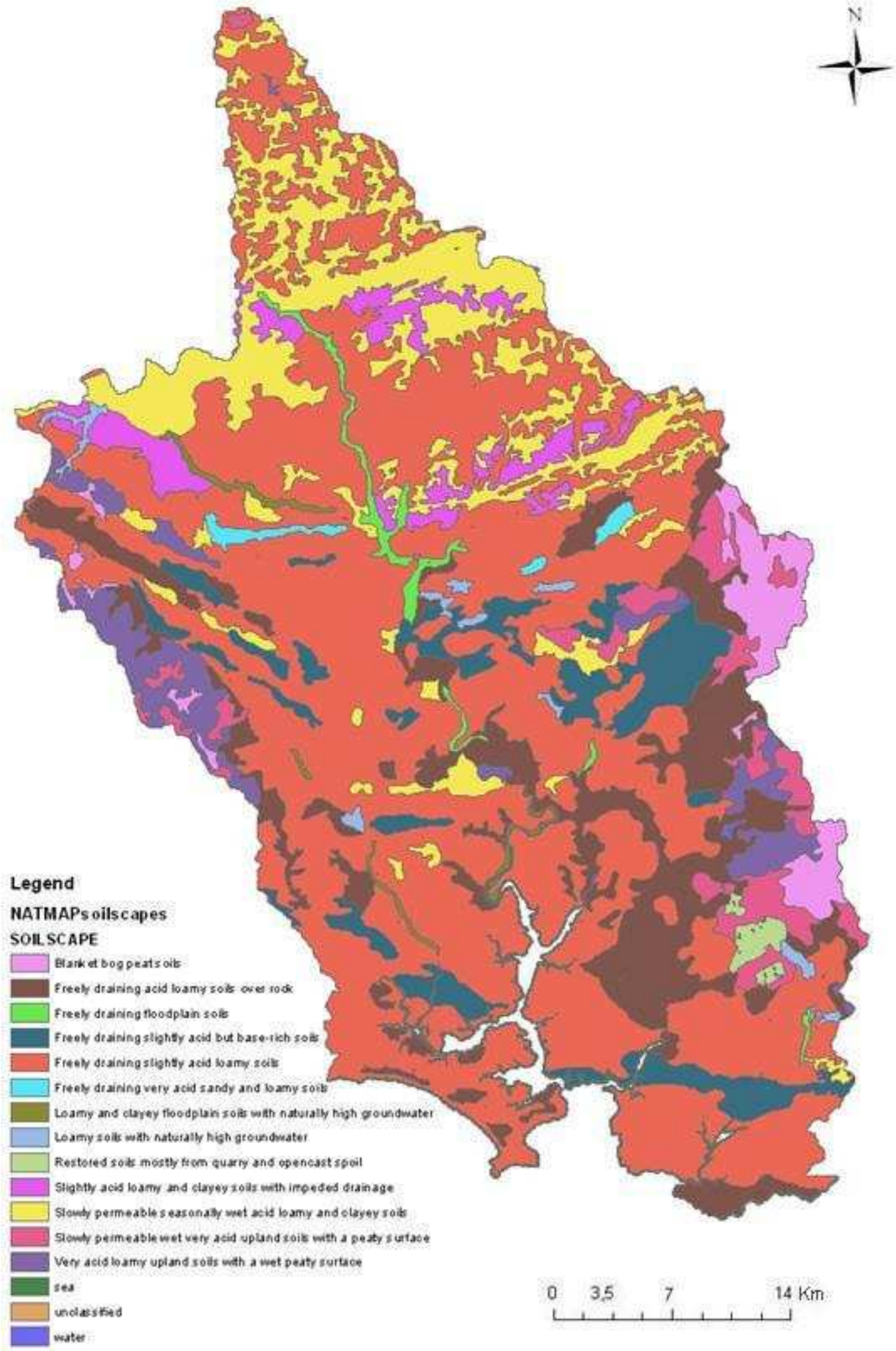
y) **Trusham:** Brown to dark brown gritty loam, stony, slightly stony with small angular mudstone fragments and dolerite corestones, moderately strong fine crumb structure, friable, moderate organic matter, abundant fsine grass roots. Land use: Permanent grass, ley grass, young plantation of Corsican pine occupying cleared mixed deciduous wood with some ash and sycamore saplings left standing, rich herbaceous and grassy field layer vegetation.

z) **Wilcocks 2**: Black, Stoneless humifield peat or humose clay loams.
Land use: Open moorland used for rough grazing, with a few reclaimed areas of permanent pasture. The semi-natural vegetation is mainly Molinia grassland.

aa) **Winter Hill**: Flat land; Black, semi-fibrous peat; moderate coarse platy structure. Land use: Perennially waterlogged blanket bog allows rough grazing in only the summer months.

bb) **Yeollandpark:** Stony fine loamy or fine silty cambic gley soils with occasional gleyic brown earths in slaty drift (Head) from slaty shales. Clay loam texture, fine blocky structure. Land use: permanent pasture, often rushy.

Figure 3.6: Map of the soils distribution at Tamar Valley Catchment.



3.2.4 Land cover Description in the Tamar Valley Catchment

Two sources of data on land use exist for the Tamar valley catchment; a survey by the British Geological Survey (1985) and the ITE land cover data in the GIS (ITE, 1984 and 1990). From the dominant land use types recorded at sample sites the relative proportions of the different land use types throughout the catchment during the BGS survey were: Pasture (46%), Deciduous forest (36%), Rough Grazing (10%), Arable (7%), with Heather Moor and Coniferous Forest forming the remainder (Figure 3.8). The dominant land use types (pasture and deciduous forest) and land cover appear to be distributed relatively evenly throughout the catchment (Figure 3.7, 3.8), whilst arable land appears to be most common in the north and west. The more complete ITE (1990) data will be used in the analysis in this study.

This is important to emphasise that the difference between figure 3.7 and 3.8 at Tamar Valley catchment is a result of including/excluding two of the river catchments that flow into Plymouth Sound (the Lynher and the Plym). In this study in fact the Tamar Valley catchment area are including these (sub-) catchments, but that other workers do not.

Figure 3.7: Land use recorded at Tamar valley catchment (British Geological Survey, 1985).

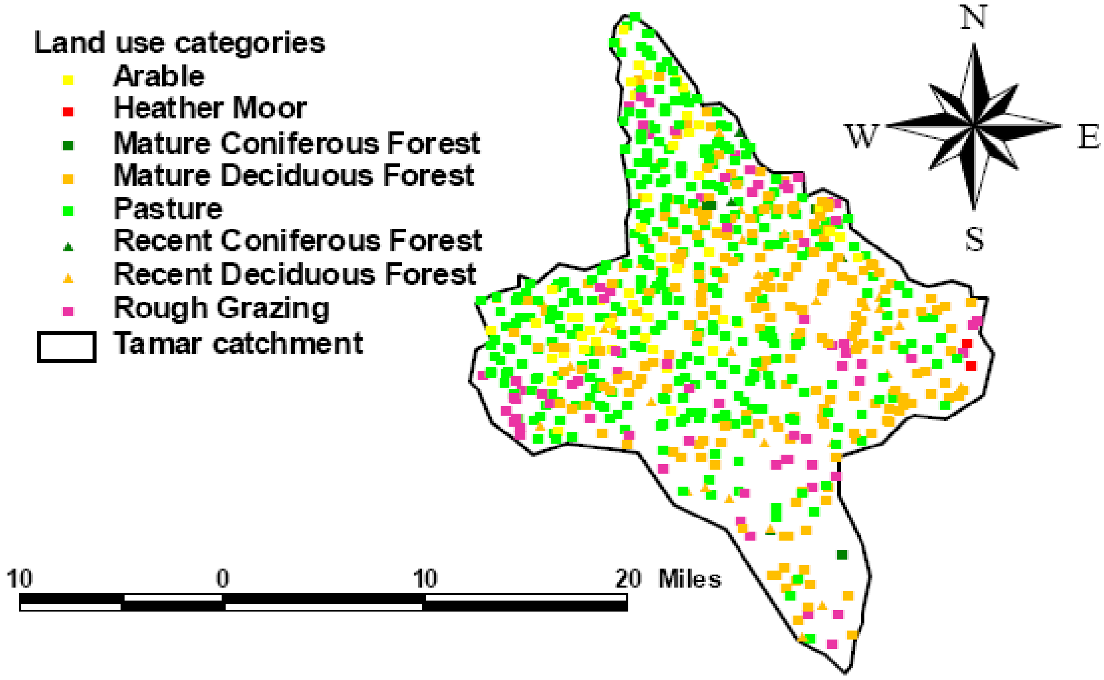
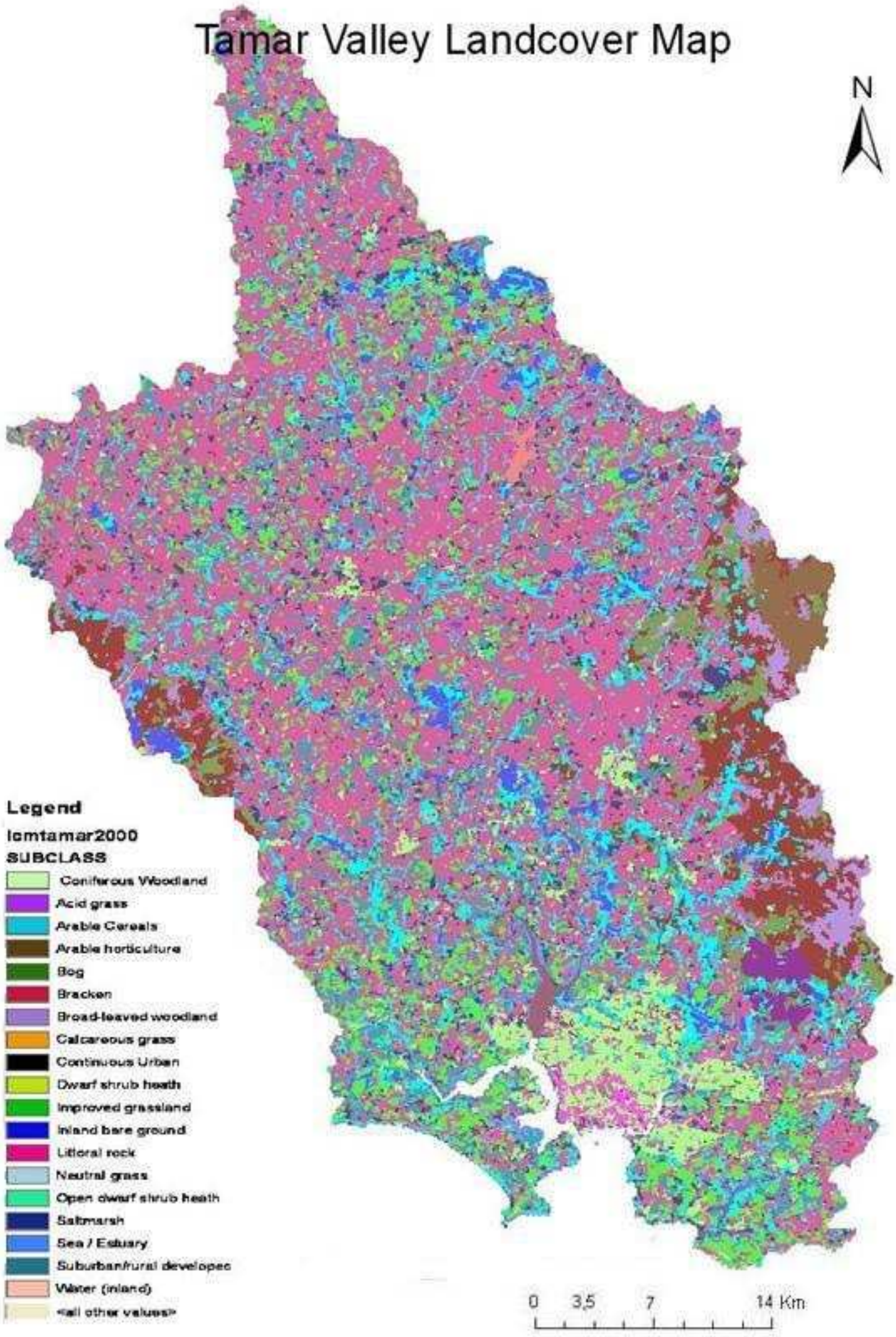


Figure 3.8: Tamar Valley Land Cover with Association Description (British Geological Survey, 1995).



Chapter 4:

Presentation of the Preliminary (Land Evaluation) Results 1

Chapter 4 Presentation of the preliminary (land evaluation) results 1

4.1 Introduction

Before generating and justifying specific land use scenarios, the solution for space and land evaluation should be identified, which is determined by the amount of carbon in biomass and soil (top soil and total soil); and energy and GHG emissions. This chapter presents data and findings from a GIS analysis of the 920 km^2 Tamar valley catchment in South-west England.

Section 4.2 of this chapter describes the total amount of carbon in top and total soils. Section 4.3 presents the amount of carbon in biomass and visualized maps with GIS. The emissions of energy and GHG are discussed in section 4.4. Land use suitability analysis is discussed in section 4.5. Finally, a summary of results is given in section 4.6.

4.2 Soil Carbon

4.2.1 Estimates of top-soil and total carbon

This study has estimated soil organic carbon (SOC) density (i.e. the amount t C ha^{-1} in a defined depth layer) in all soils in the Tamar Valley catchment. Organic carbon (OC) levels in the Ap horizon (top soil) and total soil layers are determined using published data on soil depth, bulk density and percentage of OC. To analyse topsoil carbon, the topsoil is considered as being the top 20cm of the soil profile.

These data relevant to bulk density, soils depth and percent of OC for each of these soil layers have been obtained from previous data of different sources such as (Book; soils and their use in Southwest England, see reference) and used to calculate an improved estimate of carbon in the Tamar valley catchment. The bulk densities, expressed as dry mass per unit volume, of the cores of different soil high levels. These data are shown on Table 4.1.

The database of analytical results from GIS includes determinations of SOC mass for depths up to 20 cm and total depth in the soil component and this provides a preliminary assessment of this information. This result has been calculated separately for topsoil and total soil depth. The topsoil is more vulnerable to management change such as ploughing and carbon storage and GHG and energy (direct and indirect) emissions.

This survey for separate calculation results for the topsoil and total soil depth has been based on published available data for all of the different soil types. The available useful different source which have been used include regional (Fisher et al., 1996); (Ragg et al., 1984); (Jarvis et al., 1984); (Rudeforth et al., 1984); (Hogan, 1975a); (Hogan, 1975b); (Hogan, 1977); (Hogan, 1978); (Hogan,1981); (Hogan,1982); (Palmer, 1982); (Clayden, 1971); (Curtis and Trudgill, 1976); and also some other place specific sources. These data which have been used for all calculation (Table 4.1), have required some minor calculation changes to convert it to top soil (20 cm), but for total soil calculations (up to 130 cm depth) the data have not been changed. Data for each soil type have where possible, used descriptions from the relevant area (the Southwest). The remaining few soil types have been selected from other areas. The data for this project case study is based, therefore, on the best available data in England. These data must be considered reliable as they are the only data could be used for this project methodology and work without undertaking extensive field and laboratory analysis which are beyond the scope of this project.

These values can be considered as the sum of the products of an area and a mean carbon density for each soil group. Results of the analysis from the GIS are presented as maps (Figures 4.1 and 4.2) and summary statistics are presented in a series of table (Table 4.2).

The total mass of carbon in top soils was calculated by summing the products of carbon density and total area for each soil type. The total top soils carbon mass stored in soil classes at Tamar Valley was estimated to be 2.45 Mt C (Table 4.2 and Figure 4.1) by adding the 29 soil types. **Neath** held 22.85 % (Maximum) and **Raw china clay spoil** held 0% and **Winter Hill** held 0.04% (Minimum) of the total top soil carbon in this area.

The total mass of carbon in soils was calculated by summing the product of carbon density and total area for each soil type. The total soils carbon mass stored in soils classes in the Tamar Valley was estimated to be 5.32 Mt C in (Table 4.2 and Figure 4.2) by adding the value for all 29 soil types. **Crowdy 2** held 8.02 % (Maximum) of the total soil carbon and **Raw china clay spoil** held 0% and **Onecote** is held 0.04% (Minimum) total soil carbon at this area. Figure 4.2 provides total soils carbon raster map per 625 m^2.The 625 m^2 has been calculated as the pixels are 25m x 25m (the scale of the biomass dataset, which has been used to calculate vegetation carbon) in raster version to provide the future work for monitoring the combinations of different soil type with different land cover type on the same resolution unit.

The total SOC mass which has been quantified for **top soils** is 2.45 Mt C and 5.32 Mt C for the total soil depth (Table 4.2). These values are the sum of the products of an area and a mean carbon density for each soil type. Existing soil databases have proven to be a valuable data source in calculating estimates for size and distribution of carbon pools in soil types for the Tamar valley catchment, but there may be considerable uncertainties associated with the soil carbon data from published sources. And this is discussed further in chapter 5 (sensitivity analysis). Figures 4.1 and 4.2 show the distribution of carbon in top soils and total soils for the study area.

Table 4.1: Data relevant to bulk density, soil depth and percent of organic carbon amount for each specific soil layer in Tamar Valley catchment (Source: Author).

Soils Types	Depth upper	Depth lower	Bulk density gcm^{-3}	% organic Carbon	Carbon Density ($t\ ha^{-1}$)
Neath	0	23	0.5	27.5	31.63
	23	46	1.25	1.7	4.89
	46	100	1.45	1	7.83
					44.34
Hallsworth1	0	19	1.2	5.3	12.09
	19	44	1.4	2.1	7.35
	44	100	1.4	0.8	6.28
					25.71
Hallsworth2	0	19	1.2	5.3	12.09
	19	44	1.4	2.1	7.35
	44	100	1.4	0.8	6.28
					25.71
Denbigh 1	0	22	1.15	4.4	11.14
	22	40	1.25	2.4	5.4
	40	100	1.2	2.4	17.28
					33.81
Denbigh 2	0	22	1.15	4.4	11.14
	22	40	1.25	2.4	5.4
	40	100	1.2	2.4	17.28
					33.81
Parc	0	25	1.5	1.3	4.88
	25	50	1.45	1.2	4.35
	50	100	3	0.8	12
					21.23
Hafren	0	24	1.15	9.9	27.33
	24	47	1.2	1.3	3.59
	47	54	1.1	1.1	0.85
					31.76
Moor Gate	0	25	0.5	17.05	21.32
	25	50	1.25	2.55	7.97
	50	120	1.15	1.1	8.86
					38.14
Winter Hill	0	25	1.3	2	6.5
	25	42	1.05	0.8	1.43
	42	63	2.3	0.8	3.87
					11.8
Hexworthy	0	22	1.1	1.68	4.07
	22	50	1.25	1.7	5.95
	50	87	2.8	2.5	25.9
					35.92
Wilcocks 2	0	24	1.25	5.4	16.2
	24	47	1.3	3.75	11.22
	47	74	1.35	3.5	12.76
					40.17
Powys	0	18	0.95	6.5	11.12
	18	38	2.9	1.7	9.86
	38	102	2.5	0.2	3.2
					24.18

Nordrach	0	25	1.15	4.2	12.08
	25	50	1.25	1.6	5
	50	85	1.35	1.9	8.98
					26.06
Moretonhamp-stead	0	25	1.1	3	8.25
	25	45	1.4	7	19.6
	45	58	1.12	9	13.11
					40.96
Trusham Trusham	0	25	1.15	3.2	9.2
	25	45	1.2	1.8	4.32
	45	120	1.25	1.1	10.32
					23.83
Larkbarrow	0	25	1.1	2.83	7.79
	25	50	1	4.5	11.25
	50	77	0.8	1.1	2.38
					21.41
Raw China Clay Spoil	0	0	0	0	**0**
Princetown	0	25	0.5	3.1	10
	25	50	0.5	2.9	9.30
	50	120	1.3	1.1	2.20
					21.50
Yeollandpark	0	22	1.3	5.3	15.16
	22	50	1.15	0.8	2.58
	50	63	1	0.5	0.65
					18.39
Sportsmans	0	22	1.15	4.3	10.88
	22	33	1.1	1.45	1.76
	33	90	1	1.15	6.56
					19.19
Halstow	0	21	1.16	3.6	8.77
	21	54	0.8	1	2.64
	54	130	0.82	0.6	3.74
					15.15
Crowdy 2	0	20	0.2	37	14.8
	20	45	0.2	39	19.5
	45	70	0.2	39	19.5
	70	100	0.2	56	33.6
					87.4
Conway	0	20	1.21	11.33	27.42
	20	65	1.3	3.57	20.89
	65	91	1.1	10.8	30.89
					79.19
Malvern	0	30	1.17	4.8	16.85
	30	44	1	0.85	1.19
	44	77	0.8	1.1	2.91
					20.94
Onecote	0	17	1.27	5.6	12.09
	17	68	1.1	0.5	2.81
	68	92	1	1.12	2.69
					17.59
Laployd	0	23	0.5	35.4	40.71
	23	56	0.75	15	37.16
	56	71	1	2.4	3.6
					81.44
Teme	0	20	1.23	2	4.92
	20	66	1.2	1.7	9.39
	66	130	1.25	1.5	12
					26.31
Manod	0	20	1.05	5.4	11.34
	20	39	2.08	2.05	8.11
	39	95	1.85	1.3	13.47
					32.91
Alun	0	20	1.02	3.1	6.33
	20	86	2.68	0.9	15.92
	86	127	1.6	1.1	7.22
					29.46

Table 4.2: Soil carbon density (t ha^{-1}) and total carbon amount in Tamar valley catchment in top soils (top 20 cm) and total soils (up to 130cm).

Soils Types	Depth (0-20 cm) in top soil	Depth (0-130 cm) in total soil	Area (ha)	Density of C (t ha^{-1}) in top soil	Density of C (t ha^{-1}) in total soil	Total Carbon (t) in top soil	Total Carbon (t) in total soil
Neath	**0-20**	**0-100**	**20,311**	**27.5**	**44.34**	**558,553**	**900,184**
Hallsworth 1	**0-20**	**0-100**	**13,895**	**12.7**	**25.71**	**176,467**	**357,241**
Hallsworth 2	**0-20**	**0-100**	**6,450**	**12.7**	**25.71**	**81,915**	**165,830**
Denbigh 2	**0-20**	**0-100**	**11,499**	**10.2**	**33.81**	**117,290**	**388,782**
Denbigh 1	**0-20**	**0-100**	**67,774**	**10.2**	**33.81**	**691,295**	**2,291,439**
Parc	**0-20**	**0-100**	**801**	**3.9**	**21.23**	**3,124**	**17,005**
Hafren	**0-20**	**0-54**	**1,739**	**22.8**	**31.76**	**39,649**	**55,231**
Moor Gate	**0-20**	**0-120**	**3,085**	**17.1**	**38.14**	**52,754**	**117,662**
Winter Hill	**0-20**	**0-63**	**200**	**5.2**	**11.8**	**1,040**	**2,360**
Hexworthy	**0-20**	**0-87**	**4,892**	**3.7**	**35.92**	**18,101**	**175,721**
Wilcocks 2	**0-20**	**0-74**	**1,265**	**13.5**	**40.17**	**17,078**	**50,815**
Powys	**0-20**	**0-102**	**1,950**	**12.3**	**24.18**	**23,985**	**47,151**
Yeollandpark	**0-20**	**0-63**	**1,232**	**13.8**	**18.39**	**17,002**	**22,657**
Princetown	**0-20**	**0-120**	**4,708**	**43**	**21.5**	**202,444**	**101,222**
Larkbarrow	**0-20**	**0-77**	**914**	**6.3**	**21.41**	**5,758**	**19,569**
Trusham	**0-20**	**0-120**	**10,309**	**7.4**	**23.83**	**76,287**	**245,664**
Laployd	**0-20**	**0-71**	**129**	**35.4**	**81.44**	**4,567**	**10,506**
Nordrach	**0-20**	**0-85**	**951**	**9.7**	**26.06**	**9,228**	**24,783**
Moretonhampstead	**0-20**	**0-58**	**2,656**	**6.6**	**40.96**	**17,530**	**108,790**
Raw china clay spoil	**0-20**	**0**	**872**	**0**	**0**	**0**	**0**
Onecote	**0-20**	**0-92**	**119**	**14.3**	**17.59**	**1,702**	**2,093**
Sportsmans	**0-20**	**0-90**	**2,723**	**9.9**	**19.19**	**26,958**	**52,255**
Halstow	**0-20**	**0-130**	**5,785**	**8.4**	**15.15**	**48,594**	**87,643**
Teme	**0-20**	**0-127**	**1,486**	**4.9**	**26.31**	**7,282**	**39,097**
Conway	**0-20**	**0-91**	**903**	**27.5**	**79.19**	**24,833**	**71,509**
Malvern	**0-20**	**0-77**	**1,566**	**11.3**	**20.94**	**17,696**	**32,792**
Manod	**0-20**	**0-95**	**11,449**	**11.4**	**32.91**	**130,519**	**376,787**
Alun	**0-20**	**0-127**	**165**	**6.4**	**29.46**	**1,056**	**4,861**
Crowdy 2	**0-20**	**0-100**	**4,878**	**14.8**	**87.4**	**72,195**	**426,337**
Total			**184,706**			**2,444,892**	**5,316,153**

Table 4.1 presents the amount of carbon in different layer of soils in top and total soils. Taking into account the bulk density and percent of organic carbon in different soils layer, the amount of carbon density (t ha^{-1}) has been calculated in the Tamar Valley catchment.

Figure 4.1: Tamar Valley Catchment Top Soils Carbon Density (t ha^{-1}) Map.

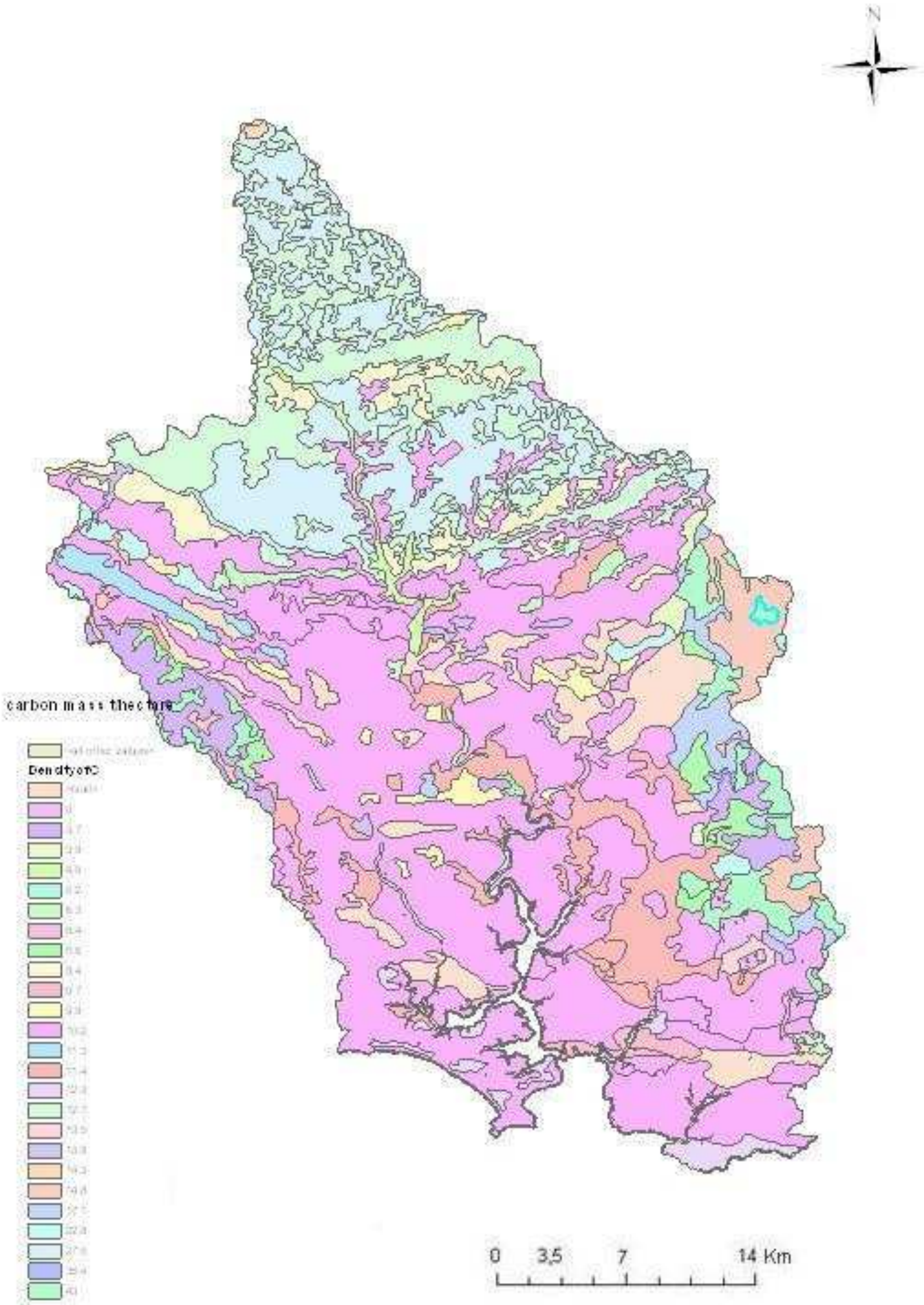
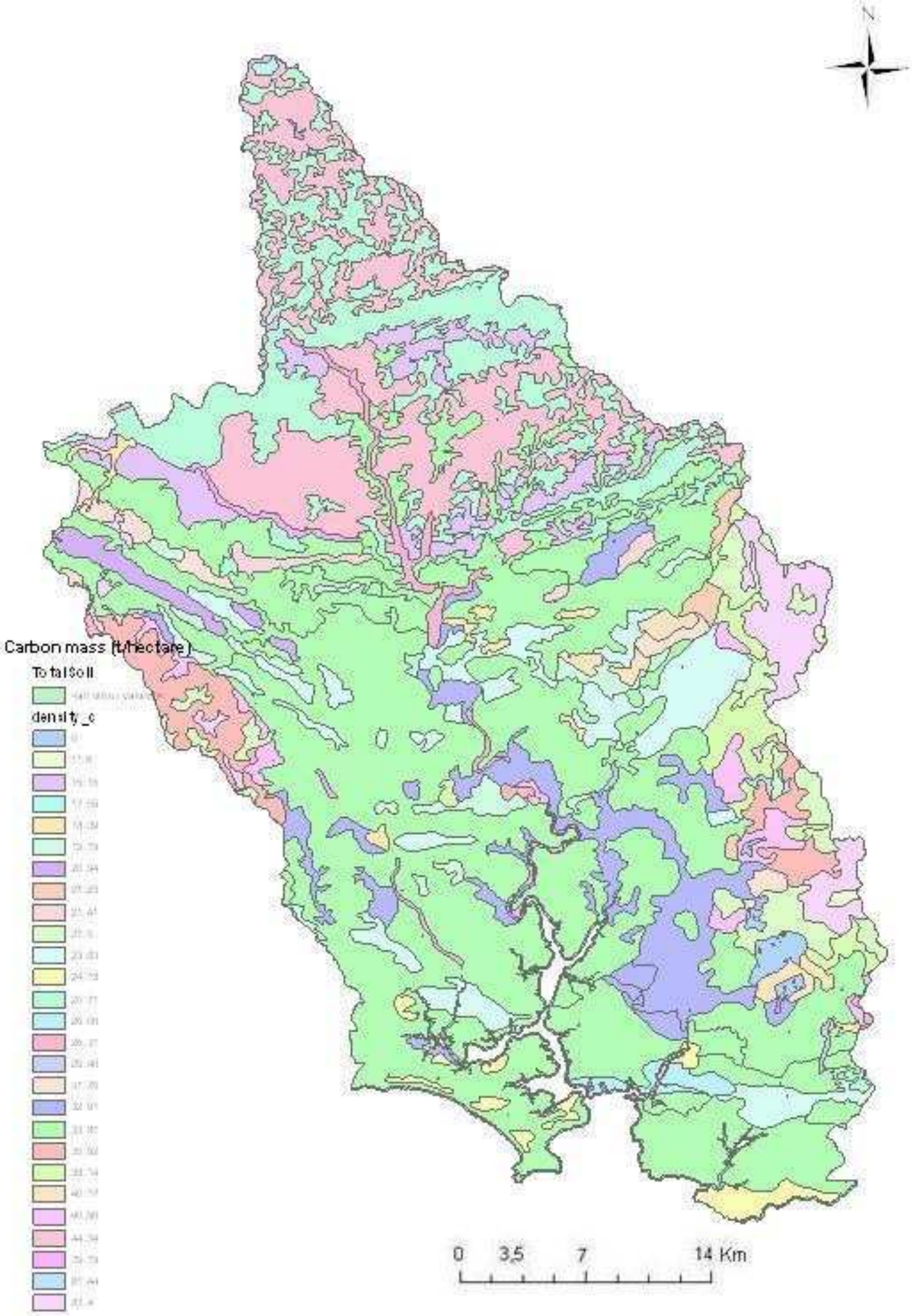


Figure 4.2: Tamar Valley Catchment Total Soils Carbon Density (t ha^{-1}) Map.



Figures 4.1 and 4.2 show the amount of total carbon density (t ha^{-1}) in top and total soils with GIS model in Tamar valley catchments. The maximum area is covered by Neath soil type in this area. Total amount of carbon (t ha^{-1}) in soils which have been converted to 625 m^2 to raster version in GIS is to allow integration of biomass and soils carbon in the Tamar Valley catchment.

4.3 Estimates of Carbon in Vegetation

In support of the UK's commitment under the Framework Convention on Climate Change, researchers have been developing an inventory of carbon in the vegetation and soils of Great Britain (Milne and Brown, 1997). Forests and other vegetation are an important part of the sink of carbon and changes in size and productivity of the sink may act as a sink or source for carbon dioxide. The total amount of carbon held by vegetation in Great Britain is estimated to be 114 M tonnes (Milne and Brown, 1997).

In the site study, the carbon store in the forest and non-forest vegetation of the Tamar Valley was estimated by combining published studies of biomass carbon densities (Milne and Brown, 1997) and the land classification data and digital map of land cover for the region using GIS model (Tables 4.3 and 4.4).

Table 4.3: Total carbon density (t ha^{-1}) for vegetation (Milne and Brown, 1997).

Cover Type	**Vegetation carbon density** (t ha^{-1})
Cereal	1
Crops	1
Pasture, etc.	1
Fallow	0
Horticulture	1
Unimproved grass	1
Shrub	2
Heath	2
Bogs, etc.	2
Maritime	2
Broadleaf	(See Table 4.4) 55.32
Conifer woodland	(See Table 4.4) 21.83
Mixed woodland	(See Table 4.4) 38.57
Non-vegetated	0

Table 4.4: Average carbon density (t ha^{-1}) of woodlands in each I.T.E (Institute of Terrestrial Ecology) land class of G.B. (Milne and Brown, 1997).

I.T.E. Land Class	Conifers (t ha^{-1})	Broadleaves (t ha^{-1})	Mixed woodland (t ha^{-1})	Mixed combined with broadleaves (t ha^{-1})
1	28.2	61.7	51.1	60.2
2	27.9	55.8	52.3	55.4
3	27.5	60.6	57.9	60.3
4	28.8	55.9	55.3	55.9
5	33.8	60.0	50.3	57.4
6	24.5	56.5	39.5	55.3
7	17.7	32.3	20.9	28.9
8	21.1	46.3	46.3	46.3
9	29.3	65.5	58.9	64.8
10	21.9	59.8	46.9	58.3
11	29.1	64.7	53.0	59.3
12	0.0	50.5	50.5	50.5
13	23.0	54.3	29.4	45.4
14	0.0	35.4	35.4	35.4
15	24.0	53.9	52.5	53.9
16	20.9	62.1	59.7	62.0
17	19.8	57.4	42.7	54.3
18	21.1	57.6	34.6	49.4
19	22.3	58.9	23.0	33.2
20	25.9	57.4	30.7	37.4
21	23.8	52.3	26.9	38.4
22	17.9	55.2	19.6	49.5
23	21.7	61.9	21.7	21.7
24	20.6	57.9	27.4	34.0
25	24.3	48.6	33.5	44.2
26	19.5	55.6	25.9	33.2
27	21.3	56.7	40.9	48.4
28	19.7	57.3	21.4	42.0
29	18.6	52.3	43.4	51.8
30	12.2	59.3	12.4	29.5
31	32.1	51.6	43.7	51.6
32	20.2	54.8	28.9	34.1
Mean	**21.83**	**55.32**	**38.57**	**46.89**

The I.T.E (Institute of Terrestrial Ecology) Countryside Surveys of 1984 and 1990 of land use in Great Britain were stratified by using a land classification system developed. This allocates each 1 km x 1 km square in G.B. to one of 32 land classes on the basis of combinations of environmental data which are already in mapped form, such as geology, climate and topography (Barr et al., 1993). It is therefore how the average of carbon amount has been calculated and estimated in different land uses in Great Britain.

Table 4.5 and Figure 4.3 show the land cover carbon density. Carbon storage in vegetation has been calculated by multiplying the area each of land cover types within the study site (Tamar Valley) by estimates for their carbon density. The total mass of carbon in vegetation on land was calculated by summing the products of carbon density and total area for each cover type.

Total mass of carbon in the vegetation of Tamar Valley was estimated to be **1.24** Mt (Table 4.5) by adding the land class totals. Woodlands (Broad-leaved and Coniferous) mainly dominated the vegetation classes and held 87.9% of this land cover. Broadleaf woodland accounted for 79.8% and conifer woodlands 8.1% of the total Tamar valley catchment carbon.

Table 4.5 also presents values of aboveground biomass and carbon content for each vegetation class represented in the study area. The value of **1.24** Mt for vegetation carbon is based on the I.T.E. land classification estimate of the total pool size in the GIS model. Figure 4.3 shows a geographical distribution of the average vegetation carbon density of the land classes for each 625 m^2 (25m x 25m) for Tamar Valley catchment.

Table 4.5: Land cover carbon density (t ha^{-1}) in Tamar valley catchment. The land cover types are matched with the cover types of Milne and Brown, (1997).

Land cover Type (GIS)	Cover Type (Milne and Brown,1995)	Vegetation Carbon Density (t ha^{-1})	Land Cover Area (ha)	Total Land Cover Carbon Mass (t)
Broad-leaved woodland	Broadleaf	55.32	17,840	986,909
Coniferous woodland	Conifer woodland	21.83	4,570	99,763
Arable Cereals	Crops	1	20,440	20,440
Arable horticulture	Crops	1	17,220	17,220
Improved grassland	Unimproved grass	1	80,790	80,790
Neutral grass	Unimproved grass	1	4,050	4,050
Calcareous grass	Unimproved grass	1	8,060	8,060
Acid grass	Unimproved grass	1	10,260	10,260
Bracken	Heath	2	1	2
Dwarf shrub heath	Heath	2	280	560
Open dwarf shrub heath	Heath	2	2,860	5,720
Inland bare ground	-	0	440	0
Bog	Bogs. etc	2	1,670	3,340
Suburban/rural development	-	0.05	9,640	482
Salt marsh	Maritime	2	120	240
Continuous urban	-	0	2,380	0
Littoral rock	-	0	850	0
Total			**181,471**	**1,237,836**

Figure 4.3: Land Cover Carbon Density (t ha^{-1}) for the Tamar valley catchment expressed as t C per 625 m^2.

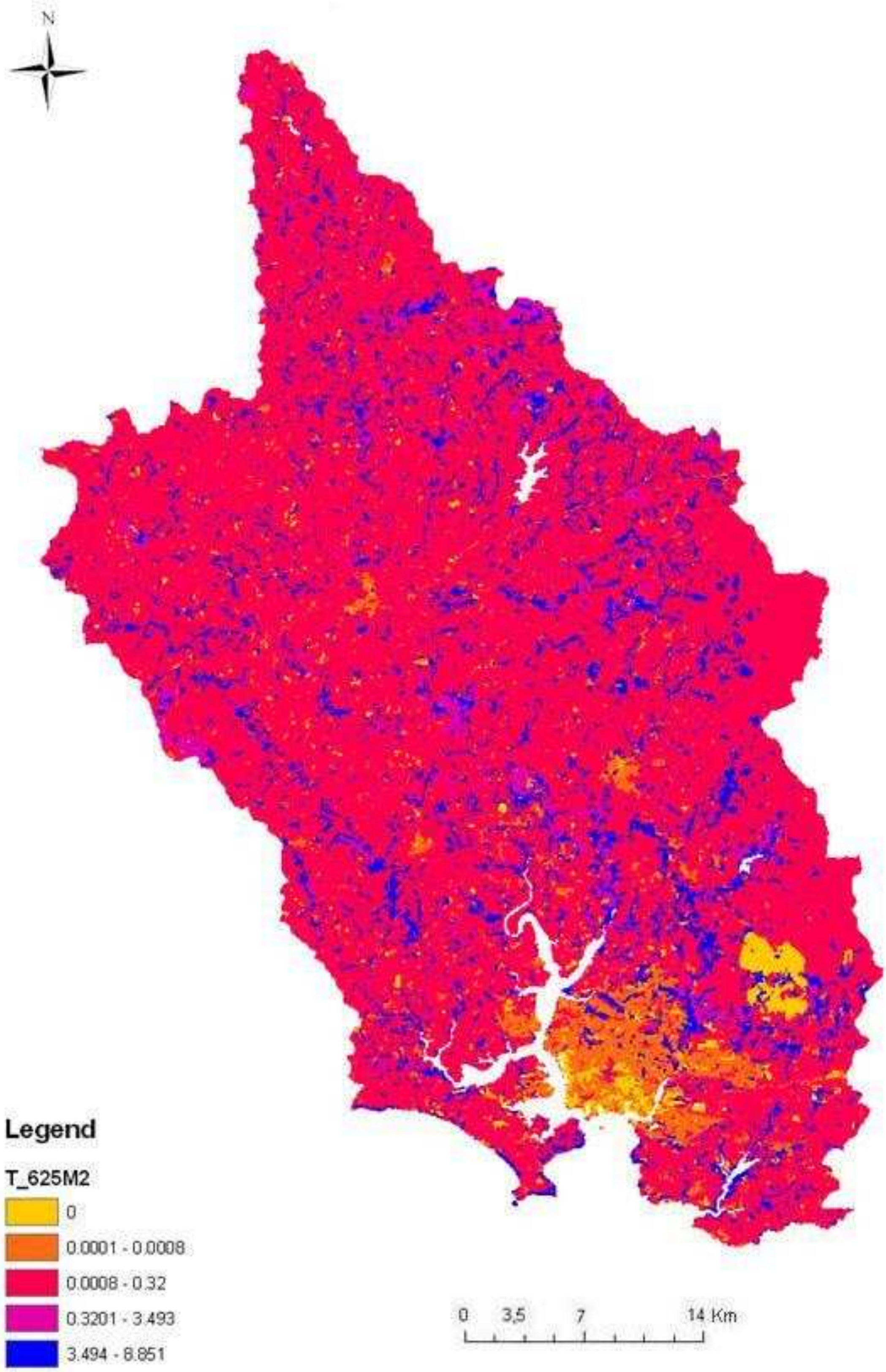
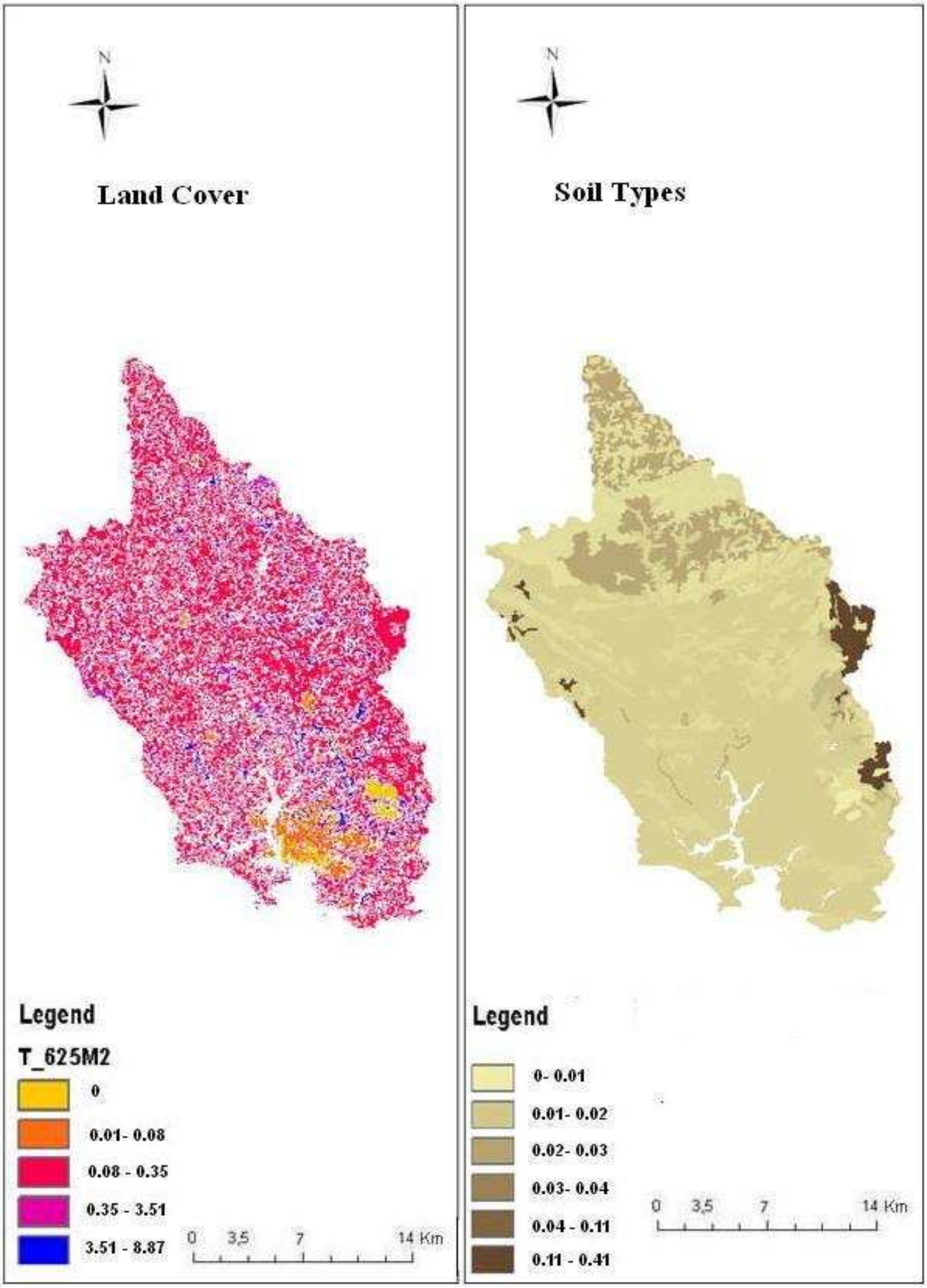


Figure 4.4: Comparison of Carbon amount in Land Cover type and Total Soil Types in Raster expressed as t C per 625 m^2.



4.3.1 Total soil and vegetation carbon

The dominant vegetation cover in each 625 m^2 (25m x 25m) of Tamar valley catchment was estimated using the land cover classes of Landsat satellite-derived I.T.E. land cover map of the study site by determining the area of different vegetation and soils types in each 625 m^2 (Figure 4.4). This land cover class were grouped into 17 dominant vegetation types using equivalencies with the cover types used in the previous estimates based on the I.T.E. land class (Milne and Brown, 1997). Figure 4.3 shows description of the geographical distribution of vegetation at Tamar Valley catchment (t ha^{-1}) and Figure 4.4 compares the total carbon amount (t $625m^{-2}$) in land cover type and soils comparison.

The database of soils series is as used previously. As shown in earlier sections of this chapter, the soils series and vegetation had already been assigned carbon content in the original work. The carbon content of the required (top and total) soil series / vegetation combinations were estimated by combining values in the existing database, using the following rules:

a) Soil under woodlands will have the most carbon content.
b) Where the land cover map indicates no vegetation, a soil carbon value of zero is used.
c) Where the soil database indicates that soil is present but the land cover map disagrees, and then the soil carbon value is used.
d) Where the land cover is water and rock, then zero carbon is assumed, thus carbon in sediments is not included, and then the soil carbon value is used.

The resulting values of top and total soil types and vegetation carbon are provided in Table 4.6. The total size of the top soil and total soil carbon pool combination with land cover for Tamar valley catchment are **3.69 Mt** and **6.56 Mt** respectively**.** In biomass, woodlands hold most of this total. In turn, woodland soils have most amount of carbon. The highest soil carbon amount is in east edge of Tamar valley catchment (Figure 4.4).

Table 4.6: Total amount of carbon (t ha^{-1}) in vegetation with top soils and total soils combination of Tamar valley catchment.

	Top Soil and vegetation (Mt)	**Total Soil and vegetation (Mt)**
Land Cover (Mt)	**3.69**	**6.56**

4.4 Estimating greenhouse gases (GHG) emissions from different land use types

Agricultural land and other vegetation types are an important part of greenhouse gases emissions. Changes in the size and productivity of the sink may act as an enhanced sink or a source for carbon dioxide and other GHG gases. For example, both nitrous oxide and methane emissions are affected by manure addition to agricultural land. The total amount of greenhouse gas emissions has been quantified for the Tamar Valley catchment based on estimates of the maximum and minimum amount of GHG emissions and the associated direct and indirect energy use from different land uses, using published data, particularly that of King et al., (2004) and references therein. Direct and indirect energy use for agriculture is the energy from machinery, fertiliser, pesticides and road transport. Direct energy costs are easy to identify and analyse as they are the fuel oils and electricity (used for machinery), gas, etc. Indirect energy for farm machinery comprises numerous costs; manufacturing energy, energy for repair and maintenance delivery and storage are the main items of indirect energy. For example, delivery includes the energy for transport from the factory to the farm either directly or indirectly via a dealer. This operation happens once in the lifetime of a machine and Larsen et al. (1972) reported the energy cost to be 8.8 MJ/kg. Indirect energy is also relatively easy to identify but more difficult to analyse. Direct GHG emissions, for example N_2O emissions from agriculture are assumed to be derived from principal sources (IPCC, 1997), such as direct emissions from soil nitrogen (N), denoted here are as ‘soil’, e.g. applied fertilisers in both manures and artificial (chemically fixed N) forms, N deposited by grazing animals, mineralization of crop residues, biological N fixation and the cultivation of high organic content soils. Indirect emissions are those such as from N lost to the agricultural system, e.g. through leaching, runoff or atmospheric deposition.

This approach is similar to that in Appendix 1 in the IPCC (1997), which suggests default methods for estimating emissions. It combines estimates of GHG emissions and uncertainty from agriculture and land use from published sources, (See Table 4.7, Tolonen and Turunen 1996; Kasimir et al., 1997; Kramer et al., 1999; Cormack, 2000; Bullard et al., 2001; Paul et al., 2002; Smith et al., 2000b; King et al., 2004) and the digital map of land cover on (GIS) resources (Tables 4.8 and 4.9).

The details and assumptions of the methodology are referred to below. King et al., (2002, 2004) published estimates of changes arising from changes in land use. Although King et al., (2004) did not publish their detailed methodology, John King (personal communication) and

King et al., (2004) have provided further details on which to base the estimates of greenhouse gas emissions from land use in the Tamar Valley catchment.

These values for direct and indirect energy with greenhouse gas emission were derived from those reports (See above) in the literature and simply summed to obtain a value for each hectare and each land type. The summation of the components was carried out as part of the GIS process. These were designed to give details for each land type, and show how this value would be applied across each rotation for each land use types. This saving rates (and ranges) per unit area are given by each land use type (Table 4.7). In considering all these land use and management changes, it has been assumed that they are made to land that is currently in normal productive agriculture as arable farms.

The total amount of GHG emission and direct and indirect energy on different land in each land class was calculated by summing the amounts and converting this total GHG emission to the CO_2 equivalent and finally to C equivalent value to saving made by changes in the other greenhouse gases was rated between this amount, which depending on different land and total area for each cover type. Direct and indirect energy for each hectare has been calculated by determining the area of different land types in each hectare (Table 4.7).

It is important to convert all the values like GHG emissions and direct and indirect energy values to C-CO_2 equivalent, as:

a) In this research, the focus is on carbon in soil and biomass, and these amounts are calculated using C conversion to C-CO_2 equivalent makes easy comparison of all data and future land data analysis.
b) It is important to standardise emissions between the different GHG (CO_2,, CH_4, N_2O). The IPCC Second Assessment Report (1995), used for reporting under the UNFCCC, states the global warming potential for next 100 years time is: carbon dioxide (CO_2) is 1, Methane is 21 and Nitrous oxide is 310. Meaning that the Methane and Nitrous oxide is 21 and 310 times worse than carbon dioxide respectively.

So, to convert the Methane to C-CO_2 equivalent, value should multiplied by **5.73**, and Nitrous Oxide value should be multiplied by **84.55** (IPCC rate). Also for converting the direct and indirect energy, the energy value should be multiplied by **0.074** CO_2-C equivalents and then convert to C-CO_2 equivalent should multiple in **12** (C atomic mass) and divided by **44** (CO_2 atomic mass), the final value all are based on C equivalent. For example the direct energy used in grassland is 10602 MJ, to convert this amount to C equivalent the calculation as:

10602 MJ x 0.074 = 785 CO_2 equivalent, and then convert to C equivalent:

785 x 12 = 9420 / 44 = 214 Kg C per hectare per year.

For each land use type, different figures are derived. Woodland type GHG emissions were **Zero** (King et al., 2002 and 2004)**,** so with this assumption, for arable land and conversion of arable to permanent woodland (because woodland figures assumed to be zero),overall combined energy savings would be of the order of that expended in general arable production, or 21 068 MJ ha-1 (Cormack, 2000) which is **425 kg ha^{-1} a^{-1} C**, If the land used was taken out of cereal production , direct energy savings would also be made at the rate of 76 kg ha^{-1}, and an indirect energy saving on fertiliser use of 196 kg ha^{-1} C, by saving 200 kg ha^{-1} N at 0.98 kg kg^{-1} C for N.

Current approval each year for change of agricultural land to woodland under the "Farm Woodland Premium Scheme" for the England Rural Development Plan is about 4000 ha, of which 90 % is actually planted and about 56% of this on arable land. For the whole of England the current annual carbon sequestration and saving from this change in land use is of the order of **7.6 kt C**. The UK is one of the least afforested countries in Europe, with about 9% of its area under permanent woodland. If this was increased to 15% (average for Europe) then an extra 6 % of the area of the UK has to be made available or 11% of the agricultural land area. Adopting the methodology of the Intergovernmental Panel on Climate Change (IPCC, 1997), contributions that give increase to N_2O that might affect total emissions include: fertiliser-N, residue-N and sources of indirect emissions (N leached and N deposited). Differences in N fertiliser applied to woody biomass **(zero)** and arable (100-200 kg/ha) crops are large but this was included by Smith et al. (2000b). However, in our calculations, it is assumed that 11% of all arable land (not simply set-aside land) is converted to woody biomass. We have assumed that this proportion is applied to each and every assumed rotation. The reduction in residue N returns to the soil was estimated to be 50% of the fertiliser-N reduction; this was based on the relationship between fertiliser N and crop residue N for UK arable agriculture using the IPCC methodology (Harrison, 1996, pers. comm.). In general the contribution to carbon sequestration and saving made by changes in the emissions of other greenhouse gases was rated at between **327** and **609 kg ha^{-1} a^{-1} C** depending on soil type and regions.

For **grassland**, with British climate condition; conversion to permanent woodland (trees or plants), when grassland is planted to trees, takes a long time. Based on that, the cover between trees is still going to be largely grass based. Equally neither do we expect an increase in net organic returns to the soil, which is the case when arable land is planted, so we have considered this change in land use to be broadly neutral as far as soil carbon sequestration is concerned. However, there will be attendant saving in direct and non direct energy use, though smaller than those for a conversion from arable land if extensively managed beef or sheep are the livestock, but more if the grassland is attached to a dairy enterprise. Direct energy savings would also be made at the rate of 75 kg ha^{-1} if the land used was taken out of silage production from the absence of cutting and baling (about 1240 MJ ha^{-1} for each cut and three cuts a year), direct energy savings would also be made at the rate of 75 kg ha^{-1}, and an indirect energy saving on fertiliser use of 294 kg ha^{-1} C, by saving 300 kg ha^{-1} N at 0.98 kg kg^{-1} C for N. In general combined energy savings would be of the order of that expended in general dairy production, or 97 279 MJ ha^{-1} a^{-1} (Cormack, 2000) which is **1963 kg ha^{-1} a^{-1} C**. However, only 891 MJ ha^{-1} a^{-1} (Cormack, 2000) which is **18 kg ha^{-1} a^{-1} C** would be saved from an upland beef or sheep farm (**Heath**). To these figures can be added the carbon in the accumulated standing biomass, which is modelled as a mean of all types of woodland, both coniferous plantation and natural broadleaf. Annual increase in carbon in woody biomass and litter products is taken to be **2.8 t ha^{-1}** by universal figure (IPCC) and from Narbuurs and Mohren (1993) up to a maximum of 48.5 t ha^{-1} at maturity which is taken as being after 20 years (Bullard et al., 2001). Exchange to woody crops (nil fertiliser-N) was assumed to be from dairy production with a storing rate of 2 cows per forage hectare and fertiliser N application of 300 kg ha^{-1}.The carbon saving and sequestration equivalent due to other greenhouse gases was **2354 kg ha^{-1} a^{-1} C**.

More sophisticated approaches could be employed (e.g. using lower figures for unimproved grassland and improved grassland) than that used here, but this research seeks to illustrate the general approach and methodology for all greenhouse gas emissions. For grassland, it would be necessary to map and use the different type of grassland which occur, including for example dairy farming, organic farming; this level of detail is not available, so all types are included in grassland. For that the minimum energy emission which is 10602 MJ has been converted to CO_2 equivalent and then C equivalent. The reason to convert to CO_2 equivalent, has been based on universal IPCC is for proportion of the GHG to CO_2. So this project base is on carbon amount in soil and biomass, and for unit equality the entire amount should be converting to C equivalent. So here for grassland the minimum energy amount after all this calculation, was **214 kg ha^{-1} a^{-1} C.**

For the maximum amount, the carbon saving and sequestration equivalent due to other greenhouse gases was **2354 kg ha^{-1} a^{-1} C**, by Cormack (2000) and King et al., (2002 and 2004) the energy flows in organic and conventional agricultural systems analysed include a comparison for conventional and organic dairy systems, which would be the most common use of managed grassland included in this study. This report cites a general energy use (direct and indirect) of 97 279 MJ ha^{-1} in a conventional dairy enterprise, which contrasts with a calculated 10 602 MJ ha^{-1} for an organic dairy system. This comprises a saving in CO_2-C of **1749 kg ha^{-1} a^{-1} C**, assuming that 0.074 kg of CO_2 are released for every MJ of energy produced (Bullard & Metcalfe, 2001). A move to clover based fertility above; fixation by clover in permanent grassland swards was assumed to be 200 kg N ha^{-1}. As mineral fertiliser N addition was **zero**, stocking speed was reduced from 2 to 1.6 cows per forage hectare, which results in the result that this saved the equivalent of **533 kg ha^{-1} a^{-1} C** using reduced N_2O and CH_4 fluxes (King, et al., 2002 and 2004). So the minimum GHG rate emission should be difference between maximum and saved equivalent, which is **1821 kg ha^{-1} a^{-1} C.**

The amount for upland and low land grazing and bogs, has been based on Nicholson et al., (1997) which states a range of chemical symbols emissions (GHG) between 4-22 kg and 0.03-0.14 kg per unit (hectare), this values been converted to C equivalent. The total greenhouse gas which been calculated **26-138 kg ha^{-1} a^{-1} C.**

Table 4.8 shows the maximum and minimum direct and indirect emission from land use and land cover types. GHG emissions in land use types have been calculated by multiplying the area each of land cover and land use types within the study site (Tamar Valley) by estimates for their GHG emissions and direct and indirect energy (kg C ha^{-1} $year^{-1}$) content.

Therefore, land use and land cover greenhouse gases emission have been calculated by multiplying greenhouse gases and direct and indirect energy amount by the surface area at this study site. Total maximum and minimum amount of greenhouse gas emissions from different land use and land cover types of Tamar Valley was estimated to be between a maximum of **266.2** Kt C and a minimum of **200.2** Kt C per year (Table 4.9).

Table 4.8 also presents values of direct and indirect energy for different land types class represented in the study area. The value of maximum is **381.4** Kt C per year and the minimum is **218.6** Kt C per year.

Table 4.7: Rates of GHG gases, direct and indirect energy (kg C $ha^{-1}yr^{-1}$) releases from different land use and land cover types.

Land Use Types	DE+IE (kg C $ha^{-1}yr^{-1}$)	GHG including (CO_2, N_2O, CH_4) (kg C $ha^{-1}yr^{-1}$)	References
Grassland	214-1963	1821-2354	King et al., 2004, Cormack, 2000, Paul et al., 2002
Arable	425	327-609	King et al., 2004, Smith et al., 2000b, Kasimir et al., 1997
Woodland	0	0	King et al., 2004
Upland grazing, Bogs, etc.	0	26-138	Kramer et al., 1999, Tolonen and Turunen 1996
Heath	18	0	Bullard et al., 2001

Table 4.8: Maximum and minimum amount of direct and indirect energy (kg C $ha^{-1}yr^{-1}$) emissions in different land uses in Tamar valley catchments.

Land Cover type	**Maximum DE+IE (kg C $ha^{-1}yr^{-1}$)**	**Minimum DE+IE (kg C $ha^{-1}yr^{-1}$)**	**Land cover area (ha)**	**Total emissions of maximum DE+IE (kg C $^{1}yr^{-1}$)**	**Total emissions of minimum DE+IE (kg C $^{1}yr^{-1}$)**
Broad-leaved woodland	0	0	17,840	0	0
Coniferous woodland	0	0	4,570	0	0
Arable Cereals	425	425	20,440	8,687,000	8,687,000
Arable Horticulture	425	425	17,220	7,318,500	7,318,500
Improved grassland	1,963	214	80,790	158,590,770	17,289,060
Neutral grass	1,963	214	4,050	7,950,150	866,700
Calcareous grass	1,963	214	8,060	15,821,780	1,724,840
Acid grass	1,963	214	10,260	20,140,380	2,195,640
Bracken	0	0	1	0	0
Dwarf shrub Heat	18	18	280	5,040	5,040
Open dwarf shrub Heat	18	18	2,860	51,480	51,480
Bog	0	0	1,670	0	0
Total			168,041	218 ,565, 100	38,138,260

Table 4.8 presents the maximum and minimum amount of direct and indirect energy (kg C $ha^{-1}yr^{-1}$) emissions in different land uses in Tamar valley catchment (more details see above descriptions). It should be noted that grassland (including Improved, Acid, Neutral and Calcareous) has a great amount of direct and indirect energy emissions (1963 kg C $ha^{-1}yr^{-1}$) in this area. Also, these results confirmed that woodlands such as Broadleaf and Coniferous have zero emissions.

Table 4.9: Maximum and minimum amount of GHG emissions (kg C $ha^{-1}yr^{-1}$) from different land uses in Tamar valley catchments.

Land Cover type	Other Maximum GHG (kg C $ha^{-1}yr^{-1}$)	Other Minimum GHG (kg C $ha^{-1}yr^{-1}$)	Land cover area (ha)	Total maximum emissions of other GHG (kg C yr^{-1})	Total minimum emissions of other GHG (kg C yr^{-1})
Broad-leaved woodland	0	0	17,840	0	0
Coniferous woodland	0	0	4570	0	0
Arable Cereals	609	327	20,440	12,447,960	6,683,880
Arable Horticulture	609	327	17,220	10,486,980	5,630,940
Improved grassland	2,354	1,821	80,790	190,179,660	147,118,590
Neutral grass	2,354	1,821	4,050	9,533,700	7,375,050
Calcareous grass	2,354	1,821	8,060	18,973,240	14,677,260
Acid grass	2,354	1,821	10,260	24,152,040	18,683,460
Bracken	138	26	1	138	26
Dwarf shrub Heath	0	0	280	0	0
Open dwarf shrub Heath	138	0	2,860	394,680	0
Bog	0	26	1,670	0	43,420
Total			168,041	266,168,398	200,212,626

Table 4.9 presents the maximum and minimum amount of GHG emissions (kg C $ha^{-1}yr^{-1}$) from different land uses in Tamar valley catchments. According to this result, Broadleaf and Coniferous woodland has smallest amount of GHG emissions (zero) and Grasslands such as Improved, Acid, Neutral and Calcareous has the highest amount (2354 kg **C** $ha^{-1}yr^{-1}$) of GHG emissions in Tamar valley catchments (addressed to above discussions in section 4.4).

4.5 Land Suitability Analysis Results: 1. Trade-off Analysis

4.5.1 Methodology for generating proportions of area in different environmental parameter classes covered by different land cover types

Overview of process:

Before scenarios of future land use change can be explored, an assessment is needed of where particular land use changes could take place. For example, if a scenario envisages conversion of grassland to arable land to take advantage of new crops under a warmer future climate, some understanding is needed of the constraints on where such conversion could take place. An initial assessment of land suitability can be provided by analysis of the distribution of current land uses in relation to key environmental parameters. As a first step in this process, the land use types can be described as a function of basic topographic variables such as slope and elevation.

In support of the land suitability analysis, the different environmental parameters which constrain different land types have been analysed in the GIS. This research is developing an inventory of suitability analysis for the different land use types based on land cover type in GIS (Table 4.5) in the Tamar valley catchment. In this study area, the suitability analysis for the land cover of the Tamar Valley was estimated by combining GIS data on different land types and land classification and the digital map of land cover.

The method generates individual raster layer for each defined class of an environmental parameter (e.g. elevation between 0-50 and 150-200 m, slope of between 2.5 and 5 degrees, aspect of 45 degrees) that can be used to extract the land cover for that particular class of parameter. Each of these ‘class rasters’ acts as a mask to remove all unwanted data. The masking process works by generating a raster layer in which cells have either a value of 0 or 1 (1=cells within the defined class). This layer is then multiplied by the land cover raster (on a cell-by-cell basis) and any cells that fall outside the required class return a value of 0, whilst the cells inside the class return their land cover code. There is a need to make sure that land cover data and environmental parameters are at the same spatial resolution (25 m), for the same spatial extent (the catchment), and in the same coordinate system (British National Grid). Layers should reclassify environmental parameters into individual class bands (e.g. for elevation, classes such as 0-50; 50-100 and up to 600, and for slope, classes such as 0-2.5, 2.5-5, and up to 30 degree and for aspect classes 0-45 and up to 360).

4.5.2 Land Suitability Analysis Results: Trade-off Analysis

These land uses should be justified and categorised for proper use before justifying and identifying the scenarios. The best way for finding out and understanding the appropriate use of land resources under different type of use by considering the other elements like slope, aspect and elevation is land suitability analysis. In this part land resources are divided into three categories: a) suitable land use that can be used for agriculture and forestry like Cereal, Horticulture and woodland; b) natural grassland and Shrub land use which can be used for grazing production (in temporary or permanent grassland); c) not-suitable land included Saltmarsh, water and sea and also land with steep slopes which are not suitable enough to use for farming (See Chapter 5 for more detail). In optimization modelling, the areas which are not suitable for particular land uses are not included and allocated in the model and are assumed to be allocated for (or added to) other land area allocation.

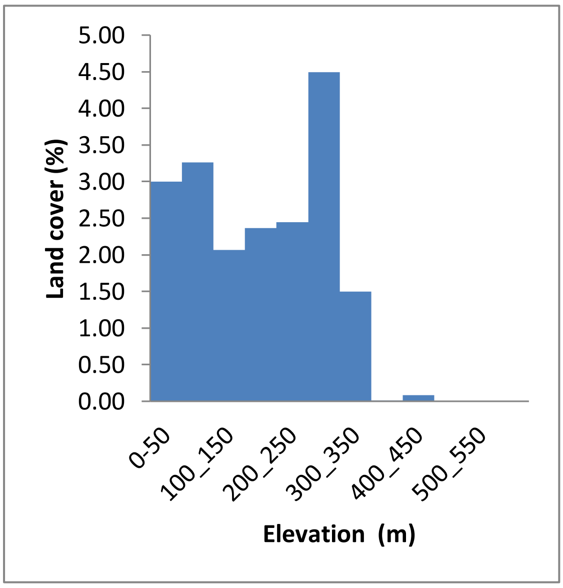
Figures 4.5, 4.6 and 4.7 present values of different land cover in relation to the different environmental parameters of elevation, aspect and slope. These figures have been calculated by analysis of each land type. The specific amounts have been found by summing the amount by each of the different parameters such as elevation, aspect and slope deviations for land cover types within the study site by estimates for future and eventually drawing graphically by charts on specific land cover types. Also they appear to proportion of the land in that topographic class covered by the land use.

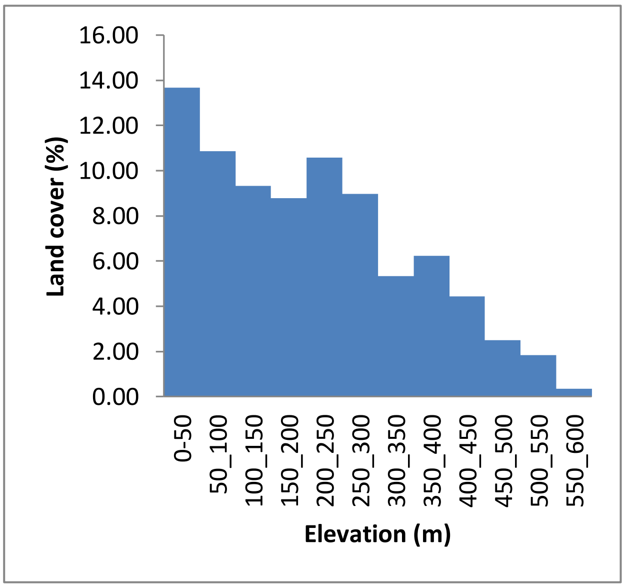
This part of the land suitability analysis attempted to monitor with different value of different parameters what may happen in the future and describe the effects of values of that parameter (elevation, slope and aspect) on different land use type, in order to eventually interprete the future land use change decisions and develop different scenarios.

These figures could be used as part of the wider land suitability analysis, for example, only allow conversion to arable or biomass crops requiring soil tillage on slopes <10 degrees or to use the shape of the observed relationship to define a probability function for conversion.

Figure 4.5: Proportion of different **land cover types** (Y- axes) on different **elevation** (m)

suitability analysis (X- axes) for the Tamar Valley catchment for land cover types.



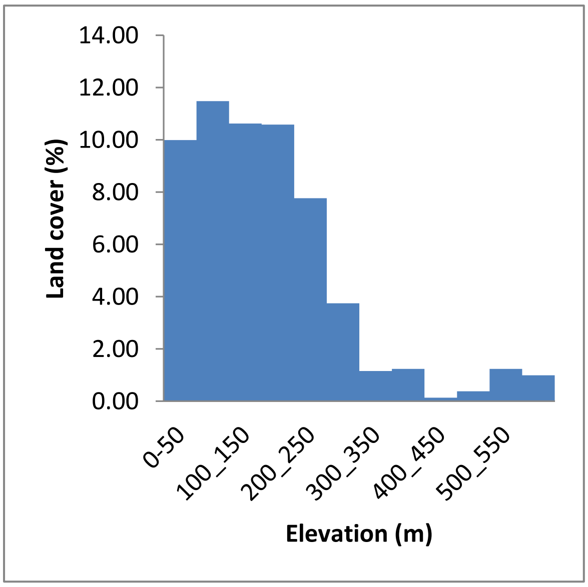


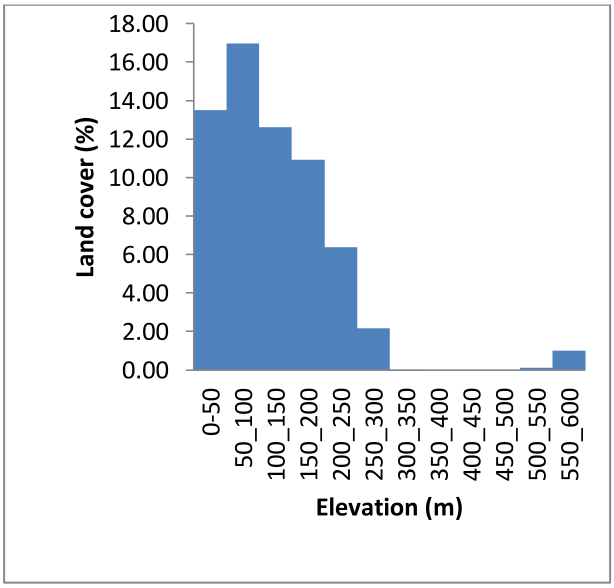
Coniferous woodland

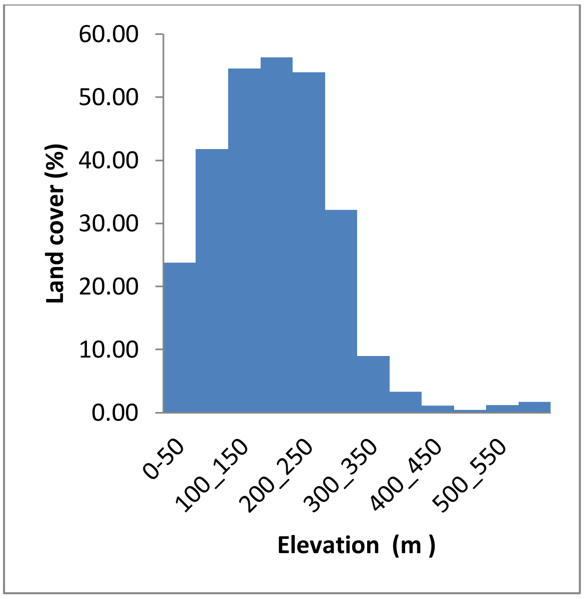
Broadleaf woodland

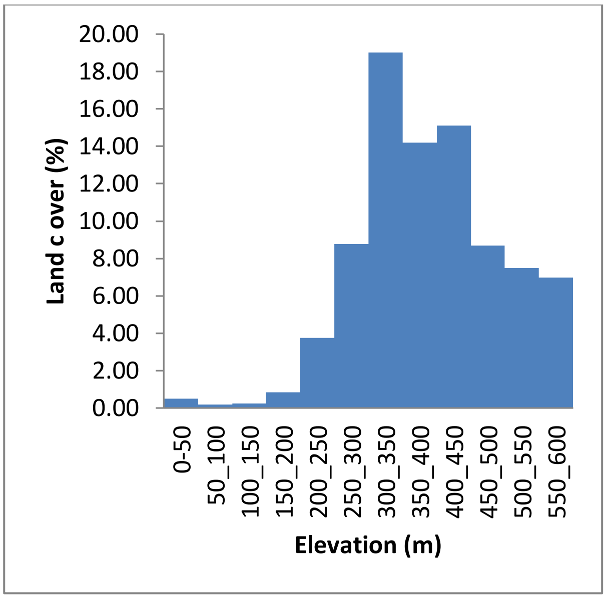
Arable Horticulture

Arable Cereals









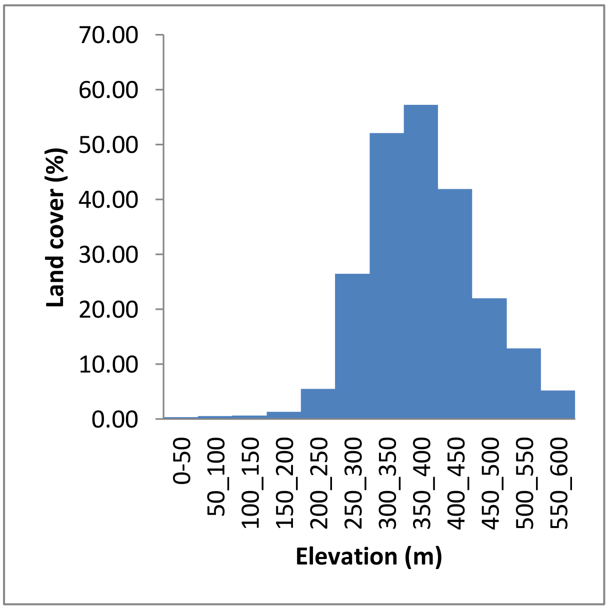
Improved grassland

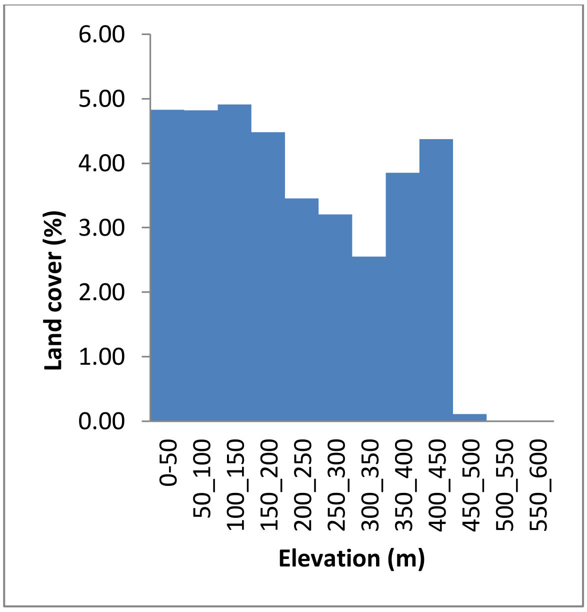
Neutral grassland

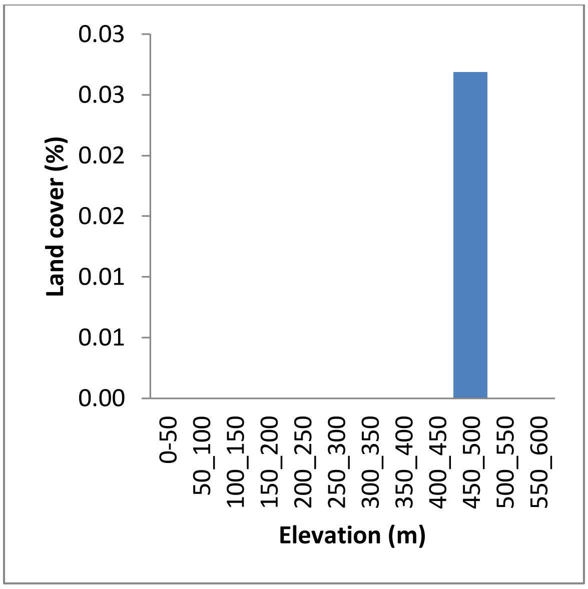
These figures presented the percentage of land cover in different range of elevation (m) in 0-50, 50-100, 100-150, 150-200, 200-250, 250-300, 300-350, 350-400, 450-500, 500-550 and 550-600 meter per each specific land cover types which is Broadleaf woodland, Coniferous woodland, Arable Horticulture, Neutral grassland, Improved grassland and Arable Cereals.

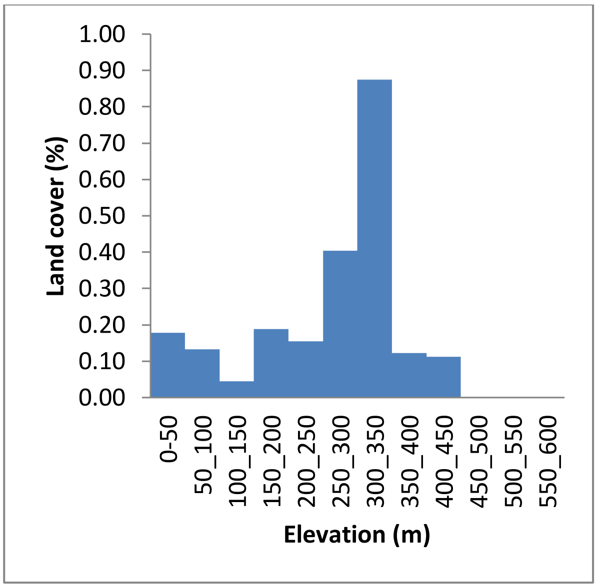
Acid grass

Calcareous grass





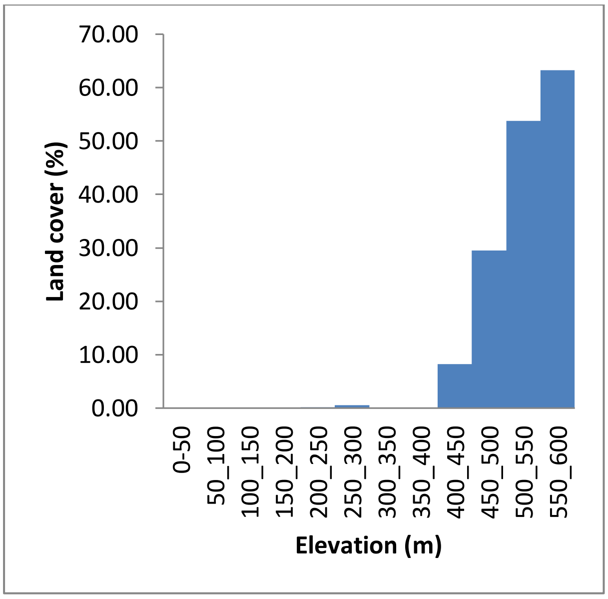


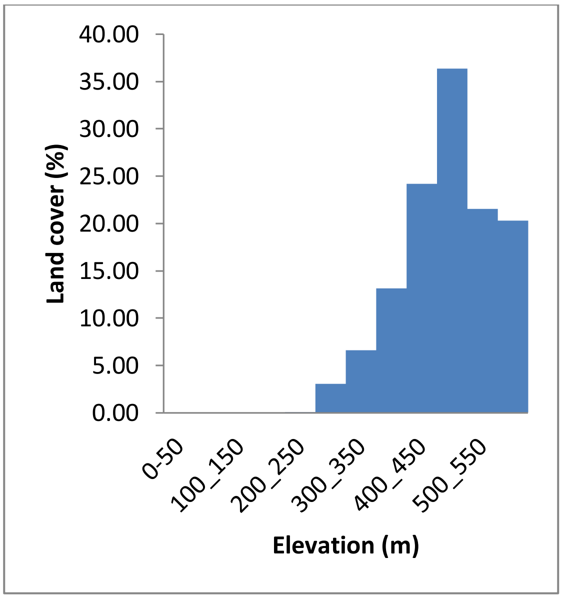


Bracken Dwarf shrub heath

These figures presented the percentage of land cover in different range of elevation (m) in 0-50, 50-100, 100-150, 150-200, 200-250, 250-300, 300-350, 350-400, 450-500, 500-550 and 550-600 meter per each specific land cover types which is Acid grassland, Calcareous grassland, Bracken and Dwarf shrub heath.

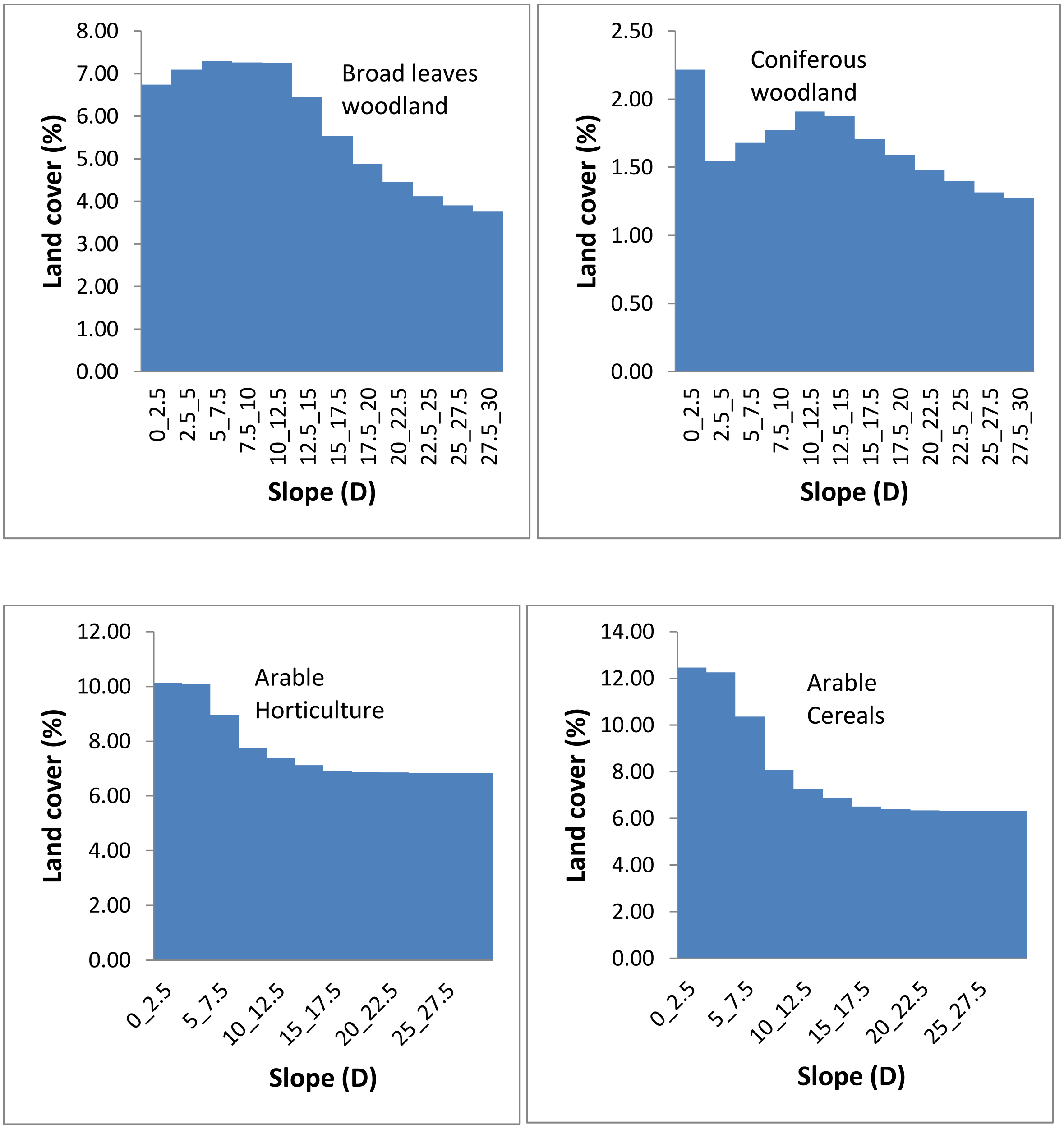
Bogs Open dwarf shrub heath



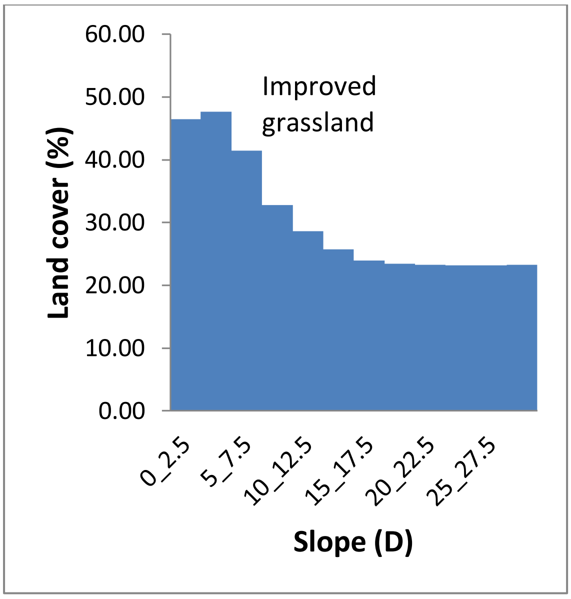


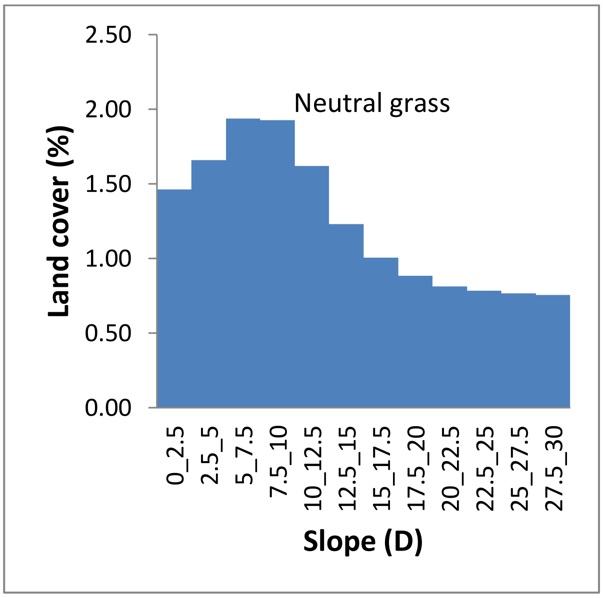
These figures presented the percentage of land cover in different range of elevation (m) per each specific land cover types which is water (Inland), Inland bare group, Bogs and open dwarf shrub heath. And finally percent of Sea/Estuary, Continuous urban, Saltmarsh and Littoral rock by different evaluation type (m) have presented here.

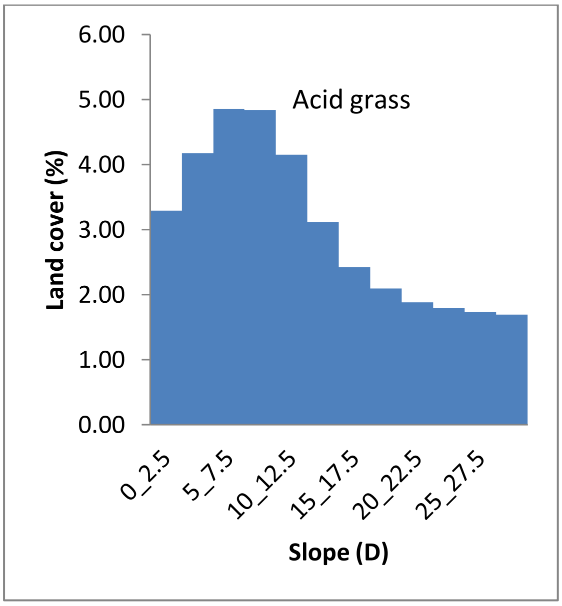
Figure 4.6: Proportion of different **land cover types** (Y- axes) on different **slope** (degree) suitability analysis (X- axes) for the Tamar Valley catchment land cover types.

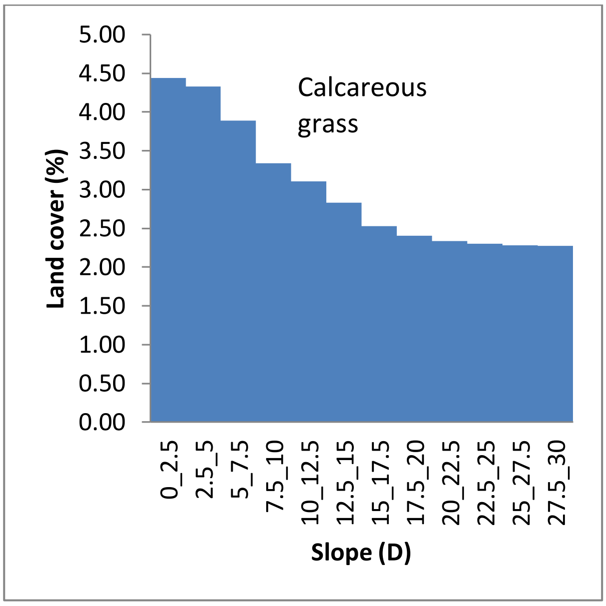


These figures show the proportion of different **land cover types** (Y- axes) on different **slope** (degree) suitability analysis (X- axes) for Broadleaf and Coniferous woodland, Arable Horticulture and Arable Cereals in Tamar valley catchment.

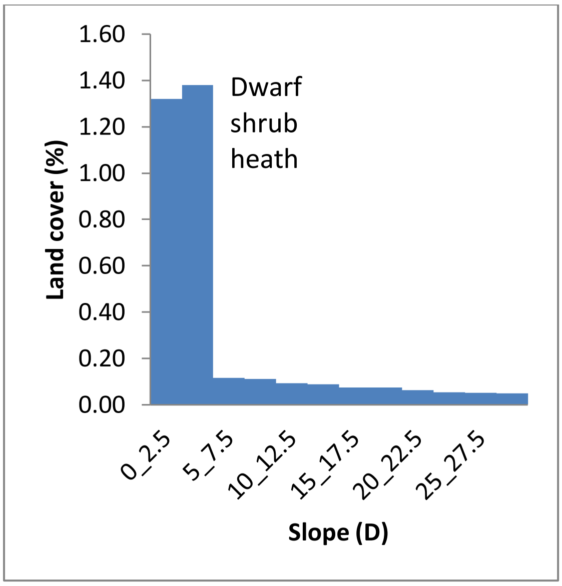


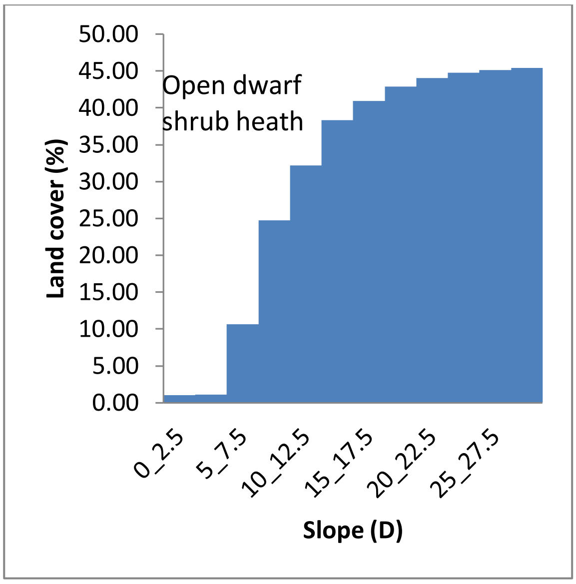


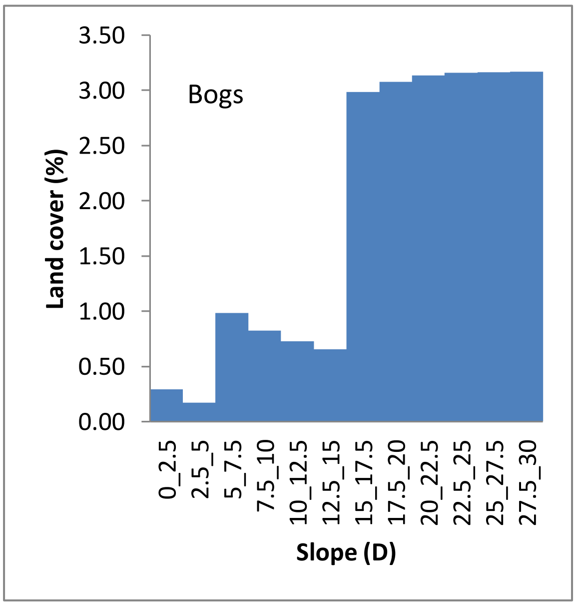


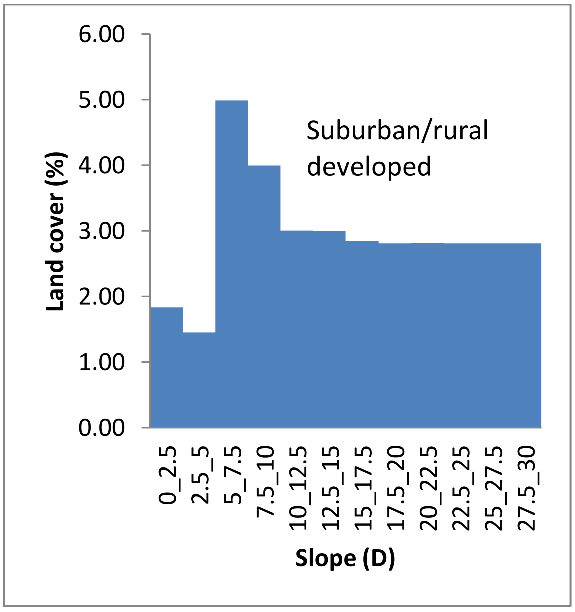


These figures present the proportion of different **land cover types** (Y- axes) on different **slope** (degree) suitability analysis (X- axes) for Improved grassland, Acid grass, Calcareous grass and Neutral grassland in Tamar valley catchment.





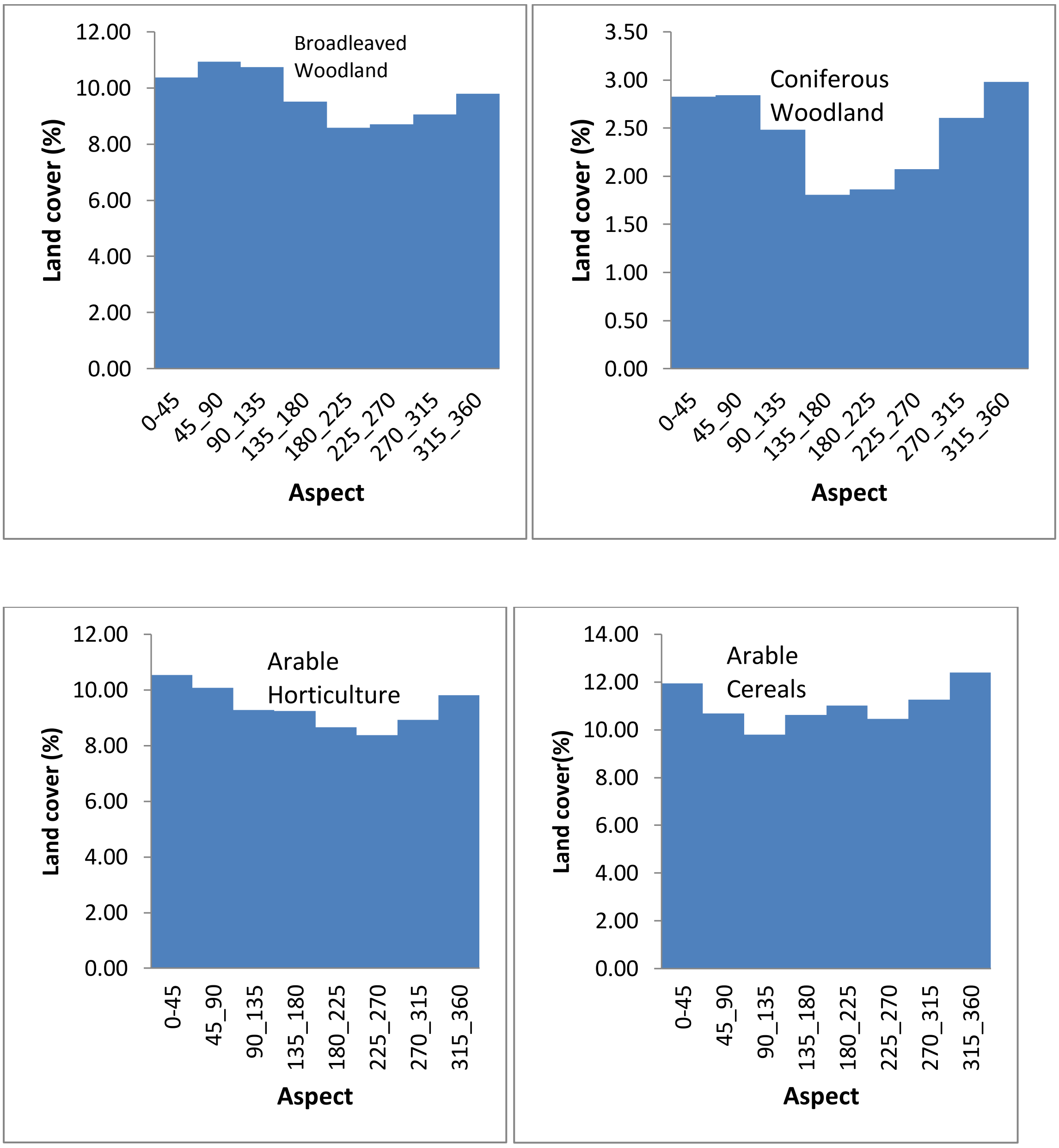


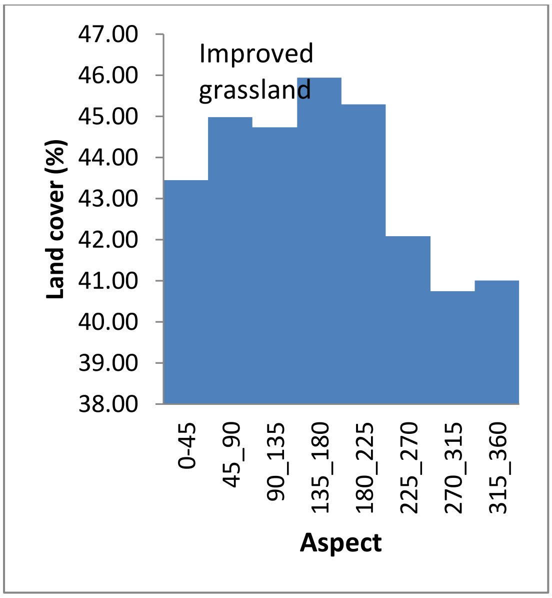


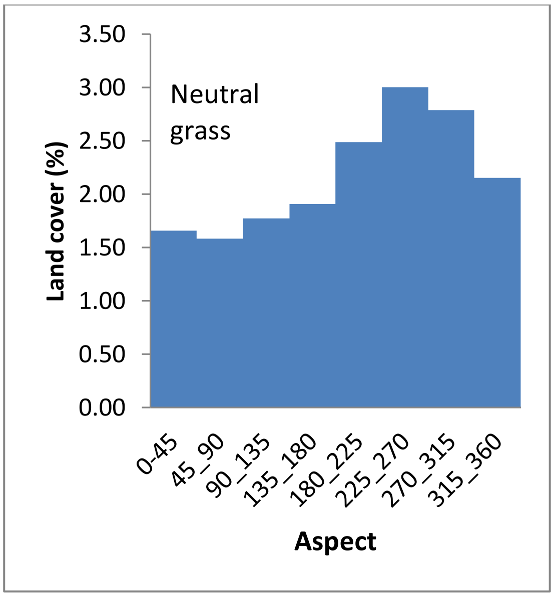
These figures show the proportion of different **land cover types** (Y- axes) on different **slope** (degree) suitability analysis (X- axes) for Water (Inland), Bogs, Open dwarf shrub heath and dwarf shrub heath in Tamar valley catchment.

In general, for all type of land covers by up to 30 degree, example of all land cover can be found.

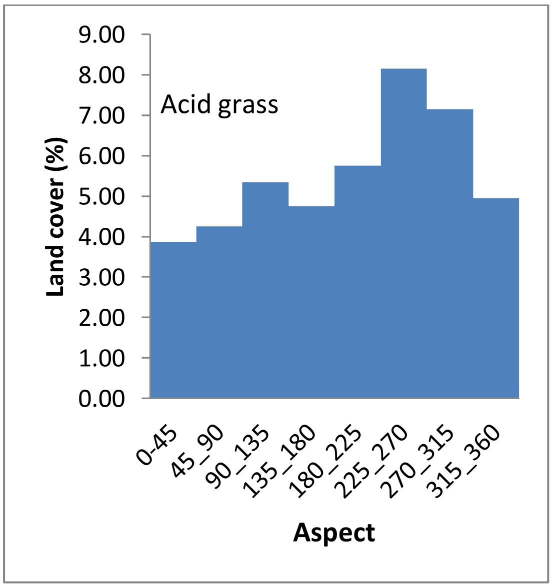
Figure 4.7: Proportion of different **land cover types** (Y- axes) on different **aspect** suitability analysis (X- axes) for the Tamar valley catchment.

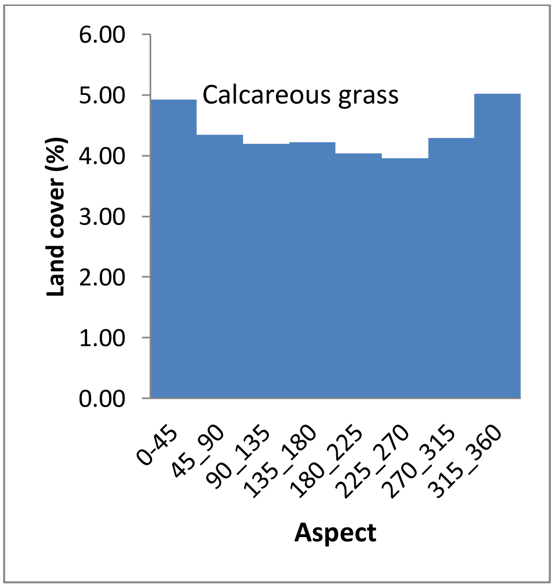


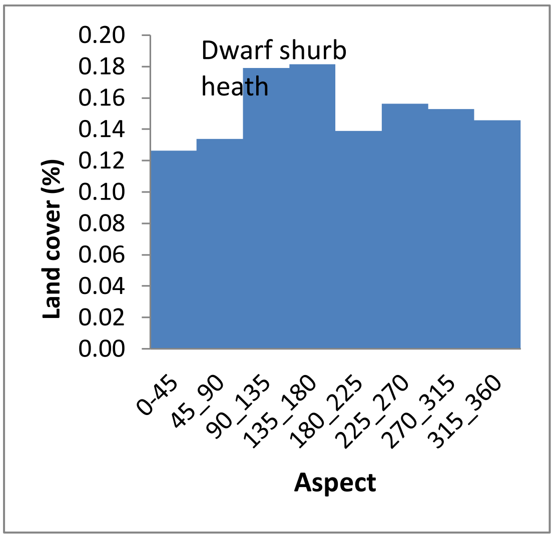


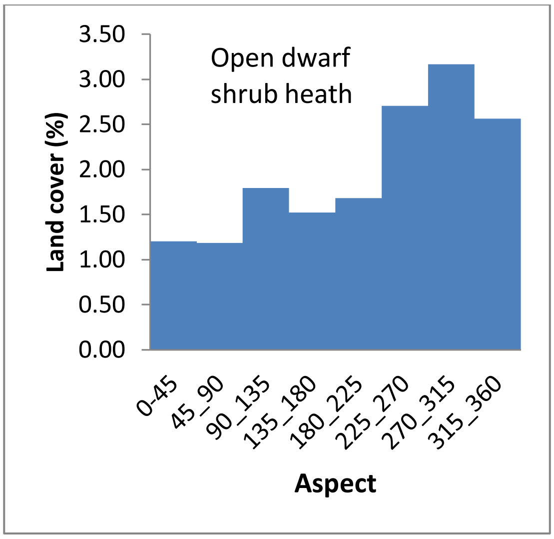


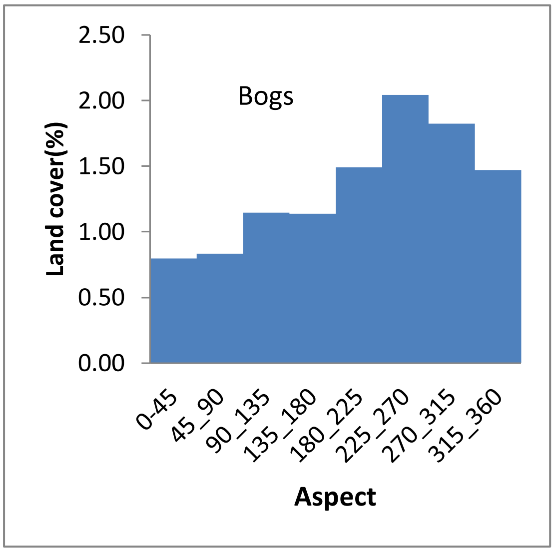
These figures present the proportion of different **land cover types** (Y- axes) on different **aspect** suitability analysis (X- axes) for Broadleaf and Coniferous woodland, Arable Horticulture, Arable Cereals, Improved grassland and Neutral grassland in the Tamar Valley catchment. The results confirmed that, each land cover types can be found on all aspects.

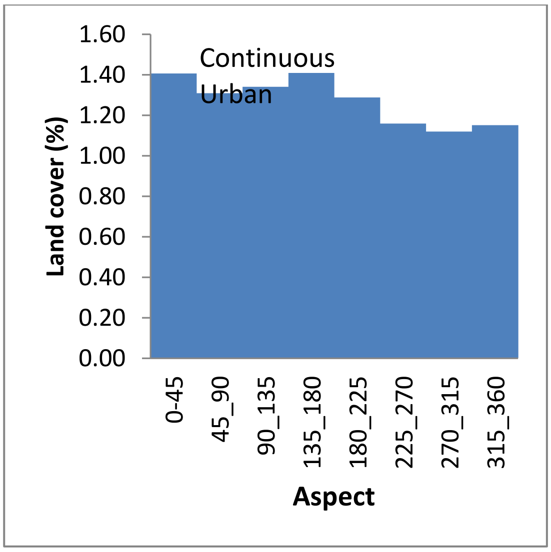












These figures present the proportion of different **land cover types** (Y- axes) on different **aspect** suitability analysis (X- axes) for Acid grass, Calcareous grass, Open dwarf shrub heath, dwarf shrub heath, Bogs, Continues urban, in the Tamar Valley catchment. As results show that, up to 360 facets all these land cover types can be find.

4.6 Conclusions: Combined C storage, and GHG and Energy emissions; Land Evaluation

In this chapter the current amount of carbon stored in biomass and soil under present land use and land cover, and GHG and energy (direct and indirect) emissions from different land use types of the Tamar Valley catchment have been summarised. Existing databases have proved to be a valuable data source in calculating estimates for the size and distribution of the carbon pools in the vegetation and soils of Tamar valley catchment. Carbon stored in the vegetation of Tamar Valley catchment has been estimated to be **1.24 Mt** (Table 4.5) and in top soils and total soils to be **2.45 Mt** and **5.32 Mt** (Table 4.2). Total carbon in vegetation and top soil, and vegetation and total soil, is **3.69 Mt** and **6.56 Mt** (Table 4.6). These values can be considered as the sum of the products of an area and a mean carbon density for each land cover group and each soil group. The most important top soils for stores of C are Denbigh 1, Neath and Princetown with high amounts of C store. Also, the most important total soils for C storage are Denbigh 1, Hallsworth 1 and Manod. The Denbigh 1 soil has the greatest amount of C storage. Also the most important land cover type for C storage is Broad-leaved woodland with a high amount of C storage in vegetation and soil.

The GHG and direct and indirect energy emissions on different land uses have been estimated. The maximum and minimum GHG emission amounts are **266.2 Kt C** and **200.2 Kt C** (Table 4.9). The maximum and minimum direct and indirect energy amounts are **38.14 Kt C** and **218.6 Kt C** (Table 4.8). The land cover type with highest GHG emission and direct and indirect energy costs is improved grassland.

Climate change mitigation based on changes in land use, for reducing CO_2 emissions and other GHG, needs to account for changes in soil carbon sinks and sources in terms of the mechanism by which these mitigation options are assessed, parties electing to include cropland management, grazing land management and re-vegetation.

Estimation of mitigation potential is often confounded by the choice of constraints. This may be biological and physically constrained potentials (e.g. land suitability), limited by available land or resources, and also economic and social constraints. The general implications for landscape are that the scale of possible GHG mitigation in agriculture will rely more upon overcoming these constraints than upon filling in gaps in scientific and technical knowledge.

In this chapter, land suitability analysis for the key land cover types has been shown by considering elevation, slope and aspect. Chapter 5 presents a series of scenarios and modelling future land cover change for each of these scenarios and will use the results of this land suitability analysis.

One of the most useful applications of GIS for planning and management is the land use suitability mapping and analysis. This analysis of land suitability combines a study of land (properties) with a study of land use and determines whether the compounded requirements of land-use are adequately met by the compounded properties of the land. Broadly, land-use suitability analysis aims at identifying the most appropriate spatial pattern for future land uses according to specific requirements, preferences, or predictors of some activity. In this chapter a GIS-based land-use suitability analysis has been applied, using environmental parameters to define land suitability for future changes. It has not included geological favourability, suitability of land for agricultural activities, landscape evaluation and planning, environmental impact assessment, selecting the best set site for the land use change management attributes of land use. This set describes the means available to the producer or defines the limits within which management measures can be taken, however, developing a long term land suitability analysis was beyond the scope of this project, and the readily available datasets.

The comparison of relevant land-use requirements with the associated land characteristics or land qualities is the essence of analysis of land-use systems. The outcome of this **matching** procedure forms the basis for assessing the suitability of the land for the defined use.

This classification system uses the term 'land capability' to express the inherent capacity of a land unit (see more in Chapter 5) to support a defined land-use for a long period of time without deterioration.

This chapter has attempted to describe spatial patterns of land use for a given area, usually involves specifying the mix of land use types, the particular pattern of these land use types, the area extent and intensity of use associated with each type.

In this type of analysis all the characteristics (such as location, size, relevant attributes, etc.) of the candidate sites are known. The problem is to rank or rate the alternative sites based on their characteristics so that the best site can be identified. If there is not a pre-determined set of candidate sites, the problem is referred to as site search analysis (Figures 4.5, 4.6 and 4.7). The characteristics of the sites (their boundaries) have to be defined by solving the problem. The aim of this chapter analysis is to explicitly identify the boundary of the best site. Both the site search problem and land suitability analysis assume that there is a given study area and the area is subdivided into a set of basic units of observation such as polygons (area units) or rasters. The land suitability analysis problem involves classification of the units of observations according to their suitability for a particular activity. The analysis defines an area in which a good site might exist. The explicit site search analysis determines not only the site suitability but also its spatial characteristics such as its shape, contiguity, and/or compactness by aggregating the basic units of observation according to some criteria. It can simply be summarised the main work in this chapter as:

a) In this chapter land suitability analysis has been undertaken,
b) This (LSA) is important for selection of areas which have the potential for change;
c) To enforce changes then we have to be able to select the best sites, which have to be defined spatially in some way.
d) This analysis is linked to Chapters 5 and 6 for justifying and identifying the scenarios and land use management practise.

Chapter 5

Presentation of the Optimization Results: 1

Chapter 5 Presentation of the Optimization Results: 1

1. Scenario Analysis

5.1 Introduction

5.1.1 UK targets to reduce the greenhouse gas emissions

As discussed in Chapter 2, the UK is committed by 2050 to decrease the net emissions of greenhouse gases (GHGs) to no less than 80% below those of 1990, based on guidance of the international body (IPCC) for action to reduce greenhouse gases (UK GHG National Inventory, 2007). This goal has been set to prevent global temperatures from increasing more than 2^0C. This UK intention would be part of a global reduction of the GHG emissions scheme to 50% below 1990 levels, to be achieved by 2050. To achieve this reduction, the UK government has considered the global economy as one of sustaining growth**.** Based on this long time target, the UK Government's assumed GDP (Gross Domestic Product) after 2014 would increase by 2.25 – 2.5% per year. This clearly means the UK economy in 2050 would be 2.8 times greater than today (DEFRA published report in July 2009). To achieve the 2050 GHG emission reduction target, the UK has to decrease its current emissions to at least one tenth of GHG emissions output levels in 2009. Also, a balance and relationship between the international emission cap and trading (purchasing of international carbon allowances), energy reduction system, GHG emissions (non-CO_2 and CO_2) is necessary. Regarding this long term target, several scenarios by the government have been assessed. Growth of the global economy by 2050 is largely expected, but the international carbon allowance would be no less than 50% below the 1990 GHG emission level. Effectively, the international carbon allowance in 2050 is quite likely to be insufficient. Based on the GLOCAF (Global Carbon Finance) model and global carbon estimated price in 2050, the UK Government has taken a critical view of the carbon evaluation analysis in 2050. On the basis of this analysis, global uncertainty and the availability price of carbon in 2050, the UK Government has assumed, for 2050, "a central estimate of £200/tCO_2e, with a low sensitivity of £100/ tCO_2e and a high sensitivity of £300/ tCO_2e" (UK's DECC and DEFRA published report in July 2009). Table 5.1 describes the UK Government scenarios for emissions targets in 2050. Compared with the current market, carbon cost in 2050 is quite high, so the UK would adapt to being cost-sufficient to attempt significant domestic and local action. Through this domestic and local abatement, it is anticipated that much of the UK's long term target would be achievable in 2050.

Table 5.1: The UK Government Scenarios in 2050 (UK Government's (DECC and DEFRA) published report in July 2009).

Scenarios	CO_2 Emissions Reductions (relative to 1990)	Other Assumptions
70% scenario	29% reduction by 2020, 70% reduction by 2050	Commissioned by the CCC.
80% high bio-energy	31% in 2020, 80% in 2050	Commissioned by DEFRA in 2007. Assumes high availability of domestic and imported biomass.
90% scenario	38% reduction by 2020 and 90% reduction by 2050	Commissioned by the CCC.

Based on the analysis by the Committee on Climate Change (CCC), when access to international carbon allowance is unexclusive, the UK cannot expect to receive more than 10% of its total emission decrease effort from the international carbon allowance contribution in 2050. Uncertainty in the relationship between international and national markets and carbon prices of abatement express the rationale for the level of emission reduction and uncertainty about the UK's 80% GHG emission reduction long term target in 2050, although the flexibility of the market such as in international Carbon pricing and trading is an important consideration in the equation. As is clear in Table 5.1, several scenarios have been building up about the level of domestic and local abatement in the UK's long term target by 2050. There is a demand for domestic carbon capturing/removal, an energy system reduction by 90% in relation to 1990 levels in 2050, and one in which a 70% decrease has been considered (UK Government's report, July 2009). In the UK reduction target, land management and land cover change have a role in an overall reduction of GHG. Based on these GHG reduction targets, different scenarios in this research have been assumed and analysed. These scenarios considered various constraints on the level of allowable emissions in 2020 and 2050 respectively. Moreover, variations in the inherent availability and cost of Farming Business Income (FBI) have been considered.

Emissions (outputs) from sectors of land use over the period 2009 to 2050 under the different scenarios require up to a 33% decrease in GHG and energy emissions in 2020 and about an 80% decrease in 2050 compared to 1990 levels. On the other hand, meeting these GHG emissions targets through land management requires a 33% decrease by 2020 and an 80% decrease by 2050 compared to 1990 levels. As mentioned above, taking into account the uncertainties, this long term target would be achievable through international carbon trading. The feasibility of an 80% decrease in non-CO_2 GHG emissions affects a scope of possible emissions levels from the energy emission system that are capable of achieving the 2050 target. Accordingly, the agricultural sector is one which has been considered in the UK emissions reduction target, to enable emissions to fall by 70% by 2050. In another considered agricultural land use change scenario, with significant purchase of carbon allowances, the emission would drop by 90%. In summary, scenarios were determined for each of the possible 15%, 20%, 40%, 70%, 80% and 90% reductions in CO_2 by storing carbon and reducing GHG and energy emission where the model has been constrained to meet the 2020 and 2050 reduction target.

Additionally, uncertainty issues other than GHG and energy emission constraints are considered in this project, such as FIB (Farm Income Business) and improvement and availability of carbon and other GHG reduction technologies, energy efficiency, carbon allowance and its cost in future to make this target achievable. The results output from scenarios under optimization modelling (Linear and Multi Goal Linear Programming) – are sensitive to assumptions about the future state as have been mentioned above. Prediction of these variables to 2050 is fundamentally uncertain and any changes in assumptions can affect importantly different modelling results. Depending on the scenario, different assumptions contribute to a larger or smaller extent to the overall emission reduction and saving in land use emissions in the study area. In combination with these factors, forecasting to get a large amount of carbon saving and GHGs emission reduction is not plausible. To demonstrate these points, Table 5.4 describes scenarios which have been run through the **Optimization** and **Linear Programming** models, which are all consistent with meeting the 2050 target for about 80% emission reduction in net UK carbon saving and GHG emissions relative to 1990, but the difference in these assumptions are associated with the carbon price and accessibility (**CAP and Trade**) of key technologies and the level of domestic and local abatement from the UK Government's policy system (see section 5.1.2).

5.1.2 CAP and Trade Policy

Cap and Trade policy, also known as allowance trading or "carbon pollution credits" is for modulating and ultimately cutting down the amount of pollution emitted into the environment. The first large emission trading policy was established by the European Union in 2005 and is an important pillar of EU climate policy; it is referred to here as the European Union Emissions Trading Scheme (EU ETS). In general terms, Cap and Trade is a market based approach to control pollution by supplying an economic motivator for attaining a decrease in the emissions of pollution, mainly focused on carbon.

A legal authority (usually a Government) sets a limit or CAP on the amount of pollution allowance which can be emitted from, for example lands and industrial works. The government then provides credits which allow users or companies to contaminate a certain amount, as long as the combined pollution amount equals or is less than the initial set limit. This limit or "cap" is allocated or can be sold to firms in the form of emissions permits which represent the right to emit or discharge a specific volume of the specified pollutant"(EU ETS policy scheme, 2005). Put simply, firms are required to hold a number of permits or credits equivalent to their emissions (European Cap and Trade definition report, 2005). The total number of allowances should not go beyond the cap or limit of emissions to that level. If a firm's pollution exceeds their permits, then permits or credits can be bought from those who require fewer permits.

Trade relates to the transfer of permits. In reality, the buyer is paying a charge for causing pollution, whilst the seller is rewarded for decreases in emissions. In general, those who can reduce their emissions and not exceed their allowance can inexpensively achieve the lowest price in pollution. On the other hand, those companies or users who can reduce the amount of pollution may be allowed the trading of additional permits. Those companies or users then can sell their extra credit to companies or users that cannot afford to decrease their contaminant amount.

5.2 Development of a Modelling Approach

5.2.1 Summary of the modelling approach

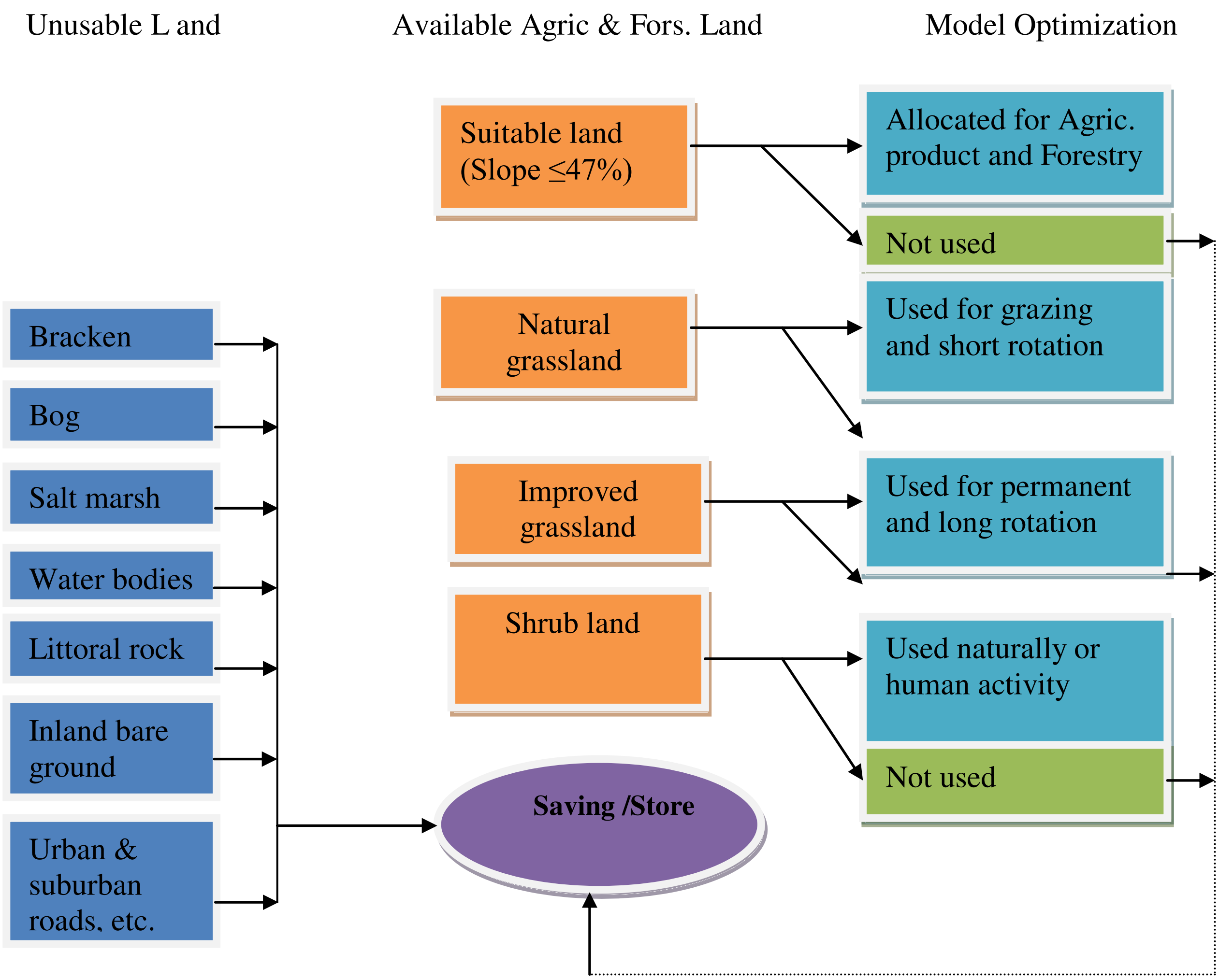
In this chapter, the approach to development of the land use analysis system (LUAS) and its constituent models are considered. LUAS and evaluation has been created in Wageningen University in the Netherlands. With respect to this, LUAS is used in this research. These include GIS, proficient systems, and linear programming (LP) models for land optimization and assessment. LUAS is intended to identify possible decision making on land use options. It is designed as a decision support system (DSS) for land use evaluation and planning (as described in chapter 3). Moreover, LUAS allows analysis of scenarios and policy changes (also as discussed in chapter 3). Four categories of land use activity (parameters that have a greater influence in this study) have been defined, i.e., land allocation (LA), carbon (C), and energy (ENE) and GHG (GHG) activities. The land use activities are based on current land-based activities, so the input-output co-efficients are quantified per hectare as tonnes per hectare (carbon), and tonnes per hectare (ENE & GHG). Not all land could be used for agriculture and forestry (as shown in Fig 5.1). Excluded areas are, preserved and unusable land including Bracken, Bog, Salt marsh, Water bodies (river and sea), Littoral rock, Inland bare ground, and non-agricultural and forestry land (urban and suburban roads, etc.). These excluded areas are not part of the optimization modelling, and they always belong in the 'preservation' category. The land available for agriculture and forest (Land) is divided into four categories: 1) suitable land (Suit) that can be used for growing agricultural products and forestry use (as identified and described in chapter 4, section 4.5.2); 2) natural grassland (Ng) that can be used for grazing and short rotation growth; 3) Improved grassland (Ig) that can be used for paramagnetic growth and long rotation; and finally 4) shrub land (Sl) that can be used naturally or for human activity. All of these suitability analyses are based on the current land cover situation and made a useful link for justifying the scenarios (see scenario section in this chapter). Uses of these types of forest and agricultural land have been optimized by the LP model. If the total area allocated to different land use types is less than the available area for this optimization model, the unused part of lands is assumed to be preserved (Fig 5.1). Based on the description above, the land allocation among different activities and the available land use area can be mathematically described as below:

$\sum LA + \sum C + \sum ENE + \sum GHG = Suit$ Eq: 5.2.1 a

$Suit + Ng + Ig + Sl = Land$ Eq: 5.2.1 b

In which LA is land area allocation per hectare.

Figure 5.1: Available land types and land allocation (Developed by Author).



Based on the research objectives discussed in chapter 1, three objective functions are defined here, as related to environmental, economic aspects of land use development in the Tamar Valley Catchment. These objective variables/ functions (Table 5.2) include maximization of total carbon storage (TC); minimization of total energy use (TENE) and TGHG emissions, and output of Net Farm Business Income (NFBI).

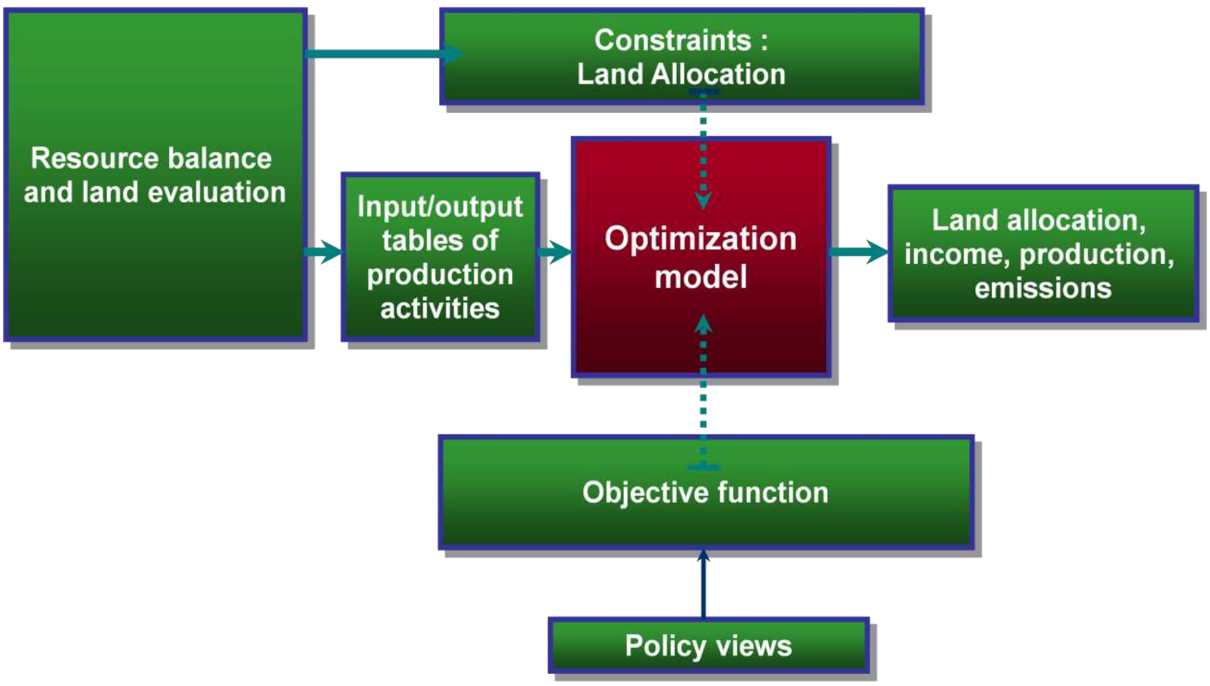
Table 5.2: Objective functions and definition of the variables used for these objective functions (Source: Author).

Objective Variable and Description		Unit
Environmental objective variable		
TC	Maximization of total carbon storage	Mega Tonne Carbon
TENE	Minimization of total energy emission	Kilo Tonne per year
TGHG	Minimization of total GHG emission	Kilo Tonne per year
Economic objective variable		
NFBI	**Output of Net Farm Business Income**	**English Pound**

In this section also, land constraints have been considered. Land use options are affected and restricted by some constraints, such as available land area, land suitability and so on, but in this research land allocation is the main constraint (section 5.2.2). The values of research objectives and the trade- offs under a set of basic constraints as defined have been calculated. These values provide the minimum and maximum limit of a specific objective function that could be attained without imposing restrictions or other objectives. Each trade-off represents the conflict between two or more particular objectives and is a consequence of prioritising one objective over another objective. These analyses will give much, but not completely, sufficient information to decision makers. Although several factors are considered, additional ones may be needed by a decision maker at any particular site. In this chapter, ten scenarios are defined, according to the key issues and government policy in relation to agricultural and forestry land uses, economic issues and environmental improvement in the UK (Table 5.4 and section 5.2.3). These ten scenarios have been structured on the basis of potential development, land allocation and regional issues. The main aims are to consider increasing soil carbon, reducing energy and GHG emissions and the potential impacts on agriculture and forestry lands in this research site area.

The range of future possible changes in land uses in the Tamar valley catchment is represented within the scenarios. In the scenarios presented here, a priority has been to try to increase Forest and Grassland areas. Scenario one is a 'business as usual' model, with no changes in land cover. This allows savings under each objective function to be calculated. Based on the objective functions, reflections on the changes will take place gradually. The scenarios also consider changes within protected areas (for conservation or recreation goals) and how these might provide a break in future land use change (ignoring the protected areas, so they can change in a long term target). **Figure 5.2** shows the integrated factors in Optimization and Linear Programming models. Based on current land allocation, the land resources have been evaluated and the land unit map has been created as described in chapter 4. In the land unit map, the soils map, elevation map, aspect map and slope maps have been integrated and overlaid. As noted earlier, the activity factors include land area, carbon, GHG and Energy. Input for this model is based on the amount of activities. Also, the Farm Business Income has been considered as an input. Considering uncertainties in the future, allocation of the land to different land units is the main constraint in this model. Decisions have been categorised as **promising (1)** and **never happening (0).** Promising means that, the combination exists now or may happen in the future. Never happening means that the combination does not exist now and cannot happen in the future (Table 4.3). The model is run for three objective functions: **1:** Maximization of total stored carbon value, **2:** Minimization of total energy emission and **3:** Minimization of total GHG emission (Table 5.2). Based on all concerns, the outputs of this model come out as several scenarios with different assumptions.

Figure 5.2: The Fundamentals of the Research Optimization Model (Developed by Author).



In the following approach, with the constraints on allocation of land uses to land units (Table 5.3), four models, under a different range of scenarios, have been designed; the models description would be as follows:

Model 1: Total Carbon Max + Prev Energy + Prev GHG + Prev Area.

Model 2: Total Energy Min + Prev Carbon + Prev GHG + Prev Area.

Model 3: Total GHG Min + Prev Carbon + Prev Energy + Prev Area.

Model 4: Carbon Max + Prev Net Farm Business Income (NFBI) + Prev Energy + Prev GHG + Prev Area.

5.2.2: Constraints on Land Allocation

In most of the scenarios, the Littoral rock, Salt marsh, water bodies and Inland bare ground lands have taken a **zero amount** constraint on their allocation area. The reason is that it is not feasible to minimize the energy and GHG emission for these land uses, as the model cannot find the solution. So, to make the model results feasible, an extra constraint was put on these land units which are not important in storing carbon, also energy & GHG emission strategy. Table 5.**3** shows constraint values for land uses in regard to present and future. In this table, land cover types are referred to GIS code (which is explained further in Appendix 1). Also, each land unit type explains information as its elevation layer code and soils type code in GIS (see more details on Appendix 1). The first digit specifies the elevation class and the second and third digits show the soil type. For instance, if the land unit code is 100; it explains the first digit as elevation (1) and the second and third digit as soil code (00) which is Neath.

Elevation has been categorised by six layers as:

0- 100 meter = layer 1, 100 – 200 meter = layer 2, 200 – 300 meter = layer 3, 300 – 400 meter = layer 4, 400 – 500 meter = layer 5, and 500 – 600 meter = layer 6.

Table 5.3: Constraint on land unit and land cover types (compatible model), zero= never possible and one = promising.

Land Unit/ Land Covers	11	21	41	42	51	61	71	81	91	101	102	121	131	161	171	172	212	221
100	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
101	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
102	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
103	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
109	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
110	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
111	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
112	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
113	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
114	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
116	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
118	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
119	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
120	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
123	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
124	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
125	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
201	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
202	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
203	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
205	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
206	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
207	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
209	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
210	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
211	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
212	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
213	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
215	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
216	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
217	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
218	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
219	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
220	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
221	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
223	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
224	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0
227	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
228	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
301	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
302	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
303	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
304	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
305	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
306	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
307	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
309	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
310	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
311	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0

312	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
315	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
317	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
318	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
321	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
322	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
323	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
324	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
326	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	0	0	0
328	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
401	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
402	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
404	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
405	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
406	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
407	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
409	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
410	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
411	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
412	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
416	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
417	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
422	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
426	1	1	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0
428	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
502	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
504	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
506	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
507	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
508	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
509	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
510	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
512	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
522	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
526	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	0
606	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0
607	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0
608	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0
610	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0
622	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0

5.2.3 Explanation and Description of Scenarios

It is difficult to forecast future UK land use change, due to uncertainties in policy, social, and economic development inside and outside of the UK. It is possible to explore an uncertain future with assumptions about environment and land changes through scenario building. The scenarios used here are developed for the range of different classes of land use. Ten scenarios with different assumptions have been developed, based on current land allocation and targets discussed in section 5.1 and refer to chapter 2.

Table 5.4: Description of Alternative Scenarios and Models Used in this Study (Dec = decrease and Inc = increase).

Scenarios: / **Land Uses Type:**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Scenario 7**	**Scenario 8**	**Scenario 9**	**Scenario 10**
Broad-leaved woodland (**11**)	**current**	**%15 Dec**	Current	current	current	current	current	**%25 Inc**	current	**%50 Inc**
Coniferous woodland (**21**)	current	**%10 Dec**	Current	**%10 Inc**	current	current	current	current	current	**%70 Inc**
Arable Cereals (**41**)	current	current	Current	current	current	**%15 Inc**	**%40 Dec**	current	current	current
Arable horticulture (**42**)	current	current	**%20 Dec**	current	current	**%15 Dec**	current	current	current	current
Improved grassland (**51**)	current	current	**%20 Inc**	current	**%30 Inc**	current	current	**%25 Dec**	current	current
Neutral grass (**61**)	current	current	Current	**%10 Dec**	**%30 Dec**	current	current	current	**%15 Inc**	**%70 Dec**
Calcareous grass (**71**)	current	current	Current	current	current	current	**%20 Inc**	current	**%15 Dec**	current
Acid grass (**81**)	current	current	Current	current	current	current	**%20 Inc**	current	current	**%50 Dec**
Bracken (**91**)	current	current	Current	current	current	current	current	current	current	current
Dwarf shrub heath (**101**)	current	current	Current	current	current	current	current	current	current	current
Open dwarf shrub heath (**102**)	current	current	Current	current	current	current	current	current	current	current
Inland bare ground (**161**)	current	current	Current	current	current	current	current	current	current	current
Bog (**121**)	current	current	Current	current	current	current	current	current	current	current
Suburban/rural development (**171**)	current	**%15 Inc**	Current	current	current	current	current	current	current	current
Salt marsh (**212**)	current	current	Current	current	current	current	current	current	current	current
Continuous urban (**172**)	current	**%10 Inc**	Current	current	current	current	current	current	current	current
Littoral rock (**211**)	current	current	Current	current	current	current	current	current	current	current

Table 5.4 gives an outline of the research scenarios. In each scenario, specific land cover has a certain amount of change in relation to the UK long term targets to store carbon and reduce GHG. Moreover, each land cover type has been specified by GIS code for easier reading and process (addressed to Appendix 1). Also, each scenario has been run under the different models as explained above (addressed to section 5.1).

Scenario 1; Business as usual: In this scenario, the assumption is to keep and save the land use allocation in its current situation with no changes. The objective functions (described in section 4.2.2) have been considered after creating the land unit map allocation for each land cover type.

Scenario 2; Increasing Urbanization: In this scenario, the assumption is increased urbanisation, so the amount of urban and sub/urban land area increases. To meet this aim, forestry land cover (Broad-leaf and Coniferous woodland) allocation decreases by about 25%, therefore Suburban/rural development and Continuous urban land allocation increases by about 25%.

This scenario is based on population demand and the spatial allocation data base. The main driving force for more urban and sub/urban demand in this study area were assumed as: (a) Population, affected by statistical and experimental tendencies (with exponential growth) and housing demand. Based on FAO's report in 2009, the UK has about 1.01% population growth rate annually, so in the distant future housing demand would be likely to increase; (b) Economic evolution, corresponding to the activity level, action amounts and types (Nieto et al., 2010).

Scenario 3; Develop Grassland: In this scenario, the assumption is to develop more permanent grassland allocation, therefore Improved Grassland allocation increases by 20% through reducing about 20% from Arable Horticultural land allocation. Across Europe, the biggest land cover and agricultural land use-type changes have happened in the past four decades, and decline in agricultural land has been by about 13% (Smith et al., 2008). Limitations in land availability, development of other land use types with respect to environmental sustainability, put limits on expansion of further agricultural land use. In reality, with plausible description of the system under the bio-technology development method and investigation in the future make this scenario possible.

Scenario 4; Develop Forest land: In this scenario, the assumption is to develop and expand more forest land allocation; therefore Coniferous woodland allocation increases about 10% through about 10% reduction from Neutral grassland allocation. With reference to the UK forestry principals and clear strategy to extend and/or revive forest and woodland areas across England (DEFRA and NERC, 2000), this scenario has been planned by 2020.

Note: forest and woodland have a long period of rotation time compared with Grassland. Also forest and woodland biomass contain a massive amount of carbon storage. This change under the certain circumstance description in this scenario is taken into consideration by 2020 and with even longer targets.

Scenario 5; Increase Permanent Grassland: In this scenario, the assumption is to have more permanent and short rotation grassland allocation, therefore Improved grassland allocation increases about 30% through reducing about 30% of Neutral grassland allocation. In this site area, there is a finite amount of area available for land use activities. The goal of this scenario is development and integration of management of pasture and grassland, understanding better trade-off between carbon sink, carbon cycle changes and other GHG emissions.

Scenario 6; Increase Agricultural Land: Reviewing the situation across the world, the most striking changes were always in agricultural land use types, with big areas of reduction with different assumptions about land use development, with changes considered in the supply and demand for agricultural products in the future (King et al., 2004; Smith et al., 2007b). In this scenario, the assumption is to have more Arable Cereal land allocation, therefore increases of about 15% of the Arable Cereal land through reducing Arable Horticulture by about 15%. In this scenario, population increase affects food demands in the future (by 2020, 2050 and 2080). The basic principle is that if the demand for food increases, the agricultural land area also would increase.

Scenario 7; Improve and Develop Grassland: In scenario 7, improving and developing more grassland allocation is the main target but with a greater allocation than Scenarios 3 and 5. On the other hand, to meet the aim of long term targets, the assumption for the increase of grassland is varied in relation to the target (in 2020, 2050 and 2080). Therefore the assumption of this scenario is to increase about 20% of Calcareous grassland and about 20% Acid grassland, reducing Arable Cereals land by about 40%. This scenario assumes the development of grassland management practise with an estimation for intensive cultivation of agricultural land to reach the sensible amount of production, by the Bio-energy method and new technology, in the more distant future. Towards bio-energy crops and productivity in the future and with respect to certain descriptions and available resources, if productivity increases, then the agricultural land area can decrease. For instance, meeting the equal amount of production (demand) needs a smaller amount of land (Smith et al., 2007a; Nieto et al., 2010).

Scenario 8; Increase Forest land: In this scenario, the assumption is to have more forest and woodland allocation. Therefore, Broad-leaf woodland allocation increases by 25% through reducing about 25% of Improved grassland allocation. Based on the available land area, this change in forestry land is possible. Compared to scenario 4, and taking into account the UK forest strategy, scenario 8 emphasises that forest and woodland creates the significant balance between the carbon dioxide cycle and GHG emission, i.e. woodlands act as a massive carbon sink. With interpretation of tendency in the UK's scenario target by 2020, the percentage changes in forest and forestry land allocation are estimated.

Scenario 9; Improve Grassland practise: In this scenario, the assumption is to have changes in grassland management type with an allocation strategy of increasing grassland. Regarding surface limitation of the grassland area, land management type is being considered through its relationship with saving carbon amounts. In order to fulfil this aim, Neutral grassland allocation increases by about 15%, therefore Calcareous grassland allocation is reduced by 15%.

Scenario 10; Increase and Develop Forest land: In accordance with the UK long term policy targets and UK forestry strategy, expansion and enhancement of permanent, long term rotation planting for an uncertain future by 2050 is no longer being considered. Scenarios 4 and 8 also follow this strategy but take a short term view and involve less land allocation. In this scenario, the assumption is to expand the forestry and woodland allocation area in order to reduce much more GHG emissions and to save more carbon. To meet this approach in 2050 and in the longer term, this scenario includes, increase by about 50% in Broad leaf woodland and about 70% of Coniferous woodland allocation area. Therefore, for completion of these geographical space changes, about 50% of Acid grassland and about 70% of Neutral grassland have been reduced.

5.2.4: Net Farm Income (NFI)

Based on the DEFRA definition, the net farm income is "Farm Business Income after adding back Interest (net of any interest received) and Possession Charges, minus Unpaid Manual Labour Costs and the emoluments of the principal director(s) and Rental Value and *income from separable diversified activities".* It characterizes the benefit to the farmer for their own labour, management and type of tenancy funds invested in the farm, whether borrowed or not (Definition used in farm business management, DEFRA, 2010).

Table 5.5 shows the net farm income, in English pounds sterling (£) per hectare for the most recent year availble (2009) in the Southwest region. This income includes all farm types of output (Cereals, Horticulture, General Cropping, Dairy, Grazing Livestock, Lowland Grazing Livestock and Mixed).

Table 5.5: Net Farm Income (NFI), in pounds sterling (£) per hectare of output in the Southwest region for year 2009 (DEFRA, Farm Business Survey, 2010)**.**

Land Cover Types	**Net Farm Income (year 2009, £/ha)**
Broad-leaved woodland (11)	77
Coniferous woodland (21)	77
Arable Cereals (41)	67
Arable horticulture (42)	2184
Improved grassland (51)	371
Neutral grass (61)	121
Calcareous grass (71)	143
Acid grass (81)	131
Bracken (91)	0
Dwarf shrub heath (101)	0
Open dwarf shrub heath (102)	0
Inland bare ground (161)	0
Bog (121)	0
Suburban/rural development (171)	0
Salt marsh (212)	0
Continuous urban (172)	0
Littoral rock (211)	0

Based on table 5.5, output from the latest year's net farm business survey in England, shows that Arable horticulture (£2,184) and Improved grassland (£371) have the greatest net farm income in the Southwest region. With the exception of Arable horticulture and Calcareous grassland, reduction in net farm income amounts in the year 2009 compared to previous years, 2008 is remarkable.

5.3 Comparison of Scenarios Output

5.3.1 Objective Function 1, 2, and 3: Maximize Carbon, Minimize ENE and GHG

5.3.1.1 Top soils

According to the above description and assumption, the linear programming model was run for: a) each objective function b) each of the scenarios described above and c) both top soil and total soil types. The results below show and will interpret the different outputs of the analysis of each specific scenario under the different objective functions. The first objective function is carbon maximization (maximization of carbon storage). The value for carbon unit is Mega tonne carbon (**Mt C**). All values are consistent; the results are also shown as difference from the 'business as usual' case which is scenario one. Table 5.6 summarizes the carbon stored, the amount of energy (direct and indirect) and GHG emissions for each scenario under all objective functions in top soils. The carbon store value includes the amount of carbon in soil and biomass in each scenario. The amount of energy and GHG emissions is Kilo tonne per year. All these values have been compared together under model optimization.

The amount of carbon stored in vegetation and top soil is highest in scenario 8. Also, the amount of energy and GHG emissions in scenario 8 has the lowest value. In summary, when the amount of carbon storage increases, this clearly confirms that the energy and GHG emission will decrease (Table 5.6). It is important to mention here that the amount of energy and GHG emissions on all models run is broadly the same. In fact the amounts have changed in original value but the change is minimal. In Figure 5.3, the comparison of percentage changes over the current situation in each scenario has been calculated under the optimization model (all objective functions) in top and total soils as follows:

Percentage change = ((Mt carbon on Scenario A - Mt carbon on Scenario 1) / Mt carbon on Scenario 1)*100. Eq: 5.3.1 a

A: scenario number.

Table 5.6: Total outputs under the objective functions 1, 2, and 3 on different scenarios, and percentage changes compared with the current situation in top soil.

Scenarios	Percent Changes over the current situation (C Max)	Percent Changes over the current situation (ENE Min)	Percent Changes over the current situation (GHG Min)	Mt Carbon stored (C Max)	Mt Carbon stored (ENE Min)	Mt Carbon stored (GHG MIN)	Energy emission (kt yr^{-1})	GHG emission (kt yr^{-1})
Scenario 1	-	-	-	3.63	3.70	3.70	218.48	266.07
Scenario 2	-3.86	-4.6	-4.06	3.49	3.53	3.55	218.48	266.07
Scenario 3	0.55	0.27	-1.08	3.65	3.71	3.66	223.77	272.07
Scenario 4	0.27	0.55	0.27	3.64	3.72	3.71	217.69	265.11
Scenario 5	0.28	0.06	0.28	3.64	3.70	3.71	218.48	266.07
Scenario 6	0.08	-0.54	0.05	3.63	3.68	3.70	222.45	270.57
Scenario 7	7.72	0.05	-1.35	3.91	3.70	3.65	231.05	280.33
Scenario 8	32.51	29.19	29.73	4.81	4.78	4.80	178.85	218.54
Scenario 9	2.21	-0.27	0.06	3.71	3.69	3.70	218.48	266.07
Scenario 10	11.57	8.92	8.38	4.05	4.03	4.01	202.85	247.32

Figure 5.3: Percentage changes over the current situation under the range of different scenarios in top soil.

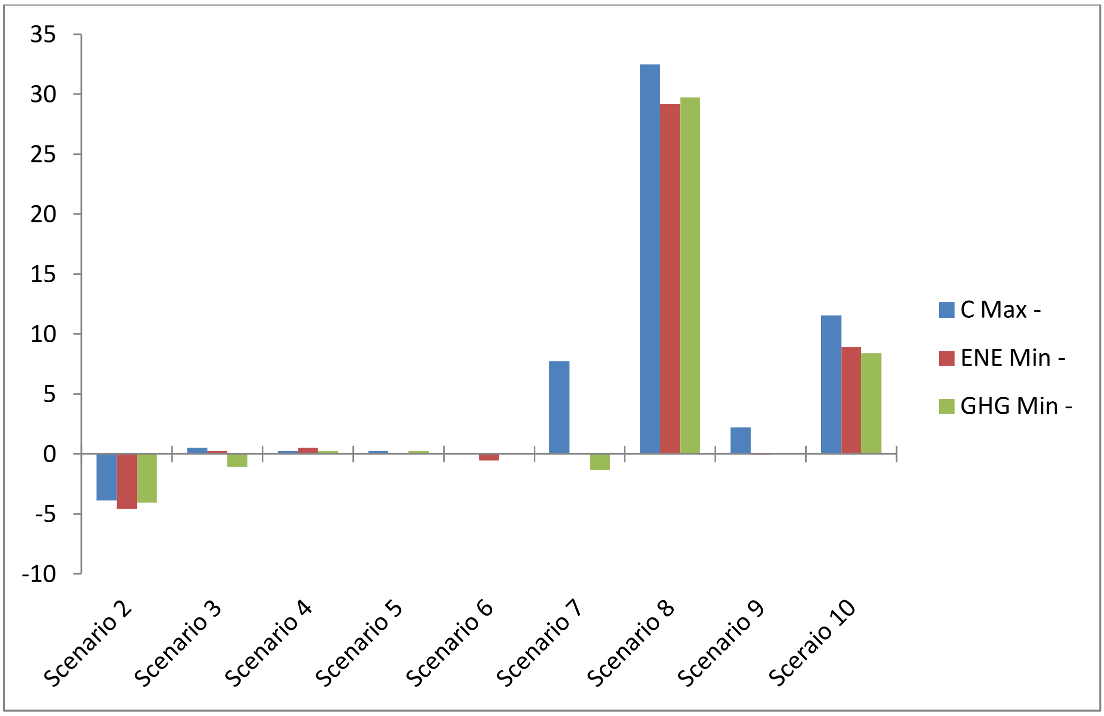


Figure 5.3 shows that the highest percentage changes in scenario 8 with 32.51 percent and the lowest amount in scenario 2 with (-4.60) percent has occurred, while scenario 6 has remained with a fairly small percentage of change.

5.3.1.2 Total soils

The same process was run for total soils with those objective functions that have already been set up (refer to section 5.3.1). The results below monitored will give an interpretation of the different outputs of analysis in each specific scenario under the different objective functions in total soils. Table 5.7 shows total output under carbon maximization, and energy (direct and indirect) and GHG minimization model optimization. Figure 5.4 shows the comparison of percentage changes under different scenarios in total soils.

Table 5.7: Total outputs under the objective function 1, 2, and 3 on different scenarios, and percentage changes compared with the current situation in total soil.

Scenarios	Percent Changes over the current situation (C Max)	Percent Changes over the current situation (ENE Min)	Percent Changes over the current situation (GHG Min)	Mt Carbon stored (C Max)	Mt Carbon stored (ENE Min)	Mt Carbon stored (GHG MIN)	Energy emission (kt yr^{-1})	GHG emission (kt yr^{-1})
Scenario 1	-	-	-	7.30	7.33	7.32	218.48	266.07
Scenario 2	-2.19	-2.18	-2.74	7.14	7.17	7.12	218.48	266.07
Scenario 3	0.14	-0.14	0.14	7.31	7.32	7.33	223.77	272.07
Scenario 4	0.27	0.14	0.28	7.32	7.34	7.34	217.69	265.11
Scenario 5	0.14	0.03	0.15	7.31	7.33	7.33	218.48	266.07
Scenario 6	0.15	-0.15	0.04	7.31	7.32	7.32	222.45	270.57
Scenario 7	0.28	-0.14	0.28	7.32	7.32	7.34	231.05	280.33
Scenario 8	15.34	15.14	15.17	8.42	8.44	8.43	178.85	218.54
Scenario 9	0.04	0.14	0.05	7.30	7.34	7.32	218.48	266.07
Scenario 10	5.07	4.64	4.65	7.67	7.67	7.66	202.85	247.32

Figure 5.4: Percentage changes over the current situation under the range of different scenarios in total soil.

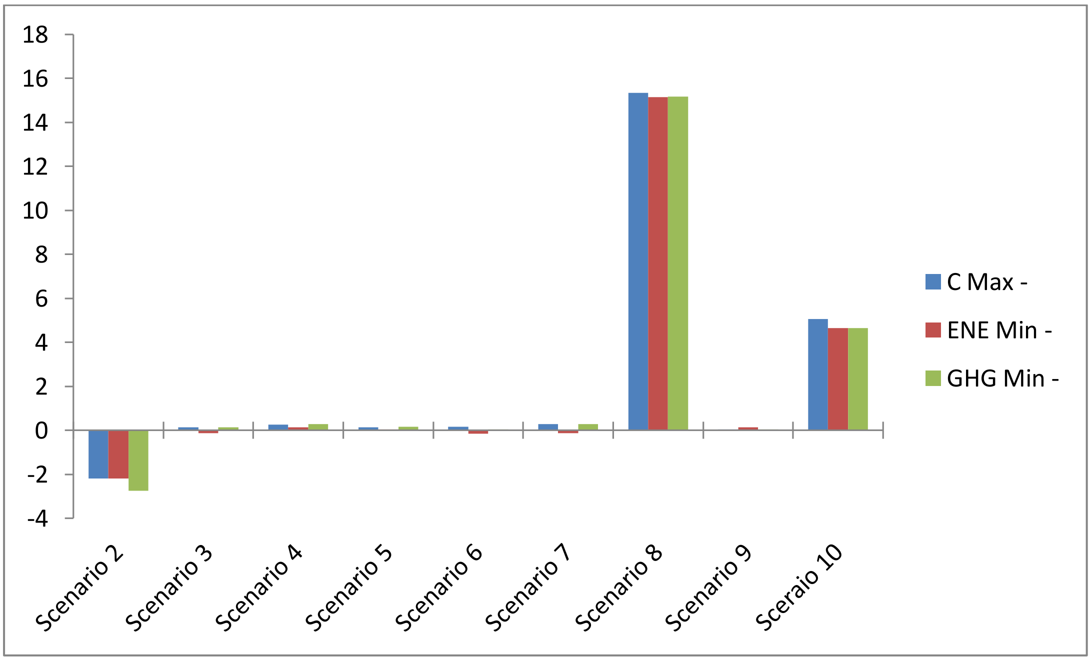


Table 5.7 describes that as for top soils, scenario 8 has a greatest value for stored carbon and lowest energy and GHG emissions under all objective functions. Also, Figure 5.4 shows that scenario 2 has a fairly substantial change, but this is negative. Scenarios 3-7 and 9 show a low percentage of changes and scenario 8 has the highest portion of change compared with other scenarios with model optimization in total soils.

With comparison between results in objective functions 1, 2 and 3, it is emphasised that carbon value is higher in all scenarios in objective function 2 (energy minimization), but the values of energy and GHG emissions are quite similar (see more detail on section 5.3.1).

5.3.2 Model 4, (Farm Business Income) under objective 1

5.3.2.1 Top soils and Total soils

Based on model 4 (section 5.2.1), the objective function is the same as model 1(carbon maximization); but here, the Farm Income values have been added to the model in top and total soils. The most recent available data (2009/2010) for farm income has been considered (Table 5.5). Those outputs describe how land conversion and changes may affect net farm income (Table 5.8). This data is important in the process of communicating the consequences of change to farmers. Based on CAP and Trade policy (addressed in section 5.1.2), and the UK national target policy, farmers are key stakeholders in making decisions to balance carbon emissions with their profit.

Table 5.8: Total outputs in model 4 under the objective function 1(Net Farm Business Income) in a range of different scenarios in M£ (Million British Pounds Sterling) in top and total soils.

Scenarios	**Total NFI Comparison under range of different scenarios (2009) in M£**
Scenario 1	**73.59**
Scenario 2	**73.35**
Scenario 3	**67.36**
Scenario 4	**73.58**
Scenario 5	**73.90**
Scenario 6	**68.92**
Scenario 7	**74.17**
Scenario 8	**67.66**
Scenario 9	**73.57**
Scenario 10	**73.19**

Table 5.8 shows that in scenario 8, farmers have the higher risk (with the lowest profit) and scenario 7 has lowest risk (with the highest profit). In scenario 8, the large conversion is from Improving Grassland to Broad-leaf woodland (371 to 77 pound per hectare). Converting grassland to forest land reduces income per hectare by a quarter. The reason is that forest product has long growth rotation (needs a long period of time), so farmers cannot make

enough profit during this time. Under UK forest policy and CAP and Trade (addressed in section 4.1.2), farmers could increase profit through trading credits until the forest product is marketable.

5.4 Sensitivity Analysis Results

5.4.1 Sensitivity Analysis (SA)

Sensitivity analysis (SA) is: “the study of how the variation (uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of the model” (Labourte, 2007). In the general case, the sensitivity analysis will be used within mathematical modelling to investigate the impact of uncertainty in the input data on the model outputs. Sensitivity analysis is a way to increase the relationship between modeller and decision makers, to make its purpose more understandable and credible. Also, sensitivity analysis helps better to interpret the system and enhance the understanding of the relationships between input and output variables (Labourte, 2006).

This model result could be analyzed by examining the sensitivity test to the parameters value or the variation of land use allocations obtained when small changes are given for the objective values. Linear programming has standard analysis (Sharifi, 2008). For example, in this study the energy and GHG emissions can be reduced, by increasing the carbon for changing parameter values. The sensitivity analysis has a disadvantage in that this is an incomplete analysis valid for only the limited range of the parameter values (Sharifi, 2008). In this study, the sensitivity analysis is carried out for three important aspects, which are related to land use input: carbon, energy and GHG in soils. Firstly, the effect of changing the carbon storage value on the scenarios results has been evaluated; secondly, the effect of increasing carbon is analysed. Clearly, carbon value in soil is the most effective parameter rather than carbon value in biomass because there is a lot more carbon in soils than in biomass. This means that carbon is the key factor in this research for model optimization, and thirdly the effect of reducing the energy and GHG is analysed. With regards to the above discussions about the Linear Programming (LP) model, the sensitivity analysis has been run. The assumption is examining the effect of change in soil carbon by ±10% (addressed in section 5.4.2), ±30%, ±50%, ±70% and ±90%, on each specific value of top soils and total soils in only scenarios 1, 8 and 10. Referring to previous analysis of the top soil and total soil (section 4.3.1), those scenarios have shown more changes. All scenarios have been considered over the current situation (scenario one); it is important that the current situation is tested, as well. Then the current results were set up on the model and run. For more details in SA **(±10%**), refer to section 5.4.2.

5.4.1.1 Comparison of all SA (±10%, ±30%, ±50%, ±70%, and ±90%); Top soils and total soils under the objective function 1(Carbon Maximize)

- **Top Soils and Total soils**

Following our discussion about SA, the Linear programming model under objective function one has been run for top soil and total soils (for more details about soil depth and area allocation, refer to Chapter 3). The results of this analysis are shown in Table 5.9 and 5.10 for top soils and Table 5.11 and 5.12 for total soils can help to give a clear idea about the carbon value variety in land uses under the range of different scenarios for top soils and total soils. For full calculation of each SA assumption, refer to Appendix 3.

Table 5.9: Top soils sensitivity analysis for (±10%, ±30%, ±50%, ±70%, and ±90%) in the Tamar valley catchment.

Soil Types	Carbon Density ($t\ ha^{-1}$)	Density of C $t\ ha^{-1}$		Density of C $t\ ha^{-1}$		Density of C $t\ ha^{-1}$		Density of C $t\ ha^{-1}$		Density of C $t\ ha^{-1}$	
		-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Neath	27.5	24.8	30.3	19.25	37.75	13.75	41.25	8.25	46.8	2.8	52.3
Hallsworth 1	12.7	11.5	14	8.9	16.51	6.35	19.05	3.80	21.6	1.3	24.1
Hallsworth 2	12.7	11.5	14	8.9	16.51	6.35	19.05	3.80	21.6	1.3	24.1
Denbigh 2	10.2	9.2	11.3	7.14	13.26	5.1	15.3	3.05	17.4	1.1	19.4
Denbigh 1	10.2	9.2	11.3	7.14	13.26	5.1	15.3	3.05	17.4	1.1	19.4
Parc	3.9	3.5	4.3	2.73	5.07	1.95	5.85	1.2	6.7	0.4	7.4
Hafren	22.8	20.5	25.6	15.96	29.64	11.4	34.2	6.85	38.8	2.3	43.3
Moor Gate	17.1	15.4	18.8	11.97	22.23	8.55	25.65	5.15	29	1.7	32.5
Winter Hill	5.2	4.9	5.7	3.64	6.78	2.6	7.8	1.55	8.9	0.5	10
Hexworthy	3.7	3.4	4.1	2.6	4.81	1.85	5.55	1	6.3	0.4	7
Wilcocks 2	13.5	12.2	14.9	9.45	17.55	6.75	20.25	4	23	1.4	25.7
Powys	12.3	11.1	13.5	8.60	16	6.15	18.45	8.6	20.9	1.2	23.4
Yeollandpark	13.8	12.4	15.2	9.7	17.95	6.9	20.7	4.3	23.2	1.7	26.2
Princetown	43	38.7	47.3	30	56	21.5	64.5	12.9	73.1	4.4	81.7
Larkbarrow	6.3	5.7	6.9	4.4	8.2	3.15	9.45	1.9	10.7	0.7	12
Trusham	7.4	6.7	8.2	5.2	9.62	3.7	11.1	2.2	12.6	0.8	14
Laployd	35.4	31.9	38.9	24.8	46	17.7	53.1	10.6	60.2	3.6	67.3
Nordrach	9.7	8.7	10.7	6.8	12.6	4.85	14.55	2.9	16.5	1	18.4
Moretonham pstead	6.6	6	7.3	4.6	8.6	3.3	9.9	2	11	0.7	12.5
Raw china clay spoil	0		0	0	0	0	0	0	0	0	0
Onecote	14.3	12.9	15.8	10	18.6	7.15	21.45	4.3	24.3	1.5	27.2
Sportsmans	9.9	8.9	10.9	6.95	12.9	4.95	14.85	3	16.7	1	18.8
Halstow	8.4	7.6	9.3	5.9	10.95	4.2	12.6	2.5	14.3	0.9	16
Teme	4.9	4.4	5.4	3.45	6.4	2.45	7.35	1.5	8.5	0.5	9.3
Conway	27.5	24.8	30.3	19.25	35.75	13.75	41.25	8.3	46.8	2.8	52.3
Malvern	11.3	10.2	12.4	7.9	14.7	5.65	16.95	3.4	19.2	1.2	21.5
Manod	11.4	10.3	12.5	8	14.8	5.7	17.1	3.45	19.3	1.3	21.6
Alun	6.4	5.8	7.1	4.5	8.3	3.2	9.6	2.2	10.8	0.7	12.2
Crowdy 2	14.8	13.4	16.3	10.4	19.24	7.4	22.2	4.8	24.8	1.5	28.2

Table 5.10: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar Valley catchment under the objective function 1, in different Scenarios in top soils.

Scenarios	Energy Kt yr^{-1}	GHG Kt yr^{-1}	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
			-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Scenario 1	218.49	266.07	3.45	3.88	2.92	4.42	2.44	4.84	1.97	5.32	1.49	5.80
Scenario 8	178.85	218.54	4.45	4.90	4.02	5.51	3.54	5.94	3.07	6.42	2.60	7.10
Scenario 10	202.86	247.32	3.78	4.22	3.26	4.76	2.78	5.17	2.31	5.67	1.83	6.30

Table 5.11: Total soils sensitivity analysis for (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar Valley catchment.

Soil Types	Carbon Density (t ha^{-1})	Density of C t ha^{-1}		Density of C t ha^{-1}		Density of C t ha^{-1}		Density of C t ha^{-1}		Density of C t ha^{-1}	
		-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Neath	44.34	40	49	31.1	57.6	22.2	66.5	13.30	75.38	4.43	84.25
Hallsworth 1	25.71	23.2	28.8	18	33.5	12.9	38.6	7.71	43.71	2.57	48.85
Hallsworth 2	25.71	23.2	28.8	18	33.5	12.9	38.6	7.71	43.71	2.57	48.85
Denbigh 2	33.81	30.4	37.2	23.7	43.6	16.9	50.7	10.14	57.48	3.38	64.24
Denbigh 1	33.81	30.4	37.2	23.7	43.6	16.9	50.7	10.14	57.48	3.38	64.24
Parc	21.23	19.2	23.5	14.9	27.6	10.6	31.8	6.37	36.09	2.21	40.34
Hafren	31.76	28.6	35	22.3	41.3	15.9	47.6	9.53	53.99	3.18	60.34
Moor Gate	38.14	34.4	42.6	26.7	49.6	19.1	57.2	11.44	64.84	3.81	72.47
Winter Hill	11.8	10.6	13	8.3	15.4	5.9	17.7	3.54	20.06	1.18	22.42
Hexworthy	35.92	32.3	39.5	25.1	46.7	18	53.9	10.78	61.06	3.59	68.25
Wilcocks 2	40.17	36.2	44.3	28.2	52.3	20.1	60.3	12.05	68.29	4.02	76.32
Powys	24.18	21.8	26.6	17	31.4	12.1	36.3	7.25	41.11	2.42	45.94
Yeollandpark	18.39	16.6	20.5	12.9	23.9	9.2	27.6	5.52	31.26	1.84	34.94
Princetown	21.5	19.4	23.7	15	28	10.8	32.3	6.45	36.55	2.15	40.85
Larkbarrow	21.41	19.3	23.6	15	27.8	10.7	32.1	6.42	36.40	2.14	40.68
Trusham	23.83	21.4	26.3	16.7	31	11.9	35.7	7.15	40.51	2.38	45.28
Laployd	81.44	73.4	89.7	57	105.9	40.7	122.2	24.43	138.5	8.14	154.8
Nordrach	26.06	23.5	28.7	18.3	32.1	13	39.1	7.82	44.30	2.61	49.51
Moretonhampstead	40.96	36.9	45.1	28.7	53.3	20.5	61.4	12.29	69.63	4.10	77.82
Raw china clay spoil	0		0	0	0	0	0	0	0	0	0
Onecote	17.59	15.9	19.7	12.3	22.9	8.8	26.4	5.28	29.90	1.76	33.42
Sportsmans	19.19	17.3	21.2	13.4	25	9.6	28.8	5.76	32.62	1.92	36.46
Halstow	15.15	13.7	16.7	10.6	19.7	7.6	22.7	4.55	25.76	1.52	28.79
Teme	26.31	23.7	28.9	18.4	34.2	13.2	39.5	7.89	44.73	2.63	49.99
Conway	79.19	71.3	87.2	55.5	103	39.6	118.8	23.76	134.6	7.92	150.5
Malvern	20.94	18.8	23.1	14.7	27.3	10.5	31.4	6.28	35.60	2.09	39.79
Manod	32.91	29.6	36.2	23	42.8	16.5	49.4	9.87	55.95	3.29	62.53
Alun	29.46	26.6	32.6	20.7	38.6	14.7	44.2	8.84	50.08	2.95	55.97
Crowdy 2	87.4	78.7	96.2	63.3	113.6	43.7	131.1	26.22	148.9	8.74	166.1

Table 5.12: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) in the Tamar valley catchment under the objective function 1, in different Scenarios in total soils.

Scenarios	Energy Kt yr^{-1}	GHG Kt yr^{-1}	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
			-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Scenario 1	218.49	266.07	6.69	7.92	5.49	9.12	4.28	10.33	3.05	11.55	1.85	12.77
Scenario 8	178.85	218.54	7.79	9.02	6.56	10.22	5.38	11.43	4.15	12.64	2.95	13.87
Scenario 10	202.86	247.32	7.03	8.26	5.83	9.46	4.62	10.67	3.39	11.90	2.19	13.11

Table 5.9 and Table 5.11 show a variety of carbon density based on carbon density values in different soil types in top and total (addressed in Chapter 4) under different SA. Table 5.10 and table 5.12 show SA for ±10%, ±30%, ±50%, ±70%, and ±90% values under objective function one (Carbon maximize) in top and total soils. The outputs are Mtonne carbon, energy and GHG emissions. As is clear, scenario 8 has the highest amount of carbon value and lowest amount of energy and GHG emissions compared to other scenarios. Also, with all of this being SA tested, it emphasises that the carbon parameter is playing the key role in this research. The amount of energy and GHG emissions have in fact only slightly changed.

5.4.1.2 Comparison of all SA (±10%, ±30%, ±50%, ±70%, and ±90%); Top soils and total soils under the objective function 2(Energy Minimized)

- **Top Soils and Total soils**

Following our description (above) about SA, the Linear programming model under objective function two has been run for top soil and total soils. The results of this analysis are shown in Table 5.13 for top soils and Table 5.14 for total soils; it can help to give a clear idea about the carbon value variety in land uses under the range of different scenarios for top soils and total soils. For a full calculation of each SA assumption, refer to Appendix 3.

Table 5.13: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar valley catchment under the objective function 2, in different Scenarios in top soils.

Scenarios	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
	-10%	+10%	-30%	+30%	-50%	+50%	-70%	+70%	-90%	+90%
Scenario 1	3.42	3.79	2.93	4.47	2.51	4.90	2.03	5.31	1.56	5.86
Scenario 8	4.57	5.05	4.01	5.57	3.60	6.04	3.13	6.41	2.65	6.96
Scenario 10	3.80	4.29	3.32	4.81	2.84	5.24	2.38	5.65	1.90	6.20

Table 5.14: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar valley catchment under the objective function 2, in different Scenarios in total soils.

Scenarios	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
	-10%	+10%	-30%	+30%	-50%	+50%	-70%	+70%	-90%	+90%
Scenario 1	6.76	7.83	5.60	8.98	4.33	10.16	3.12	11.36	1.92	12.54
Scenario 8	7.86	9.09	6.66	10.05	5.44	11.26	4.18	12.45	3.01	13.59
Scenario 10	7.10	8.33	5.90	9.32	4.68	10.50	3.46	11.69	2.25	12.83

Table 5.13 and Table 5.14 show SA for ±10%, ±30%, ±50%, ±70%, and ±90% values under objective function two (energy minimized) in top and total soils. The outputs are in Mtonne carbon. The amount of energy and GHG emissions under this model run in fact have changed slightly, but the total amount is the same as the previous model run, so it has not been mentioned here. As is clear, in this model, scenario 8 has the highest amount of carbon value and lowest amount of energy and GHG emissions, compared with other scenarios.

5.4.1.3 Comparison of all SA (±10%, ±30%, ±50%, ±70%, and ±90%); Top soils and total soils under the objective function 3(GHG Minimized)

- Top Soils and Total soils

In this part, being subsequent to above outputs SA (±10%, ±30%, ±50%, ±70%, and ±90%) the model under objective function three which is GHG minimization for top soil and total soils has been run. Table 5.15 and Table 5.16 will describe the variety of carbon values under the range of different scenarios. For a full calculation of each SA assumption, refer to Appendix 3.

Table 5.15: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar valley catchment under the objective function 3, in different Scenarios in top soils.

Scenarios	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
	-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Scenario 1	3.42	3.95	2.93	4.47	2.47	4.90	2.04	5.38	1.56	5.86
Scenario 8	4.57	5.05	4.01	5.57	3.60	5.98	3.07	6.48	2.65	6.96
Scenario 10	3.77	4.29	3.32	4.81	2.84	5.17	2.38	5.75	1.90	6.20

Table 5.16: Total outputs of SA (±10%, ±30%, ±50%, ±70%, and ±90%) at the Tamar valley catchment under the objective function 3, in different Scenarios in total soils.

Scenarios	Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon		Mt Carbon	
	-10%	**+10%**	**-30%**	**+30%**	**-50%**	**+50%**	**-70%**	**+70%**	**-90%**	**+90%**
Scenario 1	6.70	7.99	5.56	8.98	4.34	10.17	3.12	11.26	1.92	12.51
Scenario 8	7.84	9.09	6.66	10.08	5.44	11.25	4.22	12.45	3.02	13.60
Scenario 10	7.10	8.33	5.90	9.32	4.68	10.51	3.46	11.69	2.23	12.85

Table 5.15 and Table 5.16 show SA for ±10%, ±30%, ±50%, ±70%, and ±90% values under objective function three (GHG minimize) in top and total soils. The outputs are Mtonne carbon. The amounts of energy and GHG emissions under this model are the same and show a slight difference from the amount of other objective functions. This means that minimizing the energy and GHG emissions could have an effect on capturing carbon. In this optimized model, the amount of carbon in scenario 8 is remarkable. Also, this scenario has the lowest amount of energy and GHG emissions compared with other scenarios. All considered, the amount of carbon in SA analysis under objective function three has a larger amount. In terms of carbon level exchange at SA by for ±10%, ±30%, ±50%, ±70%, and ±90%; scenario 8 still has highest amount from scenario 1.

5.4.2 Data Confidence Test

The periodical testing of a product or result is called a Confidence Test. The results presented here are based on model parameters (e.g. Soil carbon density and biomass value) taken from secondary data. Each parameter is likely to have uncertainties associated with it, and these uncertainties may impact on the output results of the analysis (Refer to section 5.4.1, SA). This section attempts to assess the importance of each parameter by under taking a confidence test for data (±10%) and sensitivity analysis as described above (addressed in section 5.4.1). The soil's carbon value is more important than biomass carbon value. A confidence test confirms that the results of a program lie within a certain range according to the expected distribution. The reason for using the confidence test in this research is to assess the impact of the error on the model. A Confidence test is necessary because it increases confidence in results. Therefore ±10% of original and key parameter value (carbon value) in top soils and total soils has been considered and then a model has been run for all of the different scenarios.

5.4.2.1 Top and Total Soils (±10%) Confidence Test; (objective function 1, 2 and 3)

- Top soils

Referring to the above description of the confidence test, the following comprehensive results have come from an assumption of ±10% under the objective functions one, two and three in the range of all scenarios in top and total soils (Tables 5.17 and 5.18). Figures 5.5 and 5.6 show the percentage changes over the current situation in top and total soils.

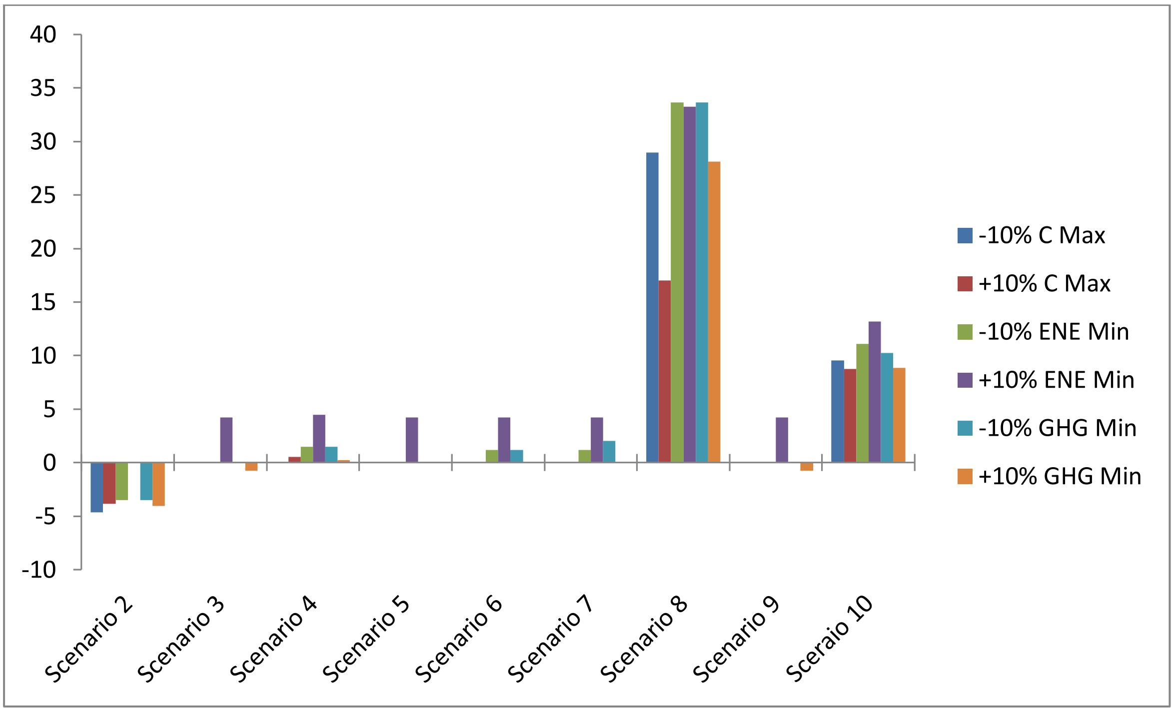
Table 5.17: Results output of confidence test (±10%) under different objective functions (one, two and three) in top soils under the different range of scenarios.

Scenarios	Mt C under Objective Function 1		Mt C under Objective Function 2		Mt C under Objective Function 3		Percent changes under objective function 1		Percent changes under objective function 2		Percent changes under objective function 3		ENE Emissio-ns Kt yr^{-1}	GHG Emissi-ons Kt yr^{-1}
	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %		
Scenario 1	**3.45**	**3.88**	**3.42**	**3.79**	**3.42**	**3.95**	**-**	**-**	**-**	**-**	**-**	**-**	**218.48**	**266.07**
Scenario 2	**3.29**	**3.73**	**3.30**	**3.79**	**3.30**	**3.79**	**-4.64**	**-3.87**	**-3.51**	**0.06**	**-3.51**	**-4.06**	**218.48**	**266.07**
Scenario 3	**3.45**	**3.88**	**3.42**	**3.95**	**3.42**	**3.92**	**0.05**	**0.04**	**0.03**	**4.22**	**0.03**	**-0.76**	**223.77**	**272.07**
Scenario 4	**3.45**	**3.90**	**3.47**	**3.96**	**3.47**	**3.96**	**0.04**	**0.52**	**1.46**	**4.49**	**1.46**	**0.26**	**217.69**	**265.11**
Scenario 5	**3.45**	**3.88**	**3.42**	**3.95**	**3.42**	**3.95**	**0.05**	**0.03**	**0.02**	**4.23**	**0.04**	**0.05**	**218.48**	**266.07**
Scenario 6	**3.45**	**3.88**	**3.46**	**3.95**	**3.46**	**3.95**	**0.03**	**0.02**	**1.17**	**4.24**	**1.17**	**0.04**	**222.45**	**270.57**
Scenario 7	**3.45**	**3.88**	**3.46**	**3.95**	**3.49**	**3.95**	**0.04**	**0.03**	**1.17**	**4.23**	**2.05**	**0.05**	**231.05**	**280.33**
Scenario 8	**4.45**	**4.54**	**4.57**	**5.05**	**4.57**	**5.06**	**28.99**	**17.01**	**33.63**	**33.25**	**33.63**	**28.11**	**178.85**	**218.54**
Scenario 9	**3.45**	**3.88**	**3.42**	**3.95**	**3.42**	**3.92**	**0.05**	**0.02**	**0.04**	**4.22**	**0.02**	**-0.76**	**218.48**	**266.07**
Scenario 10	**3.78**	**4.22**	**3.80**	**4.29**	**3.77**	**4.30**	**9.57**	**8.77**	**11.11**	**13.19**	**10.24**	**8.87**	**202.85**	**247.32**

Table 5.17 shows the amount of carbon value, energy and GHG emissions and percentage changes under consideration of different objective functions in a range of scenarios in (±10%) confidence tests in top soils. The amount of energy and GHG emissions gave minor changes. Following our discussions in SA, energy and GHG emissions have a very small value, so the impact of value changes is not great. The amount of carbon stored under objective functions two and three in (+10%) confidence tests is higher than the results under objective function one, when considering the percentage changes; the changes under different objective functions varies. Scenarios 2, 8 and 10 have higher rates of changes and scenario 6 has a small amount of change. Also, the amount of percentage change in scenario 3 under objective function 2, compared with other values in (+10%) of confidence tests is remarkable. Scenario 8 has a fairly large amount of changes under (±10%) of confidence tests. The variety of changes in carbon value in each scenario is not great but shows a clear change. So, the impact of confidence tests can show that change in input values can have an effect on the final output carbon value in each scenario.

Figure 5.5: Percentage changes of (±10%) confidence test under different objective functions

(one, two and three) in top soils under the different range of scenarios).



In accordance with the confidence test, Figure 5.5 has visualized the percentage changes under objective functions one, two and three in different scenarios. The amount of percentage changes in these scenarios clearly shows a difference compared with fundamental results (addressed to section 5.3). The percentage changes in different scenarios, compared with outputs from objective function one are remarkable. Referring to this, most of the scenarios have more potential for changes. Meanwhile, scenarios 8 and 10 have the highest portion of changes compared with other scenarios and the difference between scenario 8 and 10 and all other scenarios is apparent, even when the inputs vary by ±10%.

- **Total Soils**

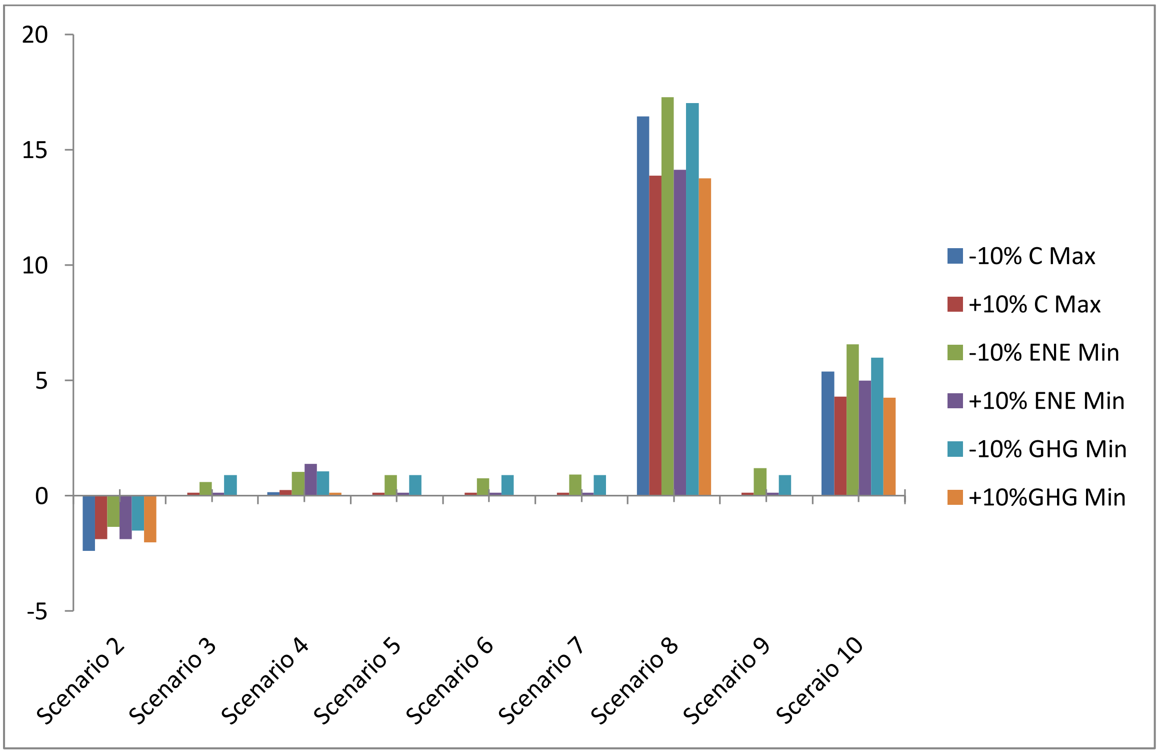
Referring to the above description of the confidence test and results output in top soils, the following results have arisen from objective functions one, two and three under all different scenarios in total soils (Table 5.18 and Figure 5.6). The same process has been followed in total soils.

Table 5.18: Results output of confidence test (±10%) under different objective functions (one, two and three) in total soils under the different range of scenarios.

Scenarios	Mt C under Objective Function 1		Mt C under Objective Function 2		Mt C under Objective Function 3		Percent changes under objective function 1		Percent changes under objective function 2		Percent changes under objective function 3		Energy emissio-ns Kt yr^{-1}	GHG Emissi-ons Kt yr^{-1}
	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %	-10 %	+10 %		
Scenario 1	**6.69**	**7.92**	**6.71**	**7.99**	**6.70**	**7.99**	**-**	**-**	**-**	**-**	**-**	**-**	**218.48**	**266.07**
Scenario 2	**6.53**	**7.77**	**6.62**	**7.84**	**6.60**	**7.83**	**-2.39**	**-1.89**	**-1.34**	**-1.88**	**-1.50**	**-2.01**	**218.48**	**266.07**
Scenario 3	**6.69**	**7.93**	**6.75**	**8.00**	**6.76**	**7.99**	**0.02**	**0.13**	**0.60**	**0.13**	**0.90**	**0.02**	**223.77**	**272.07**
Scenario 4	**6.70**	**7.94**	**6.78**	**8.10**	**6.77**	**8.00**	**0.15**	**0.25**	**1.04**	**1.38**	**1.05**	**0.13**	**217.69**	**265.11**
Scenario 5	**6.69**	**7.93**	**6.77**	**8.00**	**6.76**	**7.99**	**0.03**	**0.14**	**0.90**	**0.13**	**0.90**	**0.02**	**218.48**	**266.07**
Scenario 6	**6.69**	**7.93**	**6.76**	**8.00**	**6.76**	**7.99**	**0.01**	**0.13**	**0.75**	**0.14**	**0.90**	**0.01**	**222.45**	**270.57**
Scenario 7	**6.69**	**7.93**	**6.77**	**8.00**	**6.76**	**7.99**	**0.02**	**0.13**	**0.91**	**0.13**	**0.89**	**0.02**	**231.05**	**280.33**
Scenario 8	**7.79**	**9.02**	**7.87**	**9.12**	**7.84**	**9.09**	**16.44**	**13.89**	**17.29**	**14.14**	**17.02**	**13.77**	**178.85**	**218.54**
Scenario 9	**6.69**	**7.93**	**6.79**	**8.00**	**6.76**	**7.99**	**0.02**	**0.13**	**1.20**	**0.13**	**0.90**	**0.02**	**218.48**	**266.07**
Scenario 10	**7.05**	**8.26**	**7.15**	**8.39**	**7.10**	**8.33**	**5.38**	**4.30**	**6.57**	**5.00**	**5.98**	**4.26**	**202.85**	**247.32**

Table 5.18 shows the amount of carbon value, energy and GHG emissions, and percentage changes under consideration of different objective functions in a different range of scenarios in (±10%) confidence test in total soils. In fact, the amount of energy and GHG emissions gave minor changes. Following our discussions in SA, energy and GHG emissions have a very small value, so the impact of value changes is not great. The amount of carbon under objective functions two and three in (±10%) confidence tests is higher than results under objective function one. Considering the percentage changes, the variety of changes under different objective functions is different. Scenarios 2, 8 and 10 have more rates of change and scenario 6 has a small amount of change. Scenario 8 has a fairly great amount of changes under (±10%) in the confidence tests. The varied amount of changes in carbon value in each scenario is not great but shows a clear change. Thus, the impact of confidence tests can affect the carbon value in each scenario and as a result will affect variation amounts in different scenarios. Results are similar in significance to those for top soils.

Figure 5.6: Percent changes of (±10%) confidence test under different objective functions (one, two and three) in total soils under the different range of scenarios.



According to the discussion and model run for the confidence test, Figure 5.6 has shown the percentage changes under objective functions one, two and three in different scenarios. The amount of percentage changes in these scenarios clearly shows a difference in comparison with fundamental results (addressed to section 5.3). The percentage changes in different scenarios in comparison to outputs from objective function one are notable. In accordance with this, most of the scenarios have more potential for changes. Meanwhile, scenarios 2, 8 and 10 have the highest portion of changes with comparison to other scenarios.

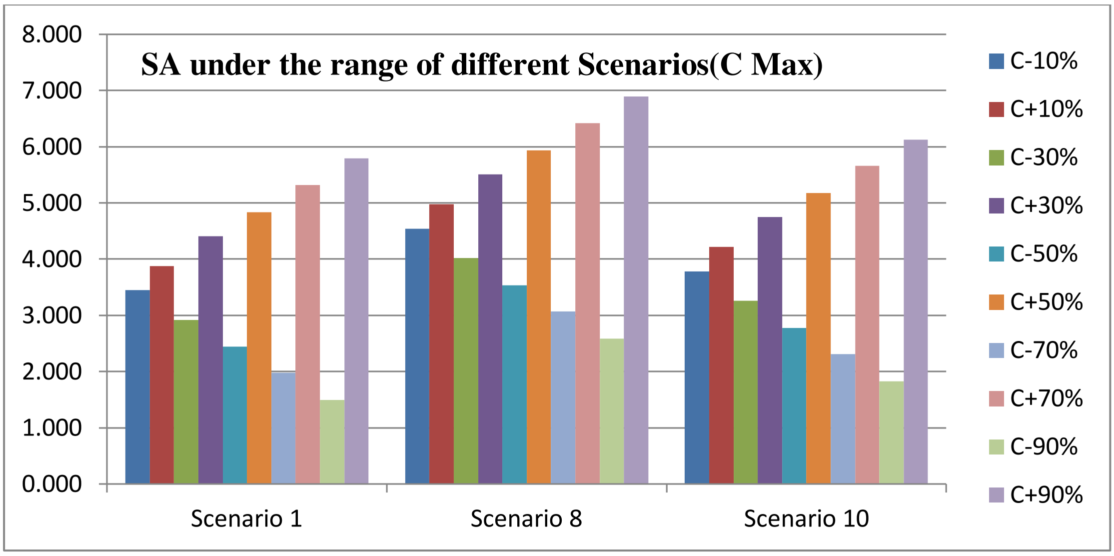
5.5 Final Overview of Sensitivity Analysis under different Assumption

5.5.1 Top Soils

According to section 5.4 outputs, the following results will give a clear idea about sensitivity analysis (SA) in this area. As the figures show, in all cases, the relationship between uncertainty amounts and output carbon is linear and scenarios 8 and 10 are the best to match with this target. Figures 5.7, 5.8 and 5.9 describe the SA comparison (±10%, ±30%, ±50%, ±70%, ±90%) under the different objective functions.

With reference to these figures, it is confirmed that there is a linear and direct relationship between values of soil carbon and output results. This point is expected, because soil values are a fixed term in the model. Soil distribution does not change in the model, and the amount of carbon in the soils does not change, but the amount of carbon under circumstances and parameters can change. In this research, this relationship with consideration of all issues has become linear. Scenario 8 has the highest value of carbon in all SA assumptions with different objective functions.

Figure 5.7: All SA carbon outputs (Mt C) comparison under the objective function one, in top soils.



The optimization model result under objective function one (carbon maximized) is presented in Figure 5.7. This result describes comparison of the amount of carbon under different sensitivity analysis assumptions in scenarios 1, 8 and 10. Total amount of carbon has increased with the increased sensitivity analysis assumption amount (+10%, +30%, +50%, +70% and +90%); and it also decreases with the decreased amount (-10%, -30%, -50%, -70% and -90%). In comparison with the current scenario, the two other scenarios have the highest amount of carbon.

Figure 5.8: All SA carbon outputs (Mt C) comparison under the objective function two, in top soils.

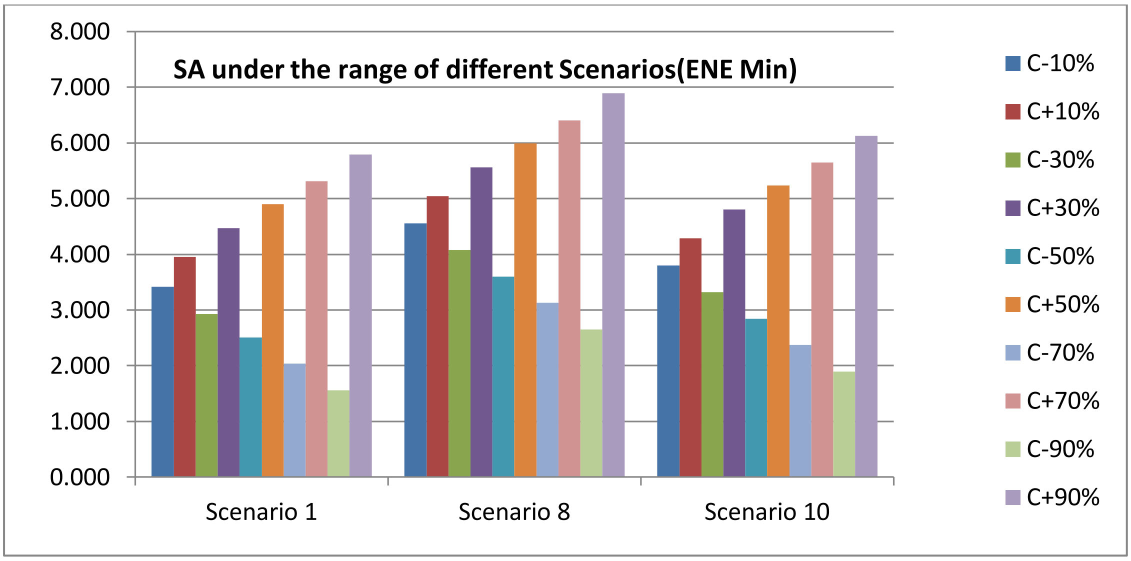
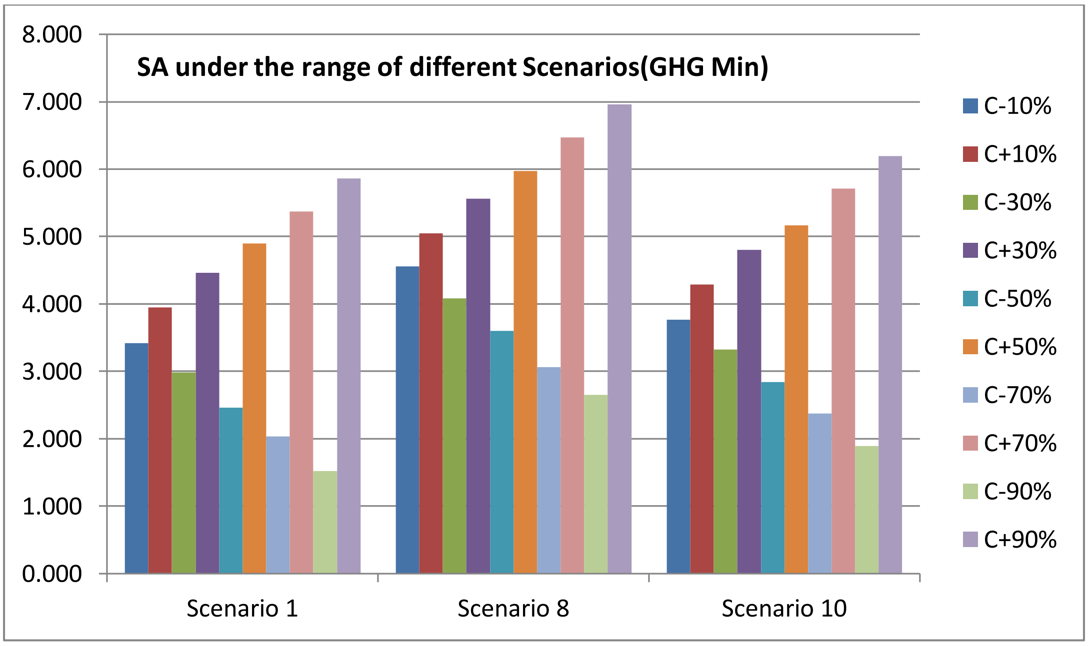


Figure 5.9: All SA carbon outputs (Mt C) comparison under the objective function three, in top soils.

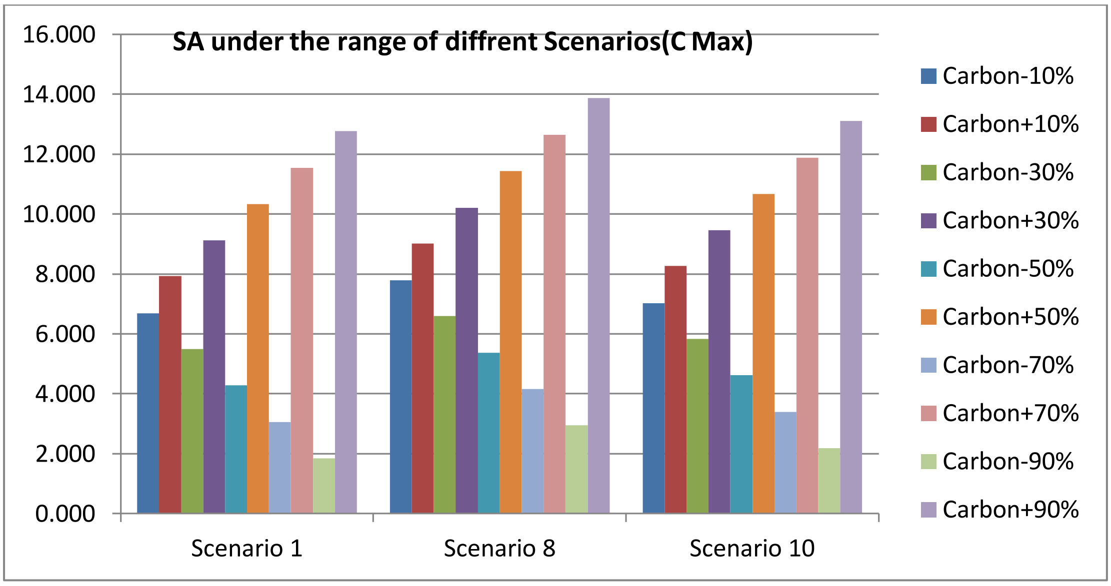


These figures show the results of the sensitivity analysis to the parameter values (carbon) for objective functions two and three (energy and GHG minimized). Figures 5.8 and 5.9 represent the output comparisons under these objective functions in top soils. In addition to the above description, the values increase with the increased sensitivity analysis and decrease with the decreased sensitivity analysis. The carbon values under objective function two are slightly higher than values under objective function three.

5.5.2 Total Soils

The same process has been followed in total soils. In total soil outputs, the relationship between soil carbon and uncertainty amount is linear as well (refer to section 5.5.1). Figures 5.10, 5.11 and 5.12 show the SA outputs under different objective functions.

Figure 5.10: All SA carbon outputs (Mt C) comparison under objective function one, in total soils.



The optimization model result under objective function one (carbon maximized) has been presented in Figure 5.10. This result described a comparison of the amount of carbon under different sensitivity analysis assumptions in scenario 1, 8 and 10. Total amount of carbon has increased with the increased sensitivity analysis assumption amount (+10%, +30%, +50%, +70% and +90%); and it also decreases with the decreased amount (-10%, -30%, -50%, -70% and -90%). Scenario 8 has the highest amount of value under all sensitivity analysis.

Figure 5.11: All SA carbon outputs (Mt C) comparison under the objective function two, in total soils.

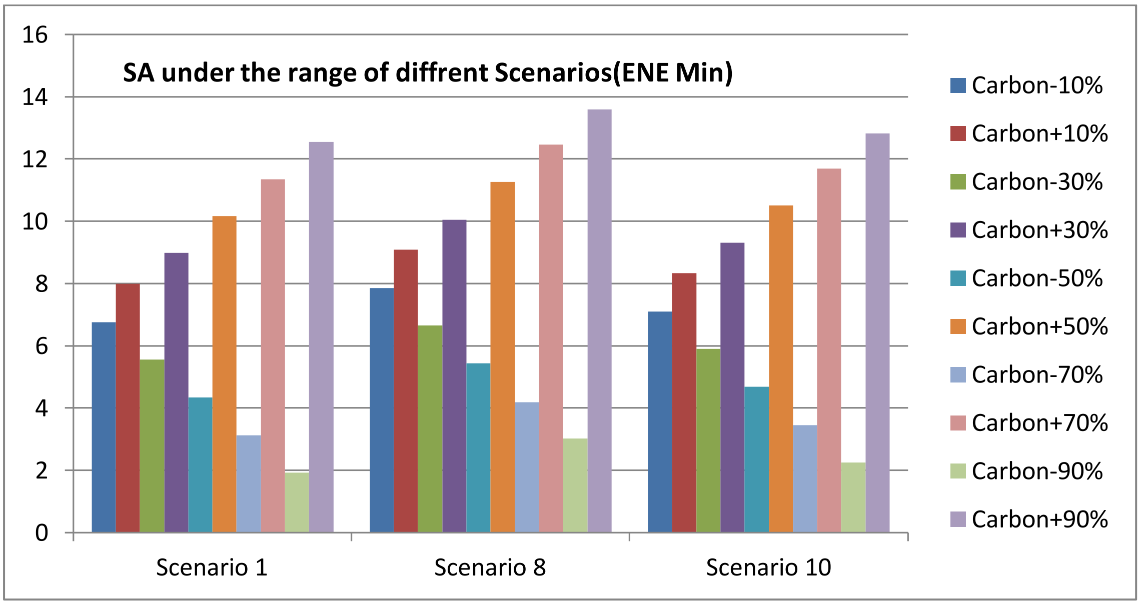
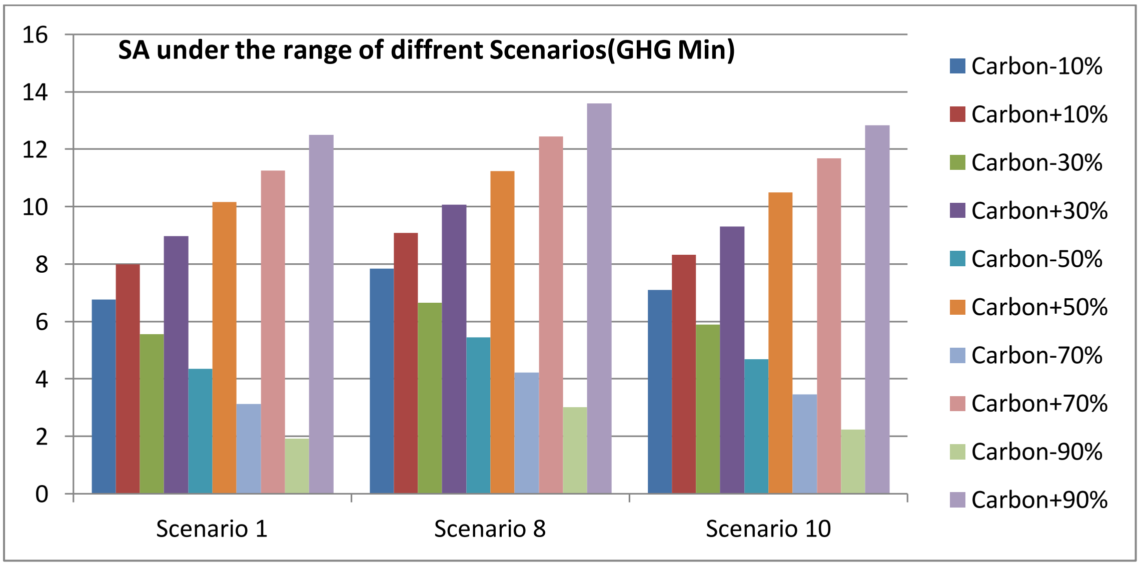


Figure 5.12: All SA carbon outputs (Mt C) comparison under the objective function three, in total soils.



Figures 5.11 and 5.12 present the outputs comparison under objective functions two and three (energy and GHG minimized). With an increase and decrease of carbon parameters in sensitivity analysis under these optimized models, the amount in the scenarios has changed too. Scenario 8 has a great amount of carbon value changes.

5.5.3 Total Area Allocation under the range of different Scenarios in Top and Total soils

Land use allocation varies with different use requirements. In the Tamar Valley catchment, nineteen land cover types have been defined (addressed in Chapter 4). The main land uses are of forestry land, grassland, agricultural land and urban land. The maximization of total carbon amount, minimization of energy and GHG emissions are used for these requirement options. Except that some land that has been limited (addressed in section 5.2) the rest of the land has not been limited. The largest land uses are forestry, grasslands and agricultural land for the model optimized. The effect of total carbon increase (storage) and energy and GHG emissions reduction on the land use allocation depends on the objectives to be optimized. In the maximization of total carbon value, the land use allocation has been strongly affected, i.e., all possible land uses for increasing carbon amounts have been considered. Table 5.19 and Figure 5.13 display the total output per area allocation per each land cover type on a range of different scenarios in top and total soils. The output of land allocation (ha) for all objective functions had the same amount, so only general output has been taken out. The maximum area allocated in top and total soils has been covered by improved grassland in the Tamar Valley catchment under all objective functions. Each land cover type has been allocated by GIS code (addressed to Chapter 4) for easier understanding and display. Scenario 3 has the highest portion of land cover and scenario 8 has the lowest cover.

Table 5.19: Area (ha) outputs comparison per each land cover type in the model optimized under the different range of scenarios (refer to Appendix 1 for the list of land cover type codes).

Land cover types	11	21	41	42	51	61	71	81	91	101	102	121	131	161	171	172	211	212	221
Scenario 1	17797.3	4562.9	20428.8	17191.9	80774.1	4048.9	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	1137.2	9628.2	2371.0	0	111.3	478.8
Scenario 2	15130.36	4106.64	20428.8	17191.9	80774.1	4048.9	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	1656.9	12295.8	2307.7	0	111.3	478.8
Scenario 3	17797.3	4562.9	20428.8	13753.6	84212.6	4048.9	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	1137.2	9628.2	2371.0	0	111.3	478.8
Scenario 4	17797.3	4967.78	20428.8	17191.9	80774.1	3644.0	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	1055.8	9628.2	2371.0	0	111.3	478.8
Scenario 5	17797.3	4562.9	20428.8	17191.9	81988.7	2834.5	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	1656.9	872.3	0	0	111.3	478.8
Scenario 6	17797.3	4562.9	20428.8	14613.5	83353	4048.9	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	0	8472.8	2371.0	0	111.3	478.8
Scenario 7	19045.7	4562.9	12257.3	17191.9	80774.1	4048.9	12134	14342	0.6	282.1	2857.4	2052.4	0	0	9628.2	2371.0	0	0	1014.2
Scenario 8	39236.95	4562.9	20428.8	17191.9	60582.8	4048.9	8048.4	10256.2	0.6	282.1	2857.4	2052.4	0	0	9628.2	2371.0	0	0	1014.2
Scenario 9	19045.7	4562.9	20428.8	17191.9	80774.1	5256.2	6841.2	10256.2	0.6	282.1	2857.4	2052.4	0	0	9628.2	2371.0	0	0	1014.2
Scenario 10	24173.76	7397.16	20428.8	17191.9	80774.1	1214.7	4024.2	5128.2	0.6	282.1	2857.4	2052.4	0	0	9628.2	2371.0	0	0	1014.2

Figure 5.13: Land area allocation (ha) outputs per each land cover type in optimized model under the different range of scenarios.

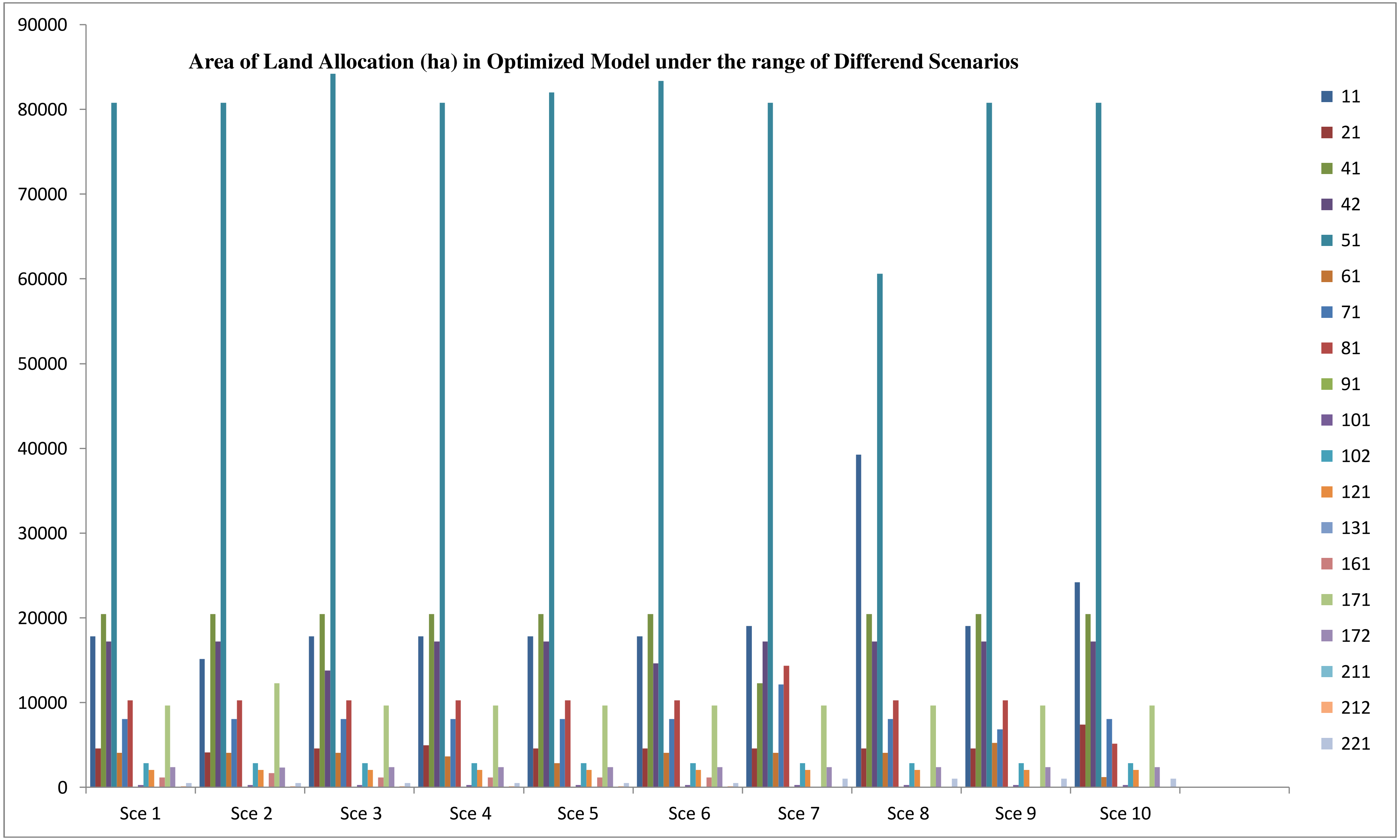


Figure 5.13 presents the land area allocation output (hectare) per each land cover type in the optimized model under the different range of scenarios (see Table 5.20 for GIS code). The highest portion of Improved grassland and Broadleaf forestry land has been allocated in scenarios 3 and 8, relatively.

Table 5.20: Land Cover types specific code in GIS system in the Tamer Valley catchment.

Vegetation Types	Vegetation Codes
Broad-leave Woodland	11
Coniferous Woodland	21
Arable Cereals	41
Arable Horticulture	42
Improved Grassland	51
Neutral Grass	61
Calcareous Grass	71
Acid Grass	81
Bracken	91
Dwarf Shrub Heath	101
Open Dwarf Shrub Heath	102
Bog	121
Water	131
Inland Bare ground	161
Suburban /Rural development	171
Continuous Urban	172
Littoral Rock	211
Salt Marsh	212
Sea	221

5.6 Conclusions

The scenarios presented in this chapter are considered to be crucial and relevant to the main problems as detected by government and globally for reducing GHG emissions. Therefore, following the government or local region's target (reducing the GHGs emissions in the near or distant future), based on current knowledge, availability and understanding of agriculture and forest land development, these scenarios have been considered. However, these presented scenarios should not be considered as a final solution. Other possibilities could be formulated and structured by other preferences. With these assumptions and goals, different scenarios have been generated and analysed by a Linear Programming (LP) model.

The scenario results presented in this chapter give the possible future land development (agriculture and forest management practises) assessed in terms of carbon dynamics. This work is based on assumptions (section 5.2.3), which does not mean that these goals will certainly be achieved in the assumed time scale. The results are generated for explicit assumptions with consideration of, e.g. the UK reduction target, the Government's policy, land structure and economic price in this area, agriculture and forest development. In changing any of these assumptions, these results may be affected. The methodology presented in this research (section 5.2), enables the analysis of consequences and outcomes of these assumptions.

This data analysis shows the results for the agriculture and forestry land uses (models 1, 2, and 3), and farm business income (model 4) models under the range of different scenarios in top and total soils. These baseline results satisfactorily reproduce the current situation under the different assumption on an uncertain future (Scenarios), as shown for above models. These models are a kind of explorative-type model, i.e. they analyse technically feasible options in a given area: and hence, their results cannot be compared with the current situation.

Model 1 results show similar carbon output values for today and for the future from different land use types in agriculture and forestry lands. Land area allocations also differ, because the land use types vary in areas. The area under Broadleaf woodland and Improved grassland are the largest for saving the carbon amounts, both of which have high proportions of land devoted to them.

The results of models 2 and 3 show aggregate results for energy and GHG emissions on different land use types in top soils and total soils. These results do not show large differences in emissions and land allocation has been compared to model 1 results as well. The objective function of models 2 and 3 considers both emissions and carbon value.

Results from model 4 show the Net Farm Business Income (Net FBI) under objective functions 1, 2 and 3, the optimum situation for the extracted values for farm income.

Assessment of agricultural and forestry policies is necessary to examine and explain which are most effective in attaining carbon saving and reduction of GHG emissions, economics and environmental goals. Quantification of the trade-offs in terms of cost of the policy and benefits delivered from its implementation would provide helpful inputs and outputs in the carbon saving and reduction policy debate and discussions (section 5.1.2). A general observation here on soil carbon: it remains unchanged in modelling but in reality it will change with land use, especially over time.

With this technical innovation, the Optimization and Linear Programming model shows the positive effect on net saving. Alternative techniques that lead to increased forest and permanent grassland have potential for adoption by farmers and contribute to attaining objectives on farm, local and regional scales.

The optimization including current and all alternative technologies show the comparative attractiveness of the alternative technologies and possible impacts of adoption. Comparison of results of models 1, 2, 3 and 4 values for this site area shows that prioritizing the carbon saving aims may conflict with economic objectives.

In the site area (Tamar Valley), a high proportion of the area is Improved grassland. Comparing land area allocations in all models with the results is Improved grassland, but an area allocation under profitable when objectives are optimized (Model 1, 2 and 3) is Broadleaf forests. The consequence is an increase in net carbon and emissions. The presented results of this chapter can be summarised with the following perspectives:

A Large potential exists for increasing carbon storage, and reducing the energy and GHG emissions in the Tamar valley catchment. In general, the carbon amount can be increased to a very high level and energy and GHG emissions decreased to a low level with a small sacrifice of the optimal values of other objective functions in top and total soils in this area (Table 5.6 and 5.7, and Fig. 5.3 and 5.4). The carbon storage aim is largely in line with the goals of increasing the permanent grassland and forestry land in this area. Conversion to forestry land has a marked impact on total carbon amount stored in most objectives, i.e., increasing the Broadleaf and coniferous forest land can considerably increase the total amount of carbon stored and reduce the energy and GHG emissions in top and total soils (scenarios 8 and 10). General potential exists for reducing the energy and GHG emissions amount by using more permanent and short growth rate grassland. Also, this study reveals a considerable possibility for increasing the amount of total carbon in top and total soils (sensitivity analysis results, Table 5.15 and 5.16).

Great potential exists to produce the agricultural requirement (Cereal and Horticulture) using a limited cropping area and increase of the grassland area. By limiting and decreasing the agricultural area in Tamar Valley to the most productive grassland product types (convert to grassland such as Acid grassland or Natural grassland), the use of fertilizers, direct and indirect energy and the total cost can be largely reduced but the total carbon amount will increase in top and total soils (scenarios 3, 6 and 7., see Tables 5.6 and 5.7). Net income will increase. This particular agricultural system is possible on an intensive agriculture farm with a minimum input of chemicals. In this system, the input of chemicals can be greatly decreased by incorporating the use of natural resources, with an organic farming system, such as growing and cultivating more leguminous product and forage crops. This agricultural production and practise system is called environment-friendly.

Excellent agriculture and forestry land development could be generated, but there are some restrictions such as allocation, economics and policy. Land allocation area resources are a major restriction for increasing the agriculture and forest land in this area. The results of scenarios and trade-off analyses all demonstrate that (section 5.2.2). Also, the analysis of total carbon and emissions with regards to net farm income demonstrated that land conversion to optimise carbon saving is not simple and has economic consequences. In the final analysis, potential for increasing and developing the forest and agricultural land is available.

Chapter 6

Presentation of the Optimization Results: 2

Chapter 6 Presentation of the Optimization Results: 2

1. Equilibrium Values and Trade-off Analysis

6.1 Introduction

In Chapter 5, the great values of three objective functions have been calculated and compared for different scenarios. These objective functions are calculated individually by various base runs of Linear Programming (LP) model under a set of constraints and other requirements. This chapter focuses on applying the linear programming (LP) modelling to calculate net carbon saving and losses under each scenario over time using an Equilibrium approach. The need to include equilibrium in the system is to analyse the carbon value exchange in biomass. The carbon flux in soil has been assumed is fixed and has no change or very minimal change, but change in biomass varies considerably with time.

Section 6.2 of this chapter describes the equilibrium values and basic constraints incorporated within this model and criteria requirements for this land use. Section 6.3 presents the net carbon saving and trade-offs, with focus on energy and GHG emission. Next, some examples of the total amount of carbon and their changing in some scenarios are presented (in map form) in section 6.4. Finally, conclusions are present in section 6.5.

6.2 Equilibrium Model

The amount of total carbon, energy and GHG emissions under different range of scenarios has been considered in Chapter 5. There are two different types of model; dynamic and equilibrium, which can be used to present these results. Dynamic modelling is large and useful for modelling simple procedures over time. Dynamic modelling has become surrounded by some conditioning. In dynamic modelling new characteristics are calculated as a function of characteristic changes over time (Paul, 1984; Ma and Nakamori, 2009). Dynamic modelling focuses the results of land use change as if the total change is achieved instantaneously.

In this chapter, the focus is on equilibrium results in land cover types in this site area. An equilibrium model shows the cumulative effect of change over time. In order to fulfil this task, firstly a fundamental model of equilibrium has been viewed, since the type of land cover (biomass) impact on the system makes a difference for a total carbon or not.

Equilibrium is a model that describes differences between temporal task and geographical scales (Aherne et al., 2011). Moreover, examination and analysis of equilibrium is significant only under some assumptions on its "representativeness" (its closeness to the actual acceptability of the system) and analytical properties, such as existence, singularity, and stability (Cannell, 2003). In equilibrium there should be a factor-clear (parameter) and land use. A dynamic equilibrium or steady state is considered in this chapter. A dynamic equilibrium exists when a chemical reaction that results in an equilibrium mixture of products stops to change its relation of products, but matters move between the chemicals at an equal rate, meaning there is no net change. It is a particular example of a system in a steady state (Laborte et al., 2007).

When a system is in a steady state, it means that the system has many possessions that are unchanging in time. This means that for any possession p of the system, the partial differential with regard to time is zero (Zhang, 2011). Steady state is a more general situation than dynamic equilibrium. On the other hand, steady state is a "condition of a physical system that does not change over time, or in which any one change is continually balanced by another, such as the stable condition of a system in equilibrium" (Sharifi, 2008). The steady state model in this research has been preferred because of the following reasons:

1): difficulty at this stage with existing Linear programming model to incorporate dynamic changes, 2): secondary data sets needed to consider biomass, sequestration and soil dynamics, and; 3) Linear programming model can be developed to characterize the relationship between the equilibrium and this model.

In this study, it has been assumed that the carbon amounts in soil are fixed (also refer to chapter 5, section SA), so there is no point in doing the optimization in soil again. Therefore, biomass values in land cover types have been optimised. This equilibrium biomass in land cover types should satisfy that total carbon amount in all system which can be shown as:

(Soil + biomass +carbon sequestration = carbon in system).

6.2.1 Top and Total Soils

In order to get equilibrium model output, the maximum and minimum amount of biomass carbon density (see Chapter 4, section 4.3) has been considered and included in analysis for carbon sequestration in top and total soils. The maximum carbon density amounts (65.5 and 32.4 (t ha^{-1})), and minimum amounts are (33.8 and 0 (t ha^{-1})) are in Broadleaf woodland and Coniferous woodlands, respectively. The rest of the land cover types are consistent and have not changed, on the other hand, the rest of the land cover types have consistently low values for carbon density (see Table 4.4). With regard to the above assumptions, the equilibrium model was run under consideration of different objective functions (addressed in Chapter 5) in all range of scenarios in top and total soils. The results are presented as Tables 6.1, 6.2 and 6.3, and Figures 6.1 and 6.2.

Table 6.1: Comparison of carbon density (Mt C) in equilibrium model in different scenarios under the range of different objective functions in top soils.

Scenarios	**Carbon Density (Mt C) under objective function 1**			**Carbon Density (Mt C) under objective function 2**			**Carbon Density (Mt C) under objective function 3**		
	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value
Scenario 1	**3.13**	**3.63**	**3.88**	**3.17**	**3.70**	**3.95**	**3.17**	**3.70**	**3.95**
Scenario 2	**3.05**	**3.48**	**3.69**	**3.08**	**3.52**	**3.76**	**3.08**	**3.54**	**3.76**
Scenario 3	**3.13**	**3.63**	**3.88**	**3.17**	**3.70**	**3.95**	**3.17**	**3.65**	**3.95**
Scenario 4	**3.13**	**3.64**	**3.89**	**3.17**	**3.71**	**3.96**	**3.17**	**3.71**	**3.96**
Scenario 5	**3.13**	**3.63**	**3.88**	**3.15**	**3.70**	**3.88**	**3.17**	**3.70**	**3.95**
Scenario 6	**3.13**	**3.63**	**3.88**	**3.17**	**3.70**	**3.95**	**3.17**	**3.70**	**3.95**
Scenario 7	**3.17**	**3.70**	**3.96**	**3.17**	**3.70**	**3.95**	**3.14**	**3.65**	**3.95**
Scenario 8	**3.81**	**4.80**	**5.26**	**3.80**	**4.80**	**5.25**	**3.74**	**4.80**	**5.24**
Scenario 9	**3.17**	**3.70**	**3.96**	**3.16**	**3.70**	**3.95**	**3.17**	**3.70**	**3.95**
Scenario 10	**3.34**	**4.04**	**4.39**	**3.33**	**4.04**	**4.37**	**3.33**	**4.01**	**4.38**

Table 6.1 presents the comparison of carbon amount (Mt C) under objective functions in all scenarios calculated by the equilibrium model in top soils. In accordance with this, the results under the equilibrium model have significant change in comparison to functional carbon value, which is (carbon value from the Optimized model, as discussed in chapter 5). Scenario 8 has a great amount of sequestrated carbon under all objective functions in both minimum and maximum carbon density value for biomass; this is especially so in objective function

one which has a higher amount of carbon sequestrated than others. Scenario two usually remains the lowest; the amount of carbon under objective function one is lowest amount compared to other scenarios in top soils. The biomass values which have been used in this model to derive and justifying the functional carbon density value. In general, the amount of carbon in most of the scenarios (except scenario 8 and 10) is greater under objective functions two and three in the equilibrium model.

This result from equilibrium model shows that the variability and changes of one parameter (biomass carbon value) can have a remarkable effect on the system. As a result, the difference between the dynamic and equilibrium models is the inclusion of carbon density in biomass.

The great implication of this output analysis is that the crucial assumptions undertaking in this section might be restricted and as a result plausible and believable.

Table 6.2: Comparison of carbon density (Mt C) in equilibrium model in different scenarios under the range of different objective functions in total soils.

Scenarios	**Carbon value (Mt/ha) under objective function 1**			**Carbon value (Mt/ha) under objective function 2**			**Carbon value (Mt/ha) under objective function 3**		
	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value	Minimum Biomass Carbon value	Functional Carbon Density	Maximum Biomass Carbon value
Scenario 1	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.55**	**6.79**	**7.32**	**7.63**
Scenario 2	**6.72**	**7.14**	**9.84**	**6.70**	**7.16**	**7.36**	**6.74**	**7.11**	**7.43**
Scenario 3	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.55**	**6.79**	**7.32**	**7.63**
Scenario 4	**6.80**	**7.31**	**10.04**	**6.79**	**7.33**	**7.56**	**6.79**	**7.33**	**7.64**
Scenario 5	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.55**	**6.79**	**7.32**	**7.63**
Scenario 6	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.55**	**6.79**	**7.32**	**7.63**
Scenario 7	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.49**	**6.79**	**7.32**	**7.63**
Scenario 8	**7.43**	**8.40**	**11.33**	**7.43**	**8.42**	**8.85**	**7.43**	**8.42**	**8.93**
Scenario 9	**6.80**	**7.30**	**10.03**	**6.79**	**7.32**	**7.55**	**6.79**	**7.32**	**7.63**
Scenario 10	**6.97**	**7.64**	**10.46**	**6.95**	**7.66**	**7.97**	**6.95**	**7.66**	**8.06**

Table 6.2 shows the amount of carbon (Mt C) in the equilibrium model under the different objective functions in total soils in all range of scenarios. The greatest amount of carbon value in scenario 8 under objective function one (maximum biomass carbon density value) is remarkable while scenario two has the lowest amount of carbon. Also, scenario two under objective function three (in minimum biomass amount), has a higher amount of carbon rather than the other objective functions (one and two). In general, all scenarios under objective

function one (in maximum biomass amount) in total soils have a highest value rather than other objective functions (two and three) in the equilibrium model.

Table 6.3: Comparison of energy and GHG emissions (kt yr^{-1}) in equilibrium model in different scenarios under the range of different objective functions in top and total soils.

Scenarios	**Energy emissions (kt yr^{-1}) under all objective functions**			**GHG emissions (kt yr^{-1}) under all objective functions**		
	Minimum Energy Value	Functional Energy Value	Maximum Energy Value	Minimum GHG Value	Functional GHG Value	Maximum GHG Value
Scenario 1	**202.85**	**218.48**	**218.48**	**247.32**	**266.07**	**266.07**
Scenario 2	**218.48**	**218.48**	**218.48**	**266.07**	**266.07**	**266.07**
Scenario 3	**223.77**	**223.77**	**223.77**	**272.07**	**272.07**	**272.07**
Scenario 4	**217.69**	**217.69**	**217.69**	**265.11**	**265.11**	**265.11**
Scenario 5	**218.48**	**218.48**	**218.48**	**266.07**	**266.07**	**266.07**
Scenario 6	**222.45**	**222.45**	**222.45**	**270.57**	**270.57**	**270.57**
Scenario 7	**231.05**	**231.05**	**231.05**	**280.33**	**280.33**	**280.33**
Scenario 8	**178.85**	**178.85**	**178.85**	**218.54**	**218.54**	**218.54**
Scenario 9	**218.48**	**218.48**	**218.48**	**266.07**	**266.07**	**266.07**
Scenario 10	**202.85**	**202.85**	**202.85**	**247.32**	**247.32**	**247.32**

Table 6.3 presents the energy and GHG emissions (kt yr^{-1}) in all scenarios under the range of different objective functions in the equilibrium model in top and total soils. According to this table, in scenario one the amount of energy and GHG emissions under the equilibrium model with minimum amount of biomass is notable. The reason is, while the minimum amount of biomass is zero, so the output has become the lowest. In general, scenario 8 has a lowest amount of energy and GHG emissions in the equilibrium model. Whilst the amount of energy and GHG emissions under different objective functions in the equilibrium model has changed, however, this amount in comparing to biomass and soils amount is very small. So, in fact the changes are not very big or significant in energy and GHG emissions amounts.

Figure 6.1: Comparison of the carbon sequestration value calculated for minimum and maximum amount of biomass carbon (Mt C) in equilibrium model under the range of different scenarios in top soil.

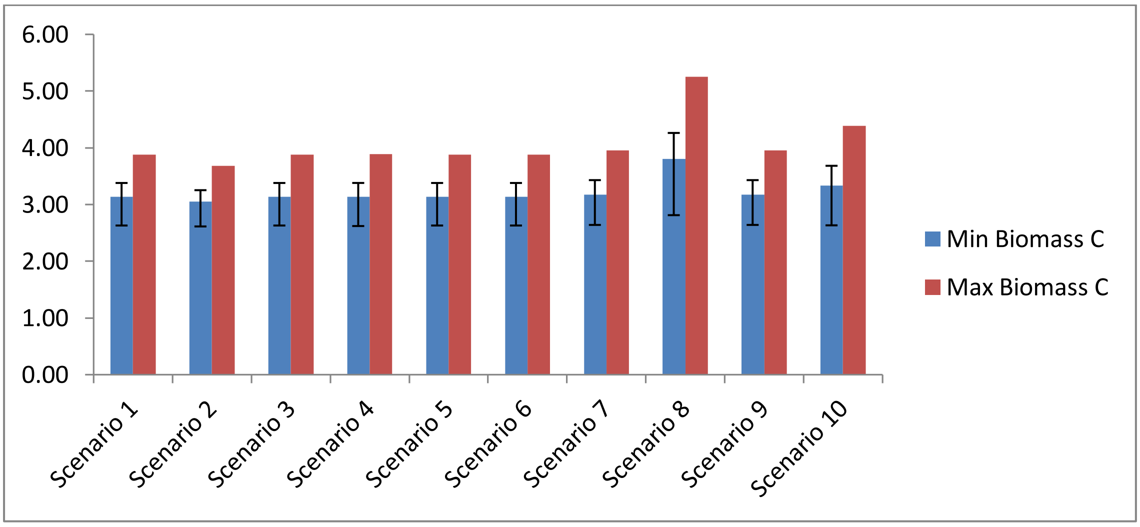
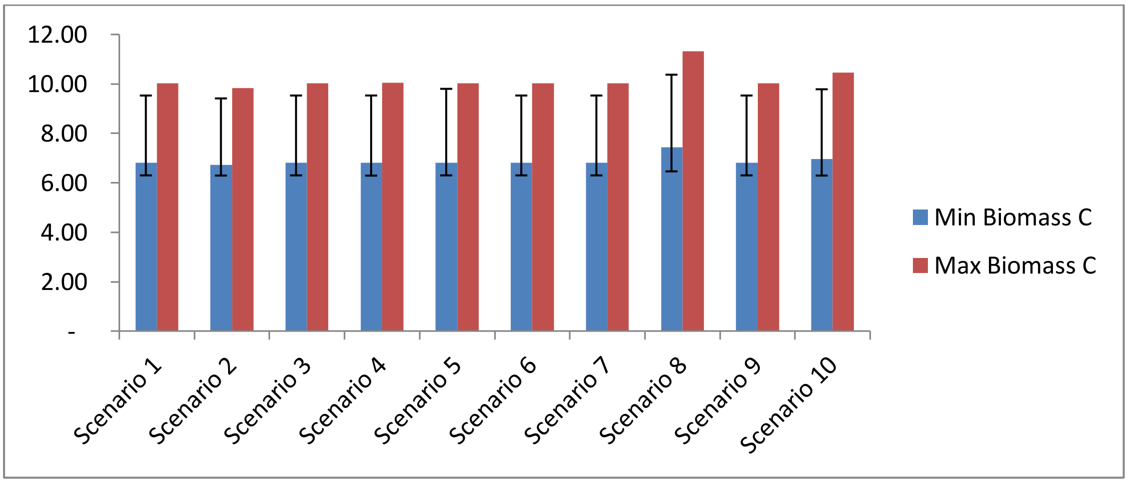


Figure 6.2: Comparison of the carbon sequestration value calculated for minimum and maximum amount of biomass carbon (Mt C) in equilibrium model under the range of different scenarios in total soil.



Figures 6.1 and 6.2 present the positive, negative values and percent changes with error bars in equilibrium model, comparing the minimum and maximum amount of biomass carbon with functional carbon in top and total soils under the range of different scenarios.

Based on the above results, scenarios 8 and 10 still are the best option for consideration in the future. Meanwhile, those scenarios have a minimum amount of energy and GHG emission.

6.3 Net Carbon Saving (Flux) and Net emissions under the range of different Scenarios over different periods of Time

In chapter 5, land management practice under the range of different scenarios has been justified and established. This section discusses the net carbon saving and net emissions in top and total soils.

6.3.1 Net Emissions in top and total soils

In table 6.4, the amount of net emissions (energy and GHGs) under the different range of scenarios is presented. Since the emission results in top and total soils are the same (relatively), therefore just one value has been considered and mentioned here. The total amount has been converted and calculated to the same value unit which is Mtonne per year, and then amount of energy and GHGs added together. This amount shows that each scenario has certain amount of emissions over a period of time.

Table 6.4: Net emissions (Mt yr^{-1}) under the range of different scenarios in top soils and total soils.

Scenarios	Energy emissions (Mt yr^{-1})	GHG emissions (Mt yr^{-1})	Net Emissions (Mt yr^{-1})
Scenario 1	0.219	0.267	0.486
Scenario 2	0.219	0.267	0.486
Scenario 3	0.224	0.273	0.497
Scenario 4	0.218	0.266	0.484
Scenario 5	0.219	0.267	0.486
Scenario 6	0.223	0.271	0.494
Scenario 7	0.232	0.281	0.513
Scenario 8	0.179	0.219	0.398
Scenario 9	0.219	0.266	0.485
Scenario 10	0.203	0.248	0.451

Table 6.4 presents the net emission (energy and GHG emissions) under the range of different scenarios in top and total soils. Referring to this result, scenario seven has a higher amount of net emissions and scenario eight has a smallest amount of net emissions per year.

Table 6.5: Total net emissions amount (Mt C) over periods of time in top soils and total soils.

Changes in land use or management (Scenarios)	After 1 year	After 5 year	After 10 year	After 25 year	After 50 year	After 80 year
Scenario 1	0.486	2.43	4.86	12.15	24.3	38.88
Scenario 2	0.486	2.43	4.86	12.15	24.3	38.88
Scenario 3	0.497	2.49	4.98	12.45	24.9	39.76
Scenario 4	0.484	2.42	4.84	12.1	24.2	38.72
Scenario 5	0.486	2.43	4.86	12.15	24.3	38.88
Scenario 6	0.494	2.47	4.94	12.35	24.7	39.52
Scenario 7	0.513	2.57	5.14	12.85	25.7	41.04
Scenario 8	0.398	1.99	3.98	9.95	19.9	31.84
Scenario 9	0.485	2.42	4.84	12.1	24.2	38.80
Scenario 10	0.451	2.26	4.52	11.3	22.6	36.08

Table 6.5 shows total net emissions (Mt C) under different periods of time which are current, 5, 10, 25, 50 and 80 year. In the near future, the net amount is lower than in the distant future. By the next 50-80 year, the net amount is fairly high compared to current situation. The relationship between time and net emissions is linear; that means when time increases the amount of net emissions has increased. According to this result, scenarios seven and eight have the highest and lowest amount of net emissions, respectively.

Figure 6.3: Total net emission (Mt C) over period of times in top and total soils.

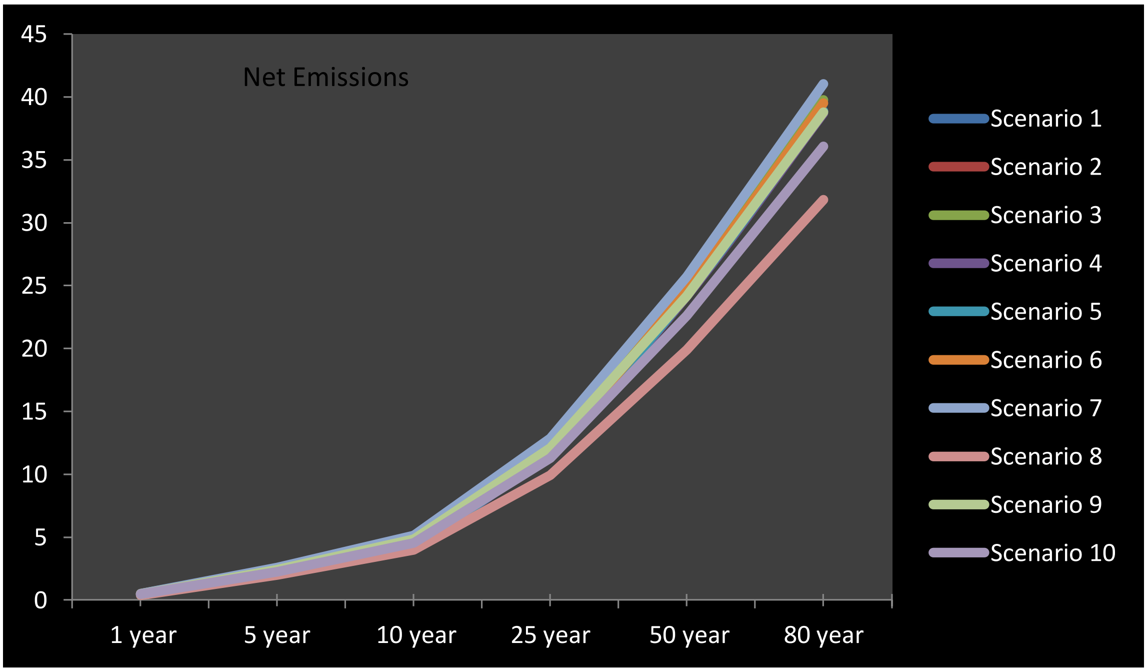


Figure 6.3 presents the net emissions amount currently, after 5, 10, 25, 50 and 80 years. Referring to this figure, over the next 80 years the net emissions are roughly linear. Although the net emissions up to the next 10 year has not great increase but after 20 years net emission amount highly increases. In accordance with this, now can be confirmed that these amounts are highly linked and relevant to the UK reduction target (addressed in Chapter 2 and 4) and is real. As it is clear in Figure 5.3, the next 10 year has lower value in all scenarios. Also, scenario seven has higher net emission and scenario eight has a lowest net emissions. It is important to note that the X-axis is not linear.

6.3.2 Net Carbon and Carbon Savings in top and total soils

In this section, the aim is to calculate the amount of carbon saving in different periods of time. Therefore it has been calculated the net carbon amount in top and total soils with respect to different period of time (up to 2080) under the different range of scenarios.

Net carbon amount in top and total soils has been calculated as follows:

Net carbon = (Biomass carbon + soil carbon) – (n year x (annual emissions)) Equation 6.1

According to this equation, the results are presented in Tables 6.6 and 6.8 for top and total soils.

Table 6.6: Net carbon amounts sequestrated (t) under the range of different scenarios in top soils.

	After 1 year	After 5 year	After 10 year	After 25 year	After 50 year	After 80 year
Scenario 1	**3,632,854**	**3,632,849**	**3,632,846**	**3,632,839**	**3,632,827**	**3,632,812**
Scenario 2	**3,475,491**	**3,475,490**	**3,475,487**	**3,475,479**	**3,475,468**	**3,475,453**
Scenario 3	**3,632,851**	**3,632,849**	**3,632,846**	**3,632,839**	**3,632,826**	**3,632,812**
Scenario 4	**3,641,283**	**3,641,284**	**3,641,279**	**3,641,272**	**3,641,260**	**3,641,245**
Scenario 5	**3,632,854**	**3,632,849**	**3,632,846**	**3,632,839**	**3,632,827**	**3,632,812**
Scenario 6	**3,632,855**	**3,632,849**	**3,632,846**	**3,632,839**	**3,632,826**	**3,632,812**
Scenario 7	**3,701,691**	**3,701,688**	**3,701,686**	**3,701,678**	**3,701,665**	**3,701,651**
Scenario 8	**4,798,481**	**4,798,480**	**4,798,478**	**4,798,471**	**4,798,462**	**4,798,450**
Scenario 9	**3,701,693**	**3,701,690**	**3,701,687**	**3,701,680**	**3,701,668**	**3,701,653**
Scenario 10	**4,039,286**	**4,039,2847**	**4,039,282**	**4,039,275**	**4,039,264**	**4,039,250**

Table 6.6 shows the net carbon amount (t) under the range of different scenarios in top soils. The amount of net carbon decreases in all scenarios over period of time. The reason is relative to net emissions (see Table 6.5). The relationship between time and net carbon is reversed; that means when time increases the amount of net carbon is reduced. In this result,

scenario 8 has a highest and scenarios 5 and 6 have a smallest amount of net carbon in different periods of time.

Table 6.7: Carbon savings amount (t) under the range of different scenarios over period of time in top soils (compared to scenario one).

	After 1 year	After 5 year	After 10 year	After 25 year	After 50 year	After 80 year
Scenario 1	0	0	0	0	0	0
Scenario 2	-157,361	-157,361	-157,361	-157,361	-157,361	-157,361
Scenario 3	0.19	0.14	0.08	-0.1	-0.4	-0.7
Scenario 4	8432.8	8432.8	8432.8	8432.8	8432.8	8,432.9
Scenario 5	0	0	0	0	0	0
Scenario 6	-0.01	-0.04	-0.08	-0.2	-0.4	-0.64
Scenario 7	68,839.7	68,839.6	68,839.4	68,839	68,838.3	68,837.6
Scenario 8	1,165,630.5	1,165,630.9	1,165,631.3	1,165,632.6	1,165,634.8	1,165,637.5
Scenario 9	68,840.8	68,840.8	68,840.8	68,840.9	68,840.9	68,840.9
Scenario 10	406,435.1	406,435.2	406,435.4	406,435.9	406,436.7	406,437.8

Table 6.7 presents the carbon saving (t) under the range of different scenarios in top soils. Carbon saving has been calculated as the difference between net carbon of each scenario minus scenario one (business as usual scenario) in top and total soils. So, based on the above table, scenario 8 has a greatest amount of carbon saving and scenario two has a minimum amount of carbon saving, in fact in scenario two, the emission is high and no saving has occurred.

Table 6.8: Net carbon amount (t) under the range of different scenarios over period of time in total soils (compared to scenario one).

	After 1 year	After 5 year	After 10 year	After 25 year	After 50 year	After 80 year
Scenario 1	7,300,628	7,300,626	7,300,624	7,300,616	7,300,604	7,300,590
Scenario 2	7,143,268	7,143,267	7,143,267	7,143,256	7,143,244	7,143,230
Scenario 3	7,300,628	7,300,626	7,300,625	7,300,616	7,300,606	7,300,589
Scenario 4	7,309,068	7,309,059	7,309,057	7,309,049	7,309,037	7,309,028
Scenario 5	7,300,629	7,300,626	7,300,625	7,300,616	7,300,605	7,300,590
Scenario 6	7,300,628	7,300,626	7,300,624	7,300,616	7,300,608	7,300,589
Scenario 7	7,300,628	7,300,627	7,300,623	7,300,616	7,300,607	7,300,588
Scenario 8	8,397,587	8,397,582	8,397,581	8,397,574	8,397,564	8,397,553
Scenario 9	7,300,628	7,300,626	7,300,625	7,300,616	7,300,604	7,300,590
Scenario 10	7,638,223	7,638,224	7,638,219	7,638,212	7,638,201	7,638,188

The same process for net carbon amount (t) in total soils has been followed and results presented in Table 6.8. Scenario six relatively has the lowest and scenario eight has the greatest net carbon amount in total soils. Also, in total soils the relationship between net carbon amount and time is reversed.

Table 6.9: Carbon savings amount (t) under the range of different scenarios in total soils (compared to scenario one).

	After 1 year	After 5 year	After 10 year	After 25 year	After 50 year	After 80 year
Scenario 1	0	0	0	0	0	0
Scenario 2	-157,359.7	-157,359.7	-157,359.7	-157,359.7	-157,359.7	-157,359.7
Scenario 3	0.19	0.14	0.08	-0.1	-0.4	-0.68
Scenario 4	8,433.2	8,433.1	8,433.2	8,433.5	8,433.1	8,433.6
Scenario 5	0.07	0.06	0.05	0.05	0.05	0.04
Scenario 6	0.06	0.03	-0.04	-0.15	-0.35	-0.58
Scenario 7	0.07	-0.04	-0.18	-0.6	-1.3	-2.06
Scenario 8	1,096,956	1,096,956.24	1,096,956.9	1,096,958	1,096,960.2	1096962.9
Scenario 9	0.01	0.01	0.02	0.05	0.1	0.08
Scenario 10	337,595.5	337,595.8	337,595.7	337,596.5	337,597	337,598.1

Table 6.9 shows the carbon saving amount (t/ha) under the range of different scenarios in total soils. Outlook of this result presents that in scenarios two and five, within different period of time carbon saving amount has not changed (except scenario five after 80 year). Scenario eight still has a greatest amount of carbon saving in all periods of time.

Based on the above figures and tables, in the distant future, the carbon saving will increase and has a relationship with time. As a result, Scenarios 8 and 10 seem to be the best assumptions to research to achieve this target. Moreover, in these scenarios the minimum net emission has occurred.

6.4 Mapping and Visualizing the Results in GIS

For indentifying the land units and their characteristics based on soils and land cover units and aspect, slope and elevation unit, land unit maps have been created. Here, only some of the selected outputs (a selection of model outputs) are presented. The main land cover types area percentage (Broadleaf and Coniferous woodland), total carbon amount in scenario one (current situation) and scenario two provide an example. Figures 6.4, 6.5, 6.6 and 6.7 present a visualization of this selection of model outputs.

Figure 6.4: Percentage of area allocation in Broadleaf forest on Scenario one under Objective function one.

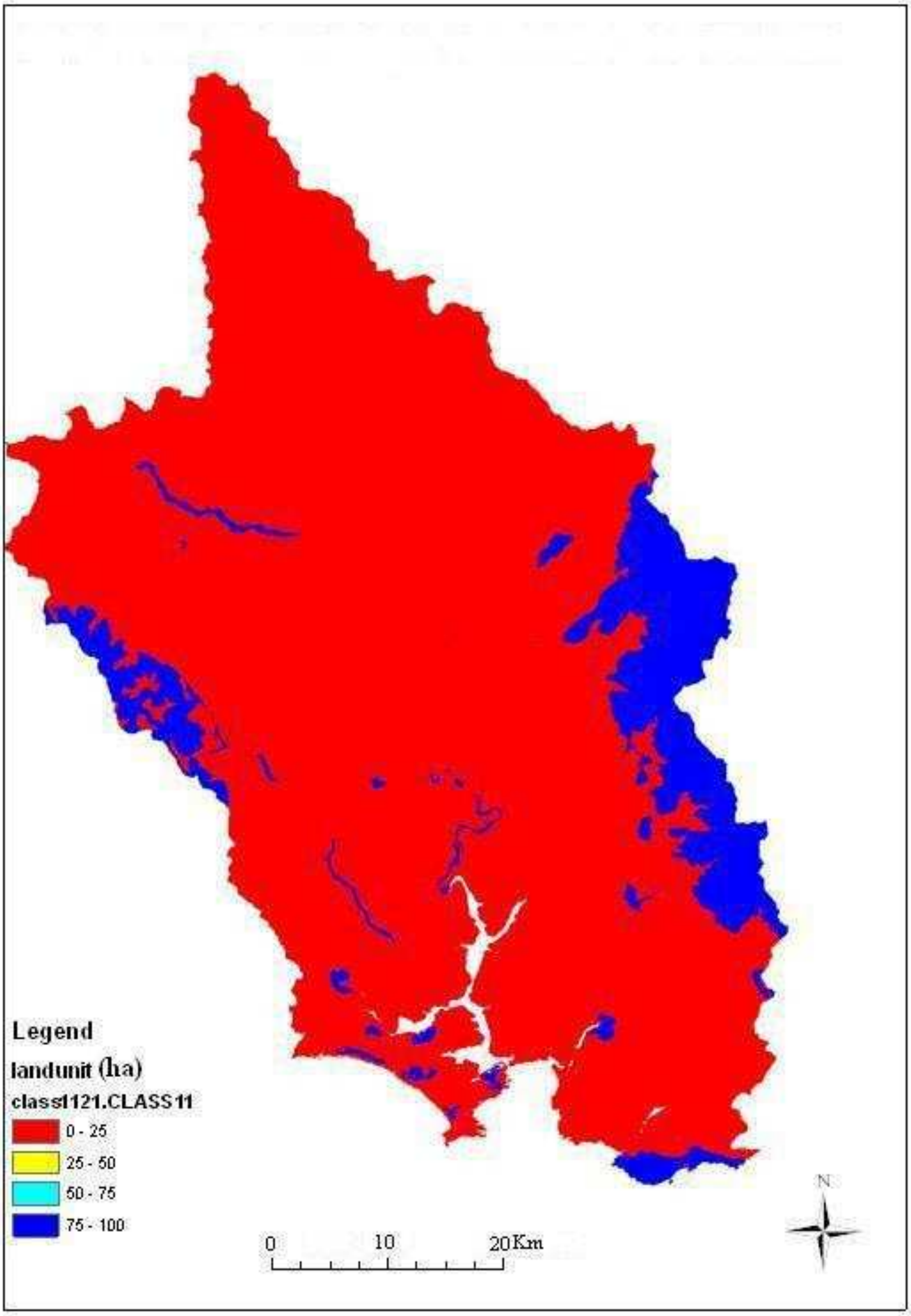


Figure 6.5: Percentage of area allocation in Coniferous forest on Scenario one under objective function one.

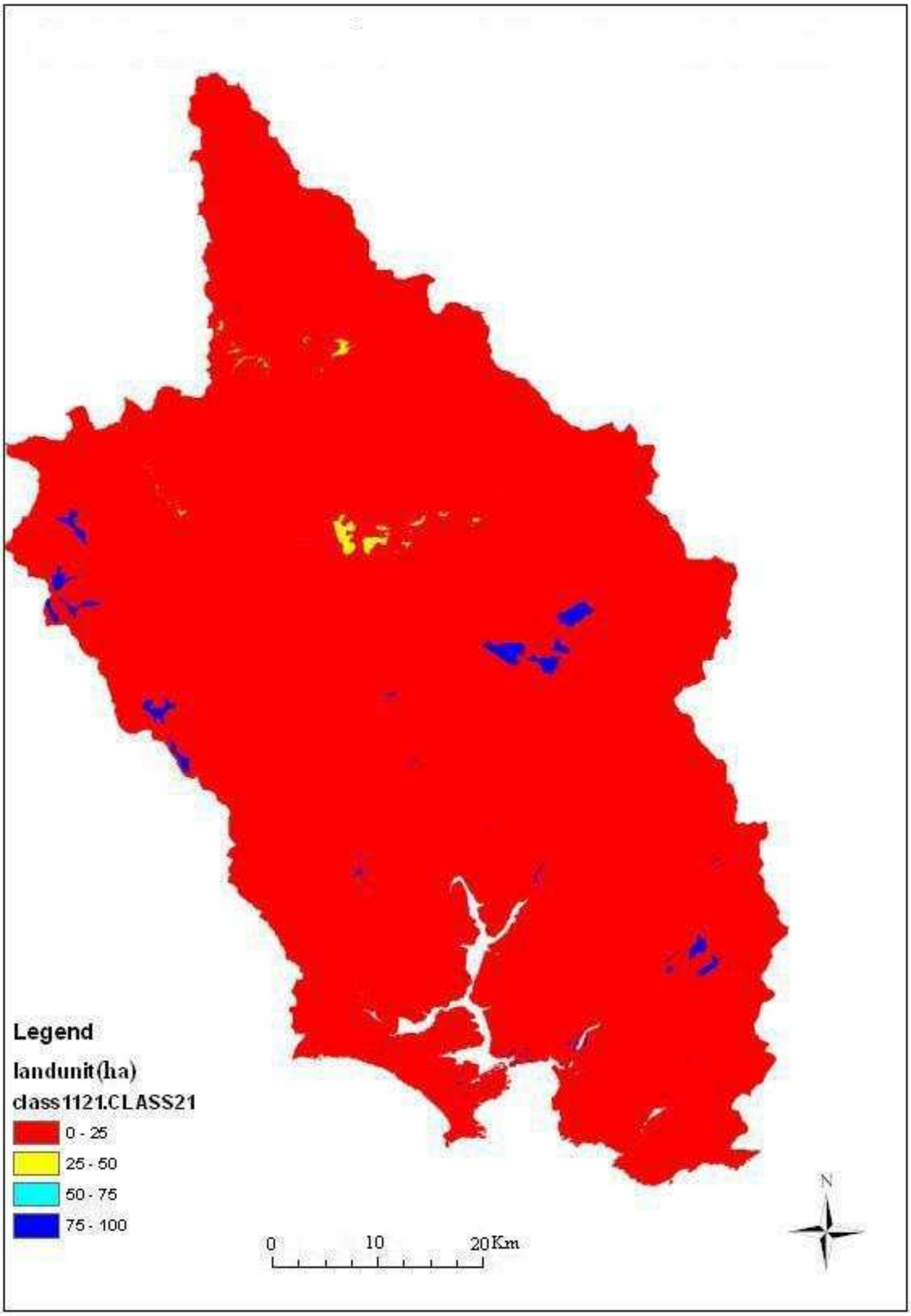


Figure 6.6: Total carbon density amount per land unit (t/ha) on Scenario one under objective function one.

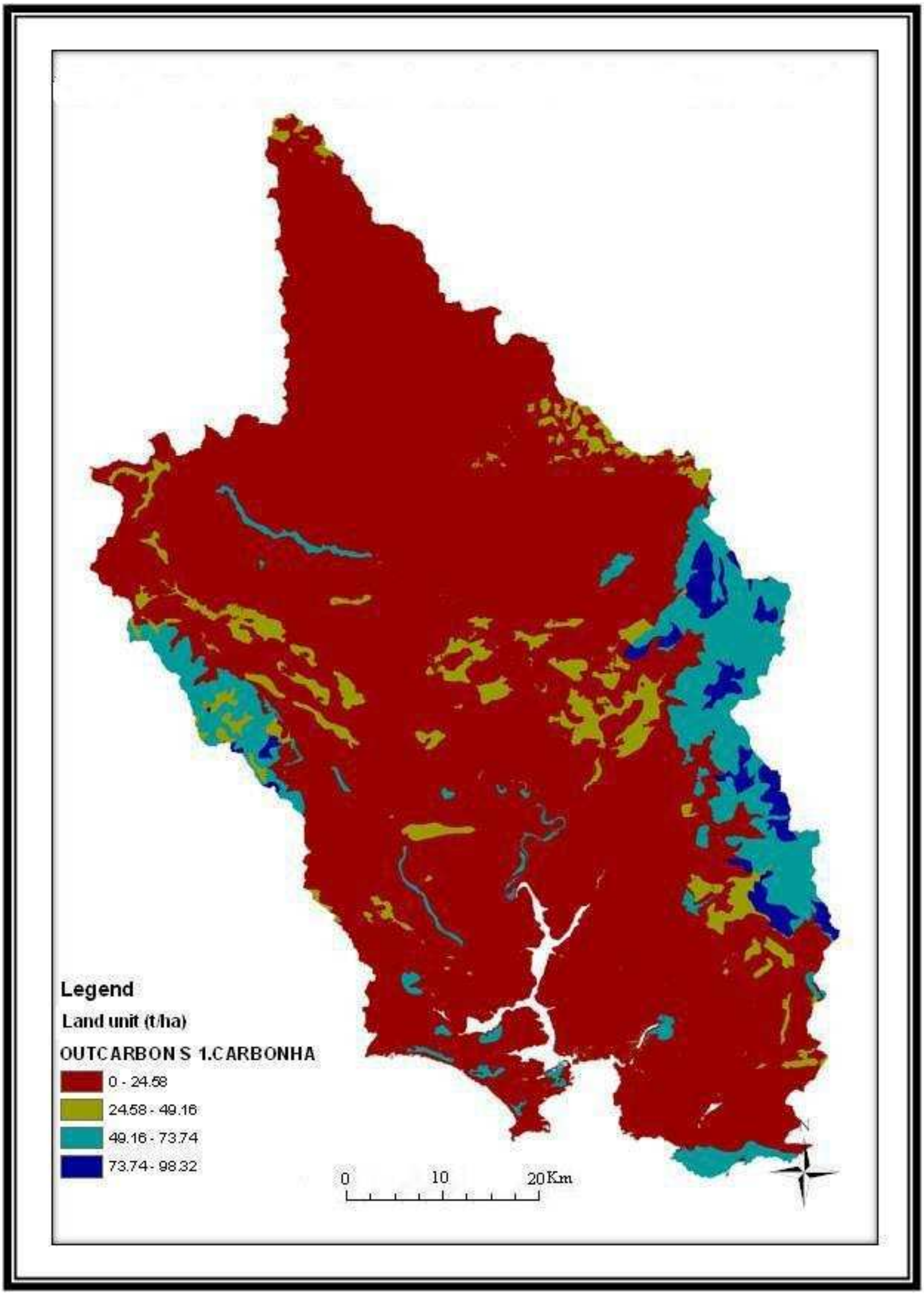
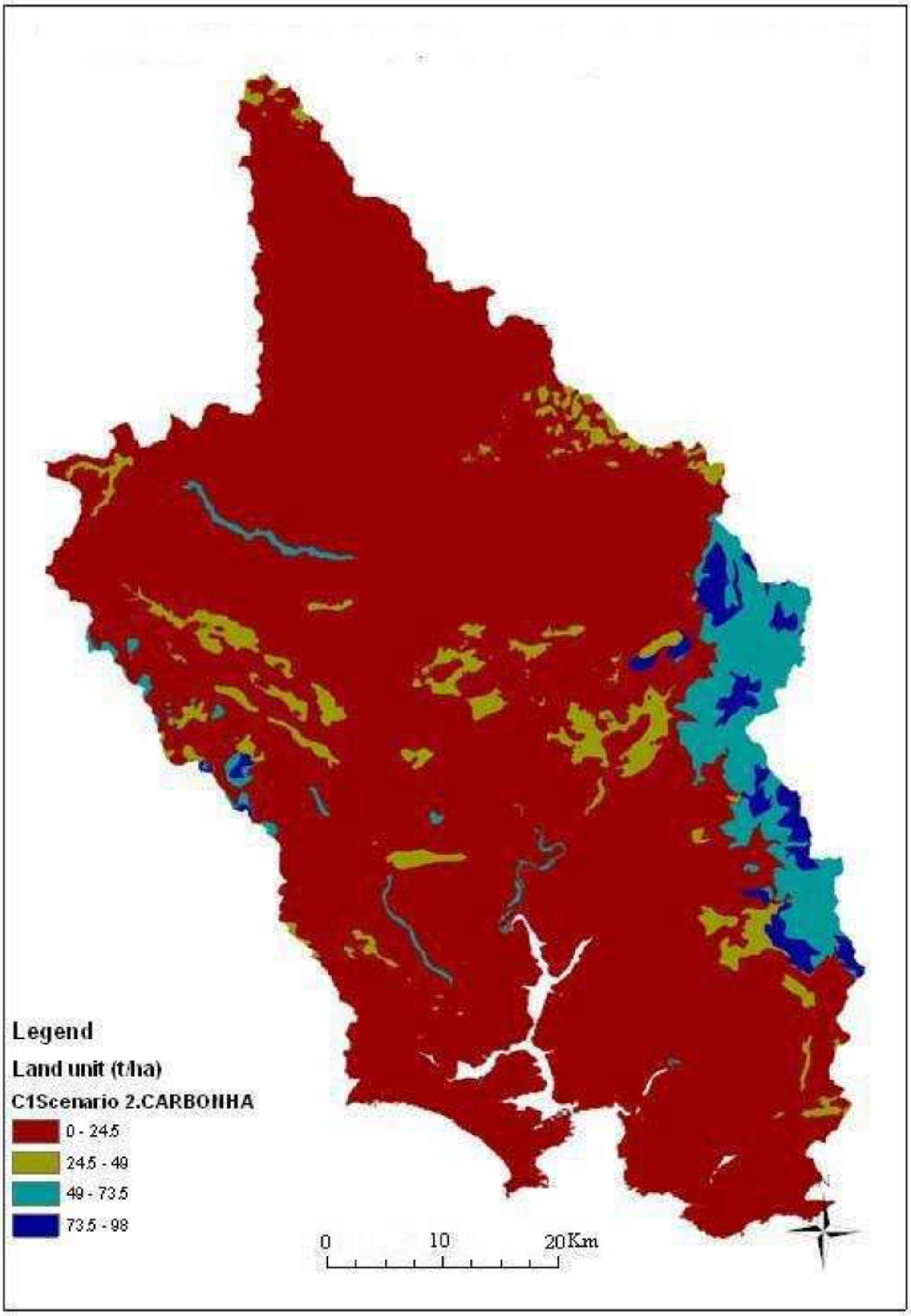


Figure 6.7: Total carbon density amount per land unit (t/ha) on Scenario two under objective function one.



Figures 6.4 and 6.5 present the percent of area allocation (ha) in Broadleaf and Coniferous woodland in scenario one after creating the land unit map in the Tamar valley catchment. In order to create these maps by GIS software; firstly land unit map (see Chapter 4 and 5, section 5.2.2) is created, therefore total amount of carbon (t ha^{-1}) has been calculated in scenario one and other scenarios. Afterward, total amount of carbon transferred to GIS and the necessary maps has been created (Table 6.7 and 6.8). The same process has been followed for area allocation and their percentage per each land cover type in different scenarios. As described above, only a selection of model outputs are presented here; these spatial solutions exist for every model run.

6.5 Conclusions

The model and scenario results are presented in chapter 4. This chapter presents the equilibrium model and net emissions and carbon results. These results allow possible future agricultural and forestry land management practise to be assessed in terms of carbon dynamics. This work is based on assumptions (sections 6.2 and 6.3), which does not mean these goals will be certainly attained in the assumed times. These results are formulated and generated for explicit assumptions which consider, e.g. the agriculture and forest land development, land structure and economic price in this area. With changing any of these assumptions, these results may be affected. The methodology presented in this research (chapters 5 and 6), enables the analysis, consequences and outcomes of these assumptions. The presented results of this chapter can provide options with the following concerns:

Large potentials exist for reducing the energy and GHG emissions, and increasing the total amount of carbon, net carbon and carbon saving in Tamar valley catchments. In general, the total carbon amount in biomass and soil can be increased to the equilibrium and optimal model of other objective in top and total soils (Tables 6.1 and 6.2). The carbon saving amount is greatly in line with the goals of increasing the biomass; net carbon amount per hectare in top and total soils in Tamar valley catchments (Table 6.8 and 6.9).

As a result, a potential for increasing and developing the forest and agriculture land is available in this site area.

Chapter 7

General Discussion and Conclusions

Chapter 7 General Discussion and conclusions

7.1 Introduction

Increasing the total carbon amount stored in soils and biomass, and reducing the GHG and energy outputs for land uses such as agriculture and forestry are important parameters for carbon management (FAO, 2009; Smith et al., 2008, King et al., 2004). Realistic scenarios for land use and carbon management in the Tamar Valley catchment are required. Discussions on these parameters are frequently basic / simplistic and refer to incomplete data. The fundamental parameters are known, but the data are not always available when needed (King et al., 2002; DEFRA, 2000). Land management is driven by a range of different parameters such as policy in land use, GHG and energy options, with a range of stakeholders such as government, policy-makers, scientists, and regional and local communities; and economic factors. There is uncertainty around the outcomes and consequences of land use policy, and economic options for carbon management due to lack of available data and the lack of enough information on certainty of future land management. Examination of the parameters is normally pointed towards one feature at a time, e.g. maximize the amount of carbon stored, by concentrating on land conversion and increasing the carbon sink (Cantarello et al., 2011). It is rare to be able to reckon and view other features at the same time, such as minimizing GHG and energy outputs, and maximising farm business income.

The cental aim of this thesis was to develop a method to evaluate the potential impact of changing land use of GHG emissions, vegetation and soil carbon. The thesis has developed a systematic approach towards future land management under a range of scenarios. The scenarios are a consequence of several parameters such as policy and economy which has been considered in the Tamar Valley catchments. There were three specific objectives to the thesis:

1. Develop an integrated spatial planning support system to model land use and land cover change in the Tamar Valley catchment.
2. Develop a general methodology and tools for scenario generation and scenario analysis for land cover change in the Tamar Valley catchment.
3. Assess the landscape-scale storage and emissions of GHG under the range of different scenarios for different time periods in the 21st century.

These objectives were really to develop a general model or approach that could be applied anywhere. In this thesis it has been demonstrated this general model works using the Tamar Valley catchment as a case study.

This chapter summarises the key considerations that have been made to better understand the carbon management, GHG and energy reduction in land uses debates in the Tamar Valley catchment. Section 7.2 will present the main conclusions of the study relevant to carbon storage in agriculture and forestry land with regards to necessary parameters affecting the GHG and energy emissions under different range of scenarios, and the important parameters affecting the land management and implementation of such scenarios (land conversion) in the Tamar Valley catchment. Section 7.3 will consider the main important methods, activities, objective functions and constraints used in this research. Section 7.4 will summarize the presentation of results, model analysis such as scenarios analysis, sensitivity analysis and equilibrium in the Tamar Valley catchment. And finally, section 7.5 of this chapter will present the focus (highlights) of scenario outputs, and consider other concerns such as policy and research implementations; and discuss the application of the approach in other regions or countries and how this thesis can be used as a platform.

7.2 Key Links to Relevant work on Carbon Saving, GHG and Energy Emissions, and Policy

The key conclusion in Chapter 2 (Literature Review) has underscored that land use (agriculture and forestry) management is recognised as a key approach to climate change mitigation. The key findings are that come out:

a) Forestry lands always have gone through a great stress and pressure because of the climate change issue, geographical scattering and human impact such as urban development, and agricultural land development (FAO, 2009; Onno et al., 2008). Therefore, some part of this enlargement and expansion is linked to the government, policy-makers, and stakeholders and national policy targets that promoted mainly the agricultural section evolution to hold food supply. Meanwhile, forestry lands are playing the main role as a sink of carbon capture and balance resource for GHG emissions control (Ostle, 2009; DEFRA, 2008c).

b) Agricultural lands are one of the main sources of GHG and energy (direct and indirect) emissions (Wise et al., 2009; IPCC, 2007b; FAO, 2005). The main options for mitigation of GHG emissions (particularly methane and carbon dioxide) are to improve and develop agronomic performance, tillage and residue management, restoration of organic soils which are taken for crop creation and restoration of degraded lands (IPCC, 2007a; FAO, 2009). Agricultural GHG mitigation alternatives should be agonistic (affected) with non-agricultural options (e.g., energy, transportation, and forestry) for attaining long-term (i.e., 2080) climate mitigation (IPCC, 2007a; FAO, 2009).

c) There is a high possibility to develop land use capacity for saving and increasing carbon within forestry and agricultural management practice (King et al., 2004). These developments will also reduce the GHG, direct and indirect energy emissions to meet this aim. These changes are being encouraged through policy and environmental pressure.

d) Additional thought and consideration should be given to the range of functioning and implementation of the mitigation alternatives. GHG mitigation needs to be supported by policy measures. Action is needed at the governmental (national) level, but ultimately, management is applied and implemented at the "farm-scale" by farmers and land managers. Managing the various interests of stakeholders (e.g. farmers, policy, land managers, and environmental groups) will not be simple (Smith et al., 2004a and 2007a).

e) It is possible that a range of approaches will be needed to overcome restraints and limitations to GHG mitigation in agriculture. These may include subsidies, guidelines, rules and education. For achievable implementation, mitigation alternatives will have to have direct significance to the farmers / land-managers (Smith et al., 2007b).

f) Whether or not a specific management alternative is promising or wanted will depend upon the method and form of farm for which it is being calculated and considered. For instance, decreased tillage is implausible as an alternative on an organic farm where "herbicides" cannot be employed, and automatic weeding is the likely process of weed management and control. In practice, mitigation measures may be much more satisfactory and familiar if they are particular at the farm level, where certain activities may need to be rearranged or replaced upon implementation of given measures. A "farm gate" approach (i.e. a complete-farm input / output equilibrium) may be important in considering the suitability and acceptability of proposed GHG mitigation alternatives, particularly in the meaning, implementation and statement of GHG mitigation alternatives (Schneider et al. 2007; Smith et al., 2008).

g) GHG mitigation approaches may be packed together into a series of management systems, suited to different land forms / or approaches. Farmers may then be permitted to choose the parcel or choices that better fit their situation (FAO, 2007 and 2009). Mitigation could normally be attained purely by amending agronomy and fertiliser and manure management practise e.g. by adding and increasing fertiliser / manure use effectiveness. This allows increases in efficiency, productivity and environmental profits at the same time.

h) Other possible actions to make progress and improve GHG mitigation include, improving and developing the ability of farmers through training and education get mitigation and climate change understood by the farmer both as conception and perceptual experience (Smith et al., 2008). Supporting and encouraging the progressive contribution of farmers will assist them to acknowledge and understand how management influences emissions and C store changes, and to recognize the potential for GHG mitigation (Smith and Powlson., 2003; Smith 2004b; FAO 2007a). This requires close discussion between farmers, policy makers, decision makers, scientists and the community. More significantly there has to be recognition that some GHG mitigation approaches require investment or loss of earnings, and that GHG mitigation measures can be viewed as public goods (FAO, 2009).

i) At the policy stage, mitigation measures are possibly best supported as part of a wider environmental programme. GHG mitigation cannot be viewed in isolation and there are other challenges to land management. For instance, the IPCC (2001a and 2007a) have highlighted that global, natural, regional and local environmental subjects such as climate change, deforestation, desertification, stratospheric ozone depletion, regional acid deposition and so on are inextricably related. The IPCC (2001a and 2007a) further noted that identifying and recognising the connections between environmental subjects, and their connection to meeting human necessities and needs, presents a chance to address global environmental matters at the local, national and regional level in an integrated way that is both efficient and meets sustainable development purposes.

j) Though there are often co-advantages of GHG mitigation with other globally important issues such as biodiversity, soil erosion control, fertility, soil moisture, and soil organic carbon, there possibly will also be struggles and conflicts. For instance, broad areas that are managed for land use may possibly have low soil carbon amounts, and agricultural areas positioned under long-term GHG mitigation management can decrease the adaptive capability of the agricultural sector (McKinsey and Company, 2009; Smith et al., 2007). As discussed earlier, one must also consider the trade off between GHGs and other implications for fossil fuel use (e.g. pre-procession of fossil fuel used in the production of fertiliser and herbicides and fuel carbon prices for transport, crop drying and development and field management practices).

In addition to attempt to resolve some of the environmental difficulties together, policy, social and economic and price of soil C sequestration under different land uses and soil /

vegetation management problems must be addressed in the same system. Technical mitigation methods should have the potential to improve C sinks, but the extent to which these are sustainable must also be considered. Restoration and conservation of C sinks such as peat lands can make contributions which are the larger than those in the agricultural and forest GHG mitigation sector (Obersteiner et al., 2010; West et al., 2008). GHG and energy reduction through increasing carbon sequestration in forest and agricultural land, have been discussed at length (e.g. Martin Van Ittersum, 1997; IPCC 2001a, 2007a; Smith and powlson., 2003; Smith 2004a, 2004b; Schneider et al. 2007; FAO, 2007a, 2008b ; Smith et al., 2007; Smith et al., 2008). These results have been supported by the above authors in terms of the important role of reducing GHG emissions and increasing carbon storage.

7.3 Choices of Objective Functions, Constraints and Main Methods

7.3.1 Option, Objective Functions and Constraints in system

This thesis targets long-term examination of land use management (agriculture and forestry) opportunities and choices in terms of increasing the storage of carbon amount. It does this by demonstrating the critical outputs at the end of a process which has considered the policy, economic and environmental objectives and constraints on land management (section 6.3). This thesis has also tried to discover and explain the environmental, physical (land structure) and technical options and possibilities to meet different issues on land and GHG emissions policy; economy and environmental objectives (section 4.5). This has been done under the following assumptions: (a) the economic conditions (farm business income), and policy has no limitations for accepting and adopting new management system to increase carbon and decrease the GHG and energy emissions; and (b) the current arrangement of land cover is a real reflection of the constraints on land management. Whilst it is recognised that both of these assumptions might be questioned, this thesis seeks to develop a methodological approach that is applicable for assessment of potential land cover change in any region of the world for which appropriate data is available. In this study, system activities such as carbon, GHG and energy emissions (see chapter 5) have been defined by empirical data, knowledge of the system and present techniques in agriculture and forestry land system.

GHG and energy (direct and indirect) emissions and input to agriculture and forestry land should be decreased to minimum levels and carbon storage should be increased to maximum levels in this model- based approach. These environmental goals are achieved by optimizing these system contributions, through suitable land management system. Once these are optimized, other efforts and inputs can be used to their best effect and outcome (Van Ittersum and Rabbinge 1997). Five main land use types have been distinguished in the Tamar Valley catchment; Broadleaf woodland, Coniferous woodland, Grassland including permanent, Acid, Neutral and Improved, Horticultural land and Cereal land.

It has been shown here that increasing carbon storage and minimizing GHG, and, direct and indirect energy emissions can be achieved by land conversion to grass, improving and developing the forest land, permanent grasslands and reducing the chemical inputs (for land fertilizing), machinery use, respectively. This supports existing studies (e.g. Contanello et al., 2011; King et al., 2004).

Increasing and expanding forestry land and grassland activities are therefore recognised as key land use change directions in landscape such as the Tamar valley catchment. Carbon amount, energy and GHG emissions can be increased and reduced relatively by exchanging/conversion the land management (e.g., adding short rotation grass like forage and alfalfa grass, increase permanent grassland and woodlands) and practise (use machinery with less fuel emission (DEFRA, 2008c, Smith et al., 2008), less use of fertilizers such as nitrogen and direct land to organic farming) although these are not included in the approach used here. This study has considered and focused mainly on carbon amount and energy and GHG emissions in soils and biomass in agriculture and forestry lands under the range of different scenarios presented. This is considered one of the strengths of this approach, and one which makes it widely applicable to other, different, geographical areas. It is not necessary to integrate data or parameters about which there is considerable uncertainty or few empirical measurements for the majority of areas (e.g. carbon sequestration and flux, contribution of bio-energy). Future work might seek to include further objectives in different regions. The strength of the Linear Programming model is that each activity (e.g. carbon storage maximize, energy and GHG minimize) can be processed as a conclusion (decision) objective. The Linear Programming model has a flexible construction and hence any other objective function can smoothly be fitted and integrated, assuming that suitable data is available.

In respect to the land use developments and problems in the Tamar Valley catchment, several objective functions (Chapter 5) have been established, such as total and per hectare carbon amount, total hectare area, total and per year energy and GHG emissions, total and pound net income (economy unit). Each of these objective functions corresponds with a policy issue in connection with the future forestry and agricultural land development and GHG reduction target in the UK.

The main constraint in relation to carbon saving, GHG and energy emissions reduction, is the land allocation model which is integrated in the Linear Programming model. In the Tamar valley catchment, some areas are seriously isolated due to the land situation and low infrastructure (i.e., Bracken land, Shrub land). More sophisticated land allocation approaches, for example these that integrate access to areas, or those that use a probabilistic approach to land covers change. For example, Contanello et al. (2011) only allocated woodland to areas within a specified distance of existing woods.

7.3.2 Data Collection and Main used Methods

There are a variety of methods which have been used by other researchers in order to quantify the carbon amount and GHG emissions on the national scale (DEFRA, 2008c; UK National Reduction Inventory Report, 2007), and forecast changes based on some specific land use change with regard to the policy, socio-economic and environmental issues. These methods have drawn on a broad range of information and data set covering soil structure, bio-physical, economic, and environmental prospects taken from years books, literature, land resource surveys (British Geological Survey), satellite analysis (land cover in GIS), IPCC and FAO's resources. A key limitation of these methods is that these data are insufficient and fragmented, specifically the energy and GHG data, some soils type information; and some data indirectly used for the carbon amount and energy, GHG's calculations and measurements. The method used in this thesis has tried to incorporate more complete information that is spatially explicit. Spatially explicit data, managed in land assessment analysis also has allowed for land suitability area determination and to quantify land suitability for various types of land use based on optimization modelling. This is a major strength of this work, and approach that is easy to replicate elsewhere providing that appropriate spatial data (soils and land cover) is available. The Tamar valley catchment was selected as the case study region to develop this methodological approach. A key part of this decision was the ready availability of spatial data. This study draws on secondary data to develop the methodological approach. Developing the methodology using readily-available secondary data sources means that application of the approach elsewhere does not require collection of extensive primary datasets and the key data sources are generally available for most regions of the world. Limitations of the secondary data sources have been recognised, through this thesis, every effort has been made to make data values as accurate as possible. Further, these were undertaken using sensitivity analysis and data confidence tests, both of which support the application of the approach.

7.4 Presentations, Assessment and Analysis of Results

There are several ways to direct the model analysis and results assessment. In this study, four types of model analysis have been considered to gain the appropriate results; that include the calculation and quantification of objective values (functions), scenario analysis, sensitivity analysis and equilibrium results.

7.4.1 Quantification and calculation of Objective Functions

Quantification and analysis for three main objective functions in relation to policy under a set of constraints (limitation) and the overall project aim (increasing the carbon amount) are considered based on Linear programming (optimization) model. The outcome has been presented in Chapters 5 for the range of different scenarios. It is clear that the optimum land cover change to maximize carbon is increasing forestry land as discussed in section 7.3. However, these scenarios struggled with other objectives, such as energy and GHG emission, and farm business income as, maximising carbon saving has direct consequences on these. For instance, when total amount of carbon in top soils is maximized (4.8 Mt C in scenario 8), the norm of farm business income is lower than normal average of income (due to long rotation of forest plantation). Energy and GHG emissions amount decrease almost linearly with an increase of the total amount of carbon.

This is a limitation of the Linear programming model approach, as it is only possible to optimize one of the objective functions at any one time. A more complex approach might seek to optimize multiple objective functions, such as maximizing carbon saving and maximizing farm income. This development was beyond the scope of this thesis. It is important to recognise that scenarios that seek to maximise carbon saving will have financial works to land management, and that policies which promote carbon saving should also develop appropriate mechanisms for payment for this public service.

7.4.2 Scenario Analysis

In this study, ten scenarios based in key policy areas have been produced (see Chapter 5, scenario section) for evaluation and assessment by Linear Programming model. Various objective functions for each specific scenario has been selected and categorized by their priorities and time period in relation to policy performance.

These scenarios are based in policy issues and actions likely to increase carbon storage. These results are echoed by other studies which investigated the different scenarios in relation to national policy target for reducing the GHG and increasing the carbon storage in land uses over time (King et al., 2004; FAO, 2005b, 2007a, 2007b, 2008b; UK National Inventory Target, 2007; Macleod et al., 2010; Obersteiner et al., 2010). These scenarios also have been supported by IPCC (2007a) scenarios target and Smith et al., (2008) especially in land use management development and practises.

The selection and parameterisation of the scenarios in this methodology are critical to the success of the approach. In this study there has been no involvement of national stakeholders, regional or local communities and as a consequence they could be considered unsatisfactory. However, these scenarios have been justified with consideration of the research target of this project and to national and international policy issues, based on current information, knowledge and understanding of land use management and development. It needs to be emphasised that these scenarios should not been considered as final alternatives, but an interpretation of national policy. It is recommended that the application of this methodological approach in other regions of the UK, or overseas, pay through attention to the development of scenarios. This should include using stakeholders workshops including national policy makers and representatives of land managers who will be responsible for implementing and land cover changes. The development of scenarios should also consider the parameter for each scenario carefully, for example the area or percentage increases of different land cover types under each scenario. The integration of stakeholders will ensure region in the modelling approach, providing the most likely, or realistic scenarios.

7.4.3 Sensitivity Analysis and Future Uncertainty

There are a range of uncertainties within the modelling approach. These uncertainties are caused by the lack of initial procedure information, incomplete and insufficient data, and the assumptions within the modelling process. Some factors are estimated using incomplete information, such as energy and GHG reductions, and carbon increase which is based on collective and literature data set. The volumes of carbon in soils and biomass are key parameter in the approach, and these, also include uncertainty because of unforeseen future changes to factors that influence carbon storage, such as population growth which may effectively reduce, or climate changes that may alter biogeochemical cycles. It is clear that the quality of predictions of carbon savings under different scenarios is controlled in part by the quality of the input data.

Some of these uncertainty problems have been assessed and evaluated by sensitivity analysis, in particular those that relate to data. In Chapter 5, in the section on sensitivity analysis; the effect of changing a carbon stored amount (up to ±90%) has been analysed and presented, i.e., the effect of increasing and decreasing carbon stored amount on the different scenarios. Increasing and reducing parameter values, as input data to the Linear Programming model allowed further analysis and assessment of the effect on optimization solutions (Laborte, 2007). The results are useful to assess the sensitivity of the model to particular factors. Soil carbon values are the most sensitive parameter and have a strong influence on the output of the model. These results were supported by other studies (Sharifi et al., 2007; Laborte, 2007; Voinov et al., 2002). It is therefore recommended that most effort is put into obtaining the best estimates of soil carbon where possible, and detailed soil mapping. The aim of the sensitivity analysis within the case study was to recognise the point at which uncertainty in the input (soil C) values changed the output values so much that the different scenarios were no longer distinct. This is made possible because the Linear Programming model is well constructed (Laborte, 2007), and so the sensitivity analysis of some results can be led with the model by a slight change in the relevant linear purposes. It is recommended that the application of this methodological approach in other areas also undertakes similar sensitivity testing to demonstrate the robustness of model outputs to users of the data.

In summary, the Linear Programming model allows for analysis and evaluation of the consequence and effect of changes in the model parameters.

7.4.4 Outcomes Presentations

A tremendous amount of results in this study have been presented that related to environment, economy, policy and physical structure of land uses, and also different type of land use allocation. Therefore, approaches are demanded to expressly and explicitly demonstrate the model outputs. This study is explicitly spatial, and as such output has been produced as tables, graphic figures, maps, and diagram to show the spatial distribution of carbon and optimization outputs under the range of different scenarios with respect to different objective function. This is especially important due to many outputs such as different assumptions in regard to fundamental run constraints, objective functions priorities in scenarios, objective functions, selected and important land use systems and final goal are enormously cooperating. Furthermore, these results of Linear Programming (LP) models are particularly non-contiguous. The outcomes show the capability and potentiality of land use change practises. As a result, with land uses changes, carbon storage will increase.

7.5 Results Highlights and Outputs Implications

7.5.1 Scenario Results Highlights

The modelling approach has demonstrated that the greatest potential for maximising carbon in the study area is to increase the forest and permanent grasslands area (Scenarios 8 and 10). This also leads to reductions in GHG and energy emissions. To meet the research aim demand at the long period of time (up to 2080) for the Tamar Valley catchment with the defined based scenarios and policy target (UK's reduction target) in the year 2050, the forestry land can be expanded and increased to 70% of the legal reported compared to 1999 base line. The average carbon amount in this scenario (scenario 8) can be increase by 0.97 Mt C in comparison to the current base line. Moreover, the energy and GHG emissions can be reduced by 40 Kt ha^{-1} yr^{-1}. These amounts are significant compared to the current situation. The feasibility of these scenarios in the Tamar Valley catchment will depend very much on policy maker decisions (stakeholders; mainly farmers). Sensitivity analysis results emphasised that the carbon storage, energy and GHG emissions remarkably can be increased and decreased, respectively when forest and Grassland increase in long term (see Chapter 5, sections scenarios and sensitivity analysis). In the long term, land conversion and management exchange can be promising options for forest and agricultural lands. Also, from an economic point of view, converting to grassland such as permanent and Improved are much more promising than forest land (scenarios 7, 8 and 10) (see Chapter 5, section farm business income). The amount of carbon, energy and GHG emissions which can be stored under these scenarios is, (0.28, 1.03 and 0.43 Mt C) in top soils and (1.12 and 0.38 Mt C) in total soils , (39.64 and 15.63 Kt yr^{-1}), and (47.53 and 18.75 Kt yr^{-1}) compare to current situation, respectively. This, net carbon saving over this period of time emphasises the potentiality and plausibility of these scenarios (see Chapter 6, section 6.3.2).

These results are in line and procession with other researches and studies which proposed and emphasised that land management practise and increasing carbon storage in forest and agricultural land is important and plausible over time (King et al., 2002 and 2004; Smith et al., 2004a, 2007 and 2008).

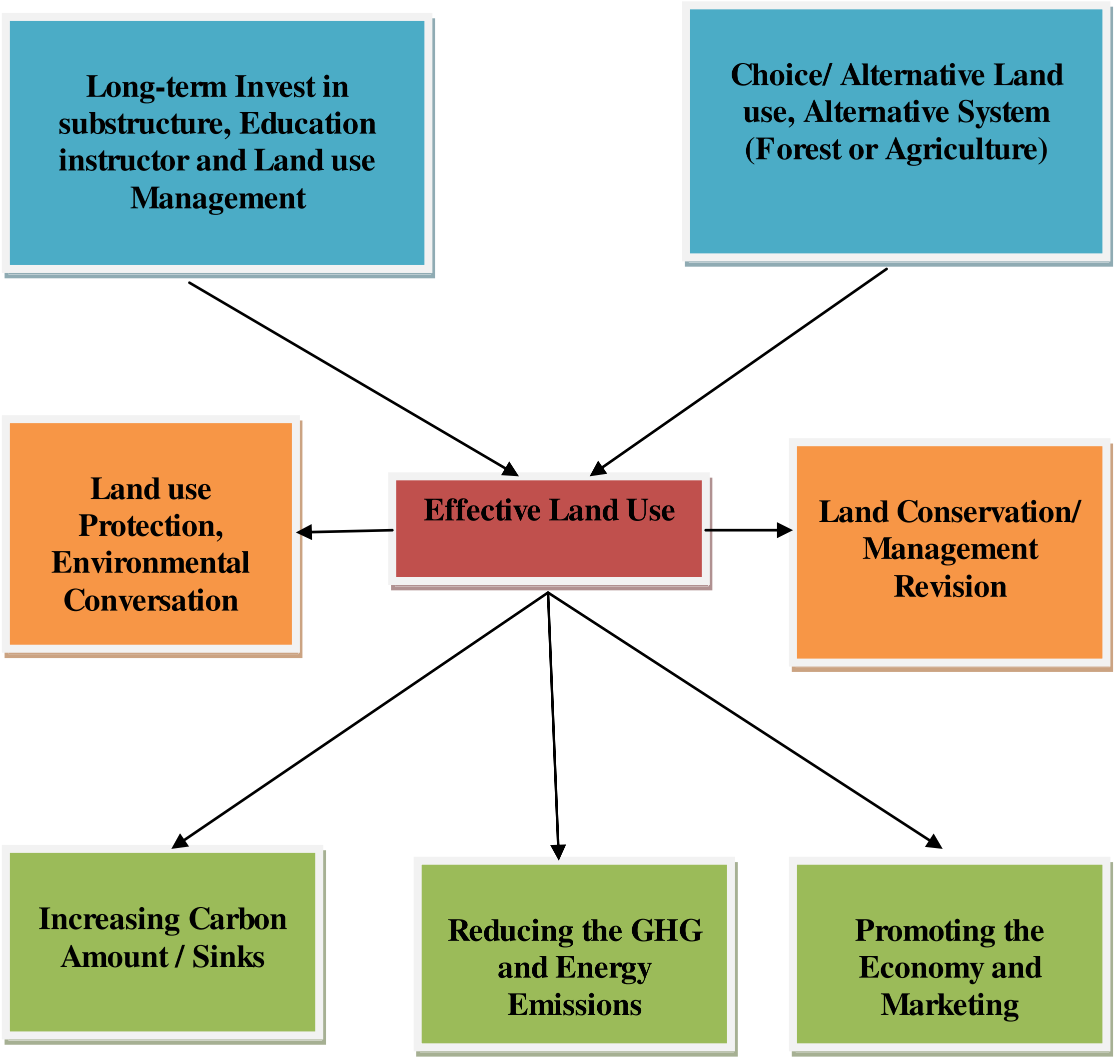
Comparing these values for carbon saving with values of equivalent of 263 Mt C for all Southwest of England and 114 Mt C in biomass for all UK in the amount with literature (especially in Cantarello et al., 2011 and Milne et al., 2005), confirms that these results presented are representative and that these scenarios can be achieved with stakeholders (e.g. governments, farmers) involvement.

7.5.2 Implications of Policy Issues

The results in this study are developed on assumptions that are based on the current limitations and structure of land cover, economic (Farm Business Income, Net Income), Government targets and farmers information. In Chapter 2, policy issues in forest and agriculture land management, the UK's energy and GHG emissions target was broadly discussed and considered. Carbon management is, to a great extent, reliant on correct land management. Over long time periods, investing in land use management (soils and biomass improvement) can significantly improve the land situation and environmental condition, with increase carbon sinks and reductions in GHG and energy emissions from agriculture and forest land. Based on this, policies that focus on carbon storage for climate mitigation should promote stakeholder's (mainly farmers) engagement and invest in or reward land managers who engage in carbon management through forestry and agricultural land conversion; and advance actions such as improving the substructure, educational activities and selling and marketing of carbon value of land.

In summary, there are many actions for policy-makers and stakeholders to select from the future development and improvement of carbon management by sufficient and effective use of land resource and set- a-side policy capacity. Figure 7.1 shows a snapshot of a range of options that would progress and promote effective land uses, to meet different targets of the land development in the UK context (Tamar Valley catchment) and further local and regional improvement in carbon management. Only some of these suggestions have been considered in depth in this research.

Figure 7.1: A representative (suggested) framework of the key policy issues to optimize effective land use for improvement in Tamar Valley catchment (Source: Author after Voinov, 2002; Laborte, 2007).



7.5.3 Implications of Research Study and Future Work

The Linear programming (optimization) model results specify and demonstrate that carbon saves / storage, energy and GHG emissions can be warranted and measured, and that there is capacity for enhanced carbon saving through land use management improvement and development. The energy and GHG emissions are generally reduced as a consequence of increasing carbon sinks in agriculture and forestry land. A mixed cultivation system (e.g. an agro-forestry system) may be considered. This will increase the amount of carbon in biomass and soils, and reduce GHG and energy emissions. For instance, converting land use to forest land in long term, Grassland with short rotation, alfalfa grass can be farmed and integrated. The methodological framework has been developed with the Tamar Valley catchment (914 Km^2) as the site study area for incorporated land use (agriculture and forestry) management with special regard to carbon saving, GHG and energy emissions reduction. However, this novel methodology is not limited to this catchment, or similar areas, but is widely transferable to any study area, regardless of scale from small catchments to regions or national inventories. Taking into account the spatial objectives of land use situations, the Linear Programming model can be considered for researching the optimal and feasible alternatives for land use (agriculture and forestry) management practise in any region of the model, provided that the appropriate spatial data on land cover and soils are available, ideally in a GIS format. The application of this methodological framework thus requires: appropriate spatial data on soils and biomass, and data that describes the carbon density of different soils and land cover types and emissions data; robust scenarios of future land cover change, ideally developed with appropriate stakeholders and embedded within policy frameworks; data on the economics of farm income. If these data are available, the approach can be used.

This methodological framework was the key aim of this project, which has been successfully realised. Therefore, the main implications of this research can be summarised as:

a) This thesis has developed an approach for quantifying carbon sequestration and assessing changes under a range of scenarios;

b) The approach has the advantages of being 1) Spatially explicit 2) informed by potential land allocation, and 3) based entirely on secondary data;

c) Whilst the model has been developed using a case study area (Tamar Valley catchment), it should be readily possible to apply this modelling approach to any other region of the world, providing that the appropriate secondary data sets (soil map and knowledge of soil carbon; land cover and biomass data; range of appropriate scenarios; data to assess land suitability and allocation) are available.

However, existing databases do not always have all the required information and future work is necessary to provide this. Forests are the main sink of carbon but their density and productivity varies and changes in land use due to policies and other parameters and climate change and schemes may also result in particular places becoming significant sources or sinks for carbon. Also on this work, data collection and meta-analysis on land use types can be modelling (see chapters 5 and 6). This meta- analysis using this data to calculate response factors for GHG with respect to driving variables, (e.g. climate, soil type, fertiliser type, soil organic carbon content), is also required. It needs to be noted that although in this research changes in soil carbon storage have not been explicitly considered within the analyses, it may be important over longer timescales such as those referred to in chapter 6. It is assumed that this will tend to exaggerate the changes in biomass carbon storage although this remains to be tested. For example conversion to woodland will not only increase biomass carbon storage, but is also likely to increase soil carbon storage. On the other hand, higher temperatures are likely to lead to increased carbon release as a consequence of enhanced rates of decomposition in soils. This is a limitation of the analyses presented in this study.

Statistical approaches will be developed. Ideally, total GHG budget on land uses should attempt to assess the combined impact of land use (Agricultural and Forestry) management, climate and indirect effects (such as increasing CO_2 concentration), and then assess realistic mitigation and adaptation options in the agricultural sector. This needs to be assessed for all different environmental factors such as policy, economic constraints and potential side effects. This thesis has made a contribution in this field, but the challenge now is to extend the work on the pool size to include rates of change of stored carbon and reduce the GHG emissions as much as possible with all different scenarios type within the period of time in which it might happen.

Glossary

Definition of key concepts and expressions used:

Before the formulation of the research, we must be clear on key concepts and the terminology used in this research. This section provides these definitions arranged in alphabetic order.

Democracy policy: is 'a form of government in which either the people have a voice in the exercise of power, typically through elected representatives or a state governed in such a way or control of a group by the majority of its members'

Direct Energy: direct energy inputs to farming are in the form of fuel oils, electricity, and gas, etc. which are consumed on the farm. These can be considered as a variable input directly proportional to the size of the respective enterprise.

Indirect Energy: in addition to the fuel directly used at farm level, indirect energy is used in agriculture in the form of other inputs and intermediate flows. The main categorise of indirect energy are: fertilisers, pesticides, field machinery, intermediate inputs and basic and variable energy inputs.

Forest management: The term management includes arrangement/disposition, skilful treatment, and control. Forest management simply refers to the dispositions that are taken to control the skilful use of the forest resources. However, foresters have long focused forest management mainly on the balance between timber extraction and the tree growth from regeneration. Nowadays, the concepts have evolved and seek to fulfil the actual and future demands for forest products and the sustainability of the forest resources. Forest management includes a planning phase, an implementation phase, and a monitoring phase.

Geographic Information System/Science (GIS): is a computer-based system for collecting, storing, manipulating and visualizing spatial data from the real world for a particular set of purposes (Burrough and McDonnell, 1998).

Land: The term land refers to an ecosystem comprising terrain, soil, vegetation, fauna, water, climate, and the underlying geology (FAO, 1976). It is a specific object, with attributes amenable to analysis, modelling, and manipulation.

Land use/ land cover (LULC): According to Turner II et al. (1995) land cover is the biophysical state of the earth's surface and immediate subsurface. Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation, the purpose for which the land is used. Land cover and land use are, however, intimately connected because a wide range of human land use activities changes the physical environment (and therefore land cover). In this sense, one land use type may involve many different land cover types.

Land use/land cover changes/dynamics: can be a conversion from one category of land cover or land use type to another (e.g. urbanization, infrastructure), or a modification of the conditions, which affect the processes within the same category (e.g. primary vs. secondary forest, intensive agriculture vs. extensive agriculture).

Landscape: As defined in Turner and Gardner (1991), landscape is referred to as the land surface and its associated habitats at a defined scale. Landscape is a spatially heterogeneous area, characterized by:

- its structure (pattern) which refers to the spatial relationship between distinctive ecosystems, in relation to the sizes, shapes, numbers, kinds, and configurations of components;
- Its function (process) which refers to the interactions between the spatial elements;
- Its change (effect, new pattern), which is the alteration in structure and function of the ecological mosaic through time.

Landscape fragmentation: refers to the structure and the changes in landscape; it is the breaking up of the landscape elements into smaller parcels. It is similar to breaking an object into pieces of diverse sizes.

Models and modelling: The term model often refers to a small reproduction or representation of an object or a phenomenon, a design to be copied, an ideal or standard situation, or a perfect thing to be imitated. In the sense in which it is used here, the term model means a simplified representation of reality, which is designed to facilitate visualization, prediction and calculation, and which can also be expressed in symbolic or mathematical form. Modelling is the process of designing and using these models. Models are considered to be linking data and theory through a set of formal equations that represent the key relationships underlying processes of change (Turner and Gardner, 1991). Models are constructed to improve our understanding of theoretical problems, not to duplicate every detail of real world (Caswell, 1988; Hoosbeek et al., 2000). Models that are set out principally to describe or mimic the observed relationships between variables are called empirical models, whereas mechanistic models are those that attempt to give both a description and an understanding of the processes. If relationships in a model are assumed to be known with certainty (cause and effect), then the model is said to be deterministic. If they are assumed to be subject to random variation, then the model is probabilistic or stochastic. Dynamic landscape models are those that predict the changes in spatial structure of the landscape and map the flows of energy, matter and information between locations (Sklar and Costanza, 1991).

Soil parameter: is a single or combined characteristic of soil that is observable or measurable. The FAO's World Reference base for soil resources (FAO-ISRIC, 1998) provides the following definitions of different types of soil parameters: soil characteristics are single parameters which are observable or measurable in the field or laboratory, or can be analysed using microscope techniques; soil properties are combinations of soil characteristics which are known to occur in soils and which are considered to be indicative of present or past soil forming processes; while soil horizons are three-dimensional pedological bodies which are more or less parallel to the earth's surface and contain one or more property, occurring over a certain depth.

Soil variables: are soil characteristics, soil properties or soil horizons that are used for statistical analyses or for modelling dynamics processes in soil.

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Appendixes

<u>Appendix 1</u>: Land Use Specific Code in GIS System

Table 1.A: Soil types specific code in GIS system in the Tamar valley catchment.

Soil Types	Soil Codes
Neath	0
Hallsworth	1
Denbigh	2
Yeollandpark	3
Parc	4
Hafren	5
Princetown	6
Moor Gate	7
Winter Hill	8
Trusham	9
Hexworthy	10
Wilcocks 2	11
Moretonhampstead	12
Powys	13
Nordrach	14
Onecote	15
Lake	16
Sportsmans	17
Halstow	18
Teme	19
Conway	20
Malvern	21
Crowdy 2	22
Manod	23
Larkbarrow	24
Alun	25
Laployd	26
Sea	27
Raw China Clays	28

Table 1.B: Land Cover types specific code in GIS system in the Tamer Valley catchment.

Vegetation Types	Vegetation Codes
Broad-leave Woodland	11
Coniferous Woodland	21
Arable Cereals	41
Arable Horticulture	42
Improved Grassland	51
Neutral Grass	61
Calcareous Grass	71
Acid Grass	81
Bracken	91
Dwarf Shrub Heath	101
Open Dwarf Shrub Heath	102
Bog	121
Water	131
Inland Bare ground	161
Suburban /Rural development	171
Continuous Urban	172
Littoral Rock	211
Salt Marsh	212
Sea	221

Appendix 2: Elevation Category and Specific GIS Code

Table 2.A: Elevation classifies (meter) and specific code for land unit in GIS.

Elevation classifies (Meter)	Specific Code
0 – 100 Meter	1
100 – 200 Meter	2
200 – 300 Meter	3
300 – 400 Meter	4
400 – 500 Meter	5
500 – 600 Meter	6

Appendix 3: Sensitivity Analysis (SA) Calculations (±10%, ±30%, ±50%, ±70%, and ±90%) in top soils and total soils.

A. Top Soils (0-20 cm) SA

Table 3.1.A: Top soils sensitivity analysis (±10%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-20	24.8- 30.3	20311	558552.5- 615423.3
Hallsworth 1	0-20	11.5- 14	13895	176466.5- 194530
Hallsworth 2	0-20	11.5- 14	6450	81915- 90300
Denbigh 2	0-20	9.2- 11.3	11499	117289.8- 129938.7
Denbigh 1	0-20	9.2- 11.3	67774	691294.8- 765846.2
Parc	0-20	3.5- 4.3	801	3123.9- 3444.6
Hafren	0-20	20.5- 25.6	1739	39649.2- 44518.4
Moor Gate	0-20	15.4- 18.8	3085	52753.5- 57998
Winter Hill	0-20	4.9- 5.7	200	1040- 1140
Hexworthy	0-20	3.4- 4.1	4892	18100.4- 20057.2
Wilcocks 2	0-20	12.2- 14.9	1265	17077.5- 18848.5
Powys	0-20	11.1- 13.5	1950	23985- 26325
Yeollandpark	0-20	12.4- 15.2	1232	17001.6- 18726.4
Princetown	0-20	38.7- 47.3	4708	202444- 222668.4
Larkbarrow	0-20	5.7- 6.9	914	5758.2- 6306.9
Trusham	0-20	6.7- 8.2	10309	76286.6- 84553.8
Laployd	0-20	31.9- 38.9	129	4566.6- 5018.1
Nordrach	0-20	8.7- 10.7	951	9224.7- 10175.6
Moretonhampstead	0-20	6- 7.3	2656	17529.6- 19388.5
Raw china clay spoil	0-20	0	872	0
Onecote	0-20	12.9- 15.8	119	1701.7- 1880.2
Sportsmans	0-20	8.9-10.9	2723	26957.7- 29680.7
Halstow	0-20	7.6- 9.3	5785	48594- 53800.9
Teme	0-20	4.4- 5.4	1486	7281.4- 8024.4
Conway	0-20	24.8- 30.3	903	24832.5- 27360.9
Malvern	0-20	10.2- 12.4	1566	17695.8- 19418.7
Manod	0-20	10.3- 12.5	11449	130518.6- 143112.5
Alun	0-20	5.8- 7.1	165	1056- 1171.5
Crowdy 2	0-20	13.4- 16.3	4878	72194.4- 79511.4
Total			**184706**	**2444891.5- 2699168.8**

Table 3.2.A: Top soils sensitivity analysis (±30%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-20	19.25- 37.75	20311	390986.8-766740.3
Hallsworth 1	0-20	8.9- 16.51	13895	123665.5-229406.5
Hallsworth 2	0-20	8.9- 16.51	6450	57405-106489.5
Denbigh 2	0-20	7.14-13.26	11499	82102.86-152476.7
Denbigh 1	0-20	7.14-13.26	67774	483906.4-898683.2
Parc	0-20	2.73- 5.07	801	2186.73-4061.07
Hafren	0-20	15.96- 29.64	1739	27754.44-51543.96
Moor Gate	0-20	11.97- 22.23	3085	36927.45-68579.55
Winter Hill	0-20	3.64- 6.78	200	728-1356
Hexworthy	0-20	2.6- 4.81	4892	12719.2-23530.52
Wilcocks 2	0-20	9.45-17.55	1265	11954.25-22200.75
Powys	0-20	8.60- 16	1950	16770-31200
Yeollandpark	0-20	9.7- 17.95	1232	11950.4-22114.4
Princetown	0-20	30- 56	4708	141240-263648
Larkbarrow	0-20	4.4- 8.2	914	4021.6-7494.8
Trusham	0-20	5.2- 9.62	10309	53606.8-99172.58
Laployd	0-20	24.8- 46	129	3199.2-5934
Nordrach	0-20	6.8- 12.6	951	6466.8-11982.6
Moretonhampstead	0-20	4.6- 8.6	2656	12217.6-22841.6
Raw china clay spoil	0-20	0- 0	872	0
Onecote	0-20	10- 18.6	119	1190-2213.4
Sportsmans	0-20	6.95- 12.9	2723	18924.85-35126.7
Halstow	0-20	5.9- 10.95	5785	34131.5-63345.75
Teme	0-20	3.45- 6.4	1486	5126.7-9510.4
Conway	0-20	19.25- 35.75	903	17382.75-32282.25
Malvern	0-20	7.9- 14.7	1566	12371.4-23020.2
Manod	0-20	8- 14.8	11449	91592-169445.2
Alun	0-20	4.5- 8.3	165	742.5-1369.5
Crowdy 2	0-20	10.4- 19.24	4878	50731.2-93852.72
Total			184706	**1712002-3219622**

Table 3.3.A: Top soils sensitivity analysis (±50%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-20	13.75- 41.25	20311	279276.3- 837828.8
Hallsworth 1	0-20	6.35- 19.05	13895	88233.25- 264699.8
Hallsworth 2	0-20	6.35-19.05	6450	40957.5- 122872.5
Denbigh 2	0-20	5.1-15.3	11499	58644.9- 175934.7
Denbigh 1	0-20	5.1-15.3	67774	345647.4- 1036942
Parc	0-20	1.95-5.85	801	1561.95- 4685.85
Hafren	0-20	11.4-34.2	1739	19824.6- 59473.8
Moor Gate	0-20	8.55-25.65	3085	26376.75- 79130.25
Winter Hill	0-20	2.6-7.8	200	520- 1560
Hexworthy	0-20	1.85-5.55	4892	9050.2- 27150.6
Wilcocks 2	0-20	6.75-20.25	1265	8538.75- 25616.25
Powys	0-20	6.15-18.45	1950	11992.5- 35977.5
Yeollandpark	0-20	6.9-20.7	1232	8500.8- 25502.4
Princetown	0-20	21.5-64.5	4708	101222- 303666
Larkbarrow	0-20	3.15-9.45	914	2879.1- 8637.3
Trusham	0-20	3.7-11.1	10309	38143.3- 114429.9
Laployd	0-20	17.7-53.1	129	2283.3- 6849.9
Nordrach	0-20	4.85-14.55	951	4612.35- 13837.05
Moretonhampstead	0-20	3.3 -9.9	2656	8764.8- 26294.4
Raw china clay spoil	0-20	0-0	872	0
Onecote	0-20	7.15-21.45	119	850.85- 2552.55
Sportsmans	0-20	4.95-14.85	2723	13478.85- 40436.55
Halstow	0-20	4.2-12.6	5785	24297- 72891
Teme	0-20	2.45- 7.35	1486	3640.7- 10922.1
Conway	0-20	13.75-41.25	903	12416.25- 37248.75
Malvern	0-20	5.65-16.95	1566	8847.9- 26543.7
Manod	0-20	5.7-17.1	11449	65259.3- 195777.9
Alun	0-20	3.2- 9.6	165	528- 1584
Crowdy 2	0-20	7.4-22.2	4878	36097.2- 108291.6
Total			**184706**	**1222446- 3667337**

Table 3.4.A: Top soils sensitivity analysis (±70%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-20	8.25- 46.8	20311	167565.8-950554.8
Hallsworth 1	0-20	3.80- 21.6	13895	52801- 300132
Hallsworth 2	0-20	3.80- 21.6	6450	24510- 139320
Denbigh 2	0-20	3.05- 17.4	11499	35071.95- 200082.6
Denbigh 1	0-20	3.05- 17.4	67774	206710.7- 1179268
Parc	0-20	1.2- 6.7	801	961.2- 5366.7
Hafren	0-20	6.85- 38.8	1739	11912.15- 67473.2
Moor Gate	0-20	5.15- 29	3085	15887.75- 89465
Winter Hill	0-20	1.55- 8.9	200	310- 1780
Hexworthy	0-20	1- 6.3	4892	4892- 30819.6
Wilcocks 2	0-20	4- 23	1265	5060-29095
Powys	0-20	8.6- 20.9	1950	16770-40755
Yeollandpark	0-20	4.3- 23.2	1232	5297.6-28582.4
Princetown	0-20	12.9- 73.1	4708	60733.2-344154.8
Larkbarrow	0-20	1.9- 10.7	914	1736.6-9779.8
Trusham	0-20	2.2- 12.6	10309	22679.8-129893.4
Laployd	0-20	10.6- 60.2	129	1367.4-7765.8
Nordrach	0-20	2.9- 16.5	951	2757.9-15691.5
Moretonhampstead	0-20	2- 11	2656	5312-29216
Raw china clay spoil	0-20	0	872	0
Onecote	0-20	4.3- 24.3	119	511.7- 2891.7
Sportsmans	0-20	3- 16.7	2723	8169-45474.1
Halstow	0-20	2.5- 14.3	5785	14462.5-82725.5
Teme	0-20	1.5- 8.5	1486	2229-12631
Conway	0-20	8.3- 46.8	903	7494.9-42260.4
Malvern	0-20	3.4- 19.2	1566	5324.4-30067.2
Manod	0-20	3.45- 19.3	11449	39499.05-220965.7
Alun	0-20	2.2- 10.8	165	363-1782
Crowdy 2	0-20	4.8- 24.8	4878	23414.4-120974.4
Total			184706	**743805- 4158967**

Table 3.5.A: Top soils sensitivity analysis (±90%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-20	2.8- 52.3	20311	56870.8-1062265
Hallsworth 1	0-20	1.3-24.1	13895	18063.5-334869.5
Hallsworth 2	0-20	1.3-24.1	6450	8385-155445
Denbigh 2	0-20	1.1-19.4	11499	12648.9-223080.6
Denbigh 1	0-20	1.1-19.4	67774	74551.4-1314816
Parc	0-20	0.4-7.4	801	320.4-5927.4
Hafren	0-20	2.3- 43.3	1739	3999.7-75298.7
Moor Gate	0-20	1.7- 32.5	3085	5244.5-100262.5
Winter Hill	0-20	0.5- 10	200	100-2000
Hexworthy	0-20	0.4- 7	4892	1956.8-34244
Wilcocks 2	0-20	1.4-25.7	1265	1771-32510.5
Powys	0-20	1.2-23.4	1950	2340-45630
Yeollandpark	0-20	1.7-26.2	1232	2094.4-32278.4
Princetown	0-20	4.4-81.7	4708	20715.2-384643.6
Larkbarrow	0-20	0.7-12	914	639.8-10968
Trusham	0-20	0.8-14	10309	8247.2-144326
Laployd	0-20	3.6-67.3	129	464.4-8681.7
Nordrach	0-20	1-18.4	951	951-17498.4
Moretonhampstead	0-20	0.7-12.5	2656	1859.2-33200
Raw china clay spoil	0-20	0	872	0
Onecote	0-20	1.5-27.2	119	178.5-3236.8
Sportsmans	0-20	1-18.8	2723	2723-51192.4
Halstow	0-20	0.9-16	5785	5206.5-92560
Teme	0-20	0.5-9.3	1486	743-13819.8
Conway	0-20	2.8-52.3	903	2528.4-47226.9
Malvern	0-20	1.2-21.5	1566	1879.2-33669
Manod	0-20	1.3-21.6	11449	14883.7-247298.4
Alun	0-20	0.7-12.2	165	115.5-2013
Crowdy 2	0-20	1.5-28.2	4878	7317-137559.6
Total			184706	**256798-4646521**

B. Total Soils (0-120 cm) SA

Table 3.1.B: Total soils sensitivity analysis (±10%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t/ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-100	40- 49	20311	812440- 995239
Hallsworth 1	0-100	23.2- 28.8	13895	322364- 400176
Hallsworth 2	0-100	23.2- 28.8	6450	149640- 185760
Denbigh 2	0-100	30.4- 37.2	11499	349569.6- 427762.8
Denbigh 1	0-100	30.4- 37.2	67774	2060330- 2521193
Parc	0-100	19.2- 23.5	801	15379.2- 18823.5
Hafren	0-54	28.6- 35	1739	49735.4- 60865
Moor Gate	0-120	34.4- 42.6	3085	106124- 131421
Winter Hill	0-63	10.6- 13	200	2120- 2600
Hexworthy	0-87	32.3- 39.5	4892	158011.6- 193234
Wilcocks 2	0-74	36.2- 44.3	1265	45793- 56039.5
Powys	0-102	21.8- 26.6	1950	42510- 51870
Yeollandpark	0-63	16.6- 20.5	1232	20451.2- 25256
Princetown	0-120	19.4- 23.7	4708	91335.2- 111579.6
Larkbarrow	0-77	19.3- 23.6	914	17640.2- 21570.4
Trusham	0-120	21.4- 26.3	10309	220612.6- 271126.7
Laployd	0-71	73.4- 89.7	129	9468.6- 11571.3
Nordrach	0-85	23.5- 28.7	951	22348.5- 27293.7
Moretonhampstead	0-58	36.9- 45.1	2656	98006.4- 119785.6
Raw china clay spoil	0	0	872	0
Onecote	0-92	15.9- 19.7	119	1892.1- 2344.3
Sportsmans	0-90	17.3- 21.2	2723	47107.9- 57727.6
Halstow	0-130	13.7- 16.7	5785	79254.5- 96609.5
Teme	0-127	23.7- 28.9	1486	35218.2- 42945.4
Conway	0-91	71.3- 87.2	903	64383.9- 78741.6
Malvern	0-77	18.8- 23.1	1566	29440.8- 36174.6
Manod	0-95	29.6- 36.2	11449	338890.4- 414453.8
Alun	0-127	26.6- 32.6	165	4389- 5379
Crowdy 2	0-100	78.7- 96.2	4878	383898.6- 469263.6
Total			**184706**	**5578355- 6836806**

Table 3.2.B: Total soils sensitivity analysis (±30%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t/ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-100	31.1- 57.6	20311	631672.1- 1169913.6
Hallsworth 1	0-100	18- 33.5	13895	250110- 465482.5
Hallsworth 2	0-100	18- 33.5	6450	116100- 281220
Denbigh 2	0-100	23.7- 43.6	11499	272526.3- 505956
Denbigh 1	0-100	23.7- 43.6	67774	1606243.8- 2982056
Parc	0-100	14.9- 27.6	801	11934.9- 22107.6
Hafren	0-54	22.3- 41.3	1739	38779.7- 71820.7
Moor Gate	0-120	26.7- 49.6	3085	82369.5- 153016
Winter Hill	0-63	8.3- 15.4	200	1660- 3080
Hexworthy	0-87	25.1- 46.7	4892	122789.2- 228456.4
Wilcocks 2	0-74	28.2- 52.3	1265	35673- 66159.5
Powys	0-102	17- 31.4	1950	33150- 61230
Yeollandpark	0-63	12.9- 23.9	1232	15892.8- 29444.8
Princetown	0-120	15- 28	4708	70620- 131824
Larkbarrow	0-77	15- 27.8	914	13710- 25409.2
Trusham	0-120	16.7- 31	10309	172160.3- 319579
Laployd	0-71	57- 105.9	129	7353- 13661.1
Nordrach	0-85	18.3- 32.1	951	17403.3- 30527.1
Moretonhampstead	0-58	28.7- 53.3	2656	76227.2- 141564.8
Raw china clay spoil	0	0- 0	872	0- 0
Onecote	0-92	12.3- 22.9	119	1463.7- 2725.1
Sportsmans	0-90	13.4- 25	2723	36488.2- 68075
Halstow	0-130	10.6- 19.7	5785	61321- 113964.5
Teme	0-127	18.4- 34.2	1486	27342.4- 50821.2
Conway	0-91	55.5- 103	903	50116.5- 93009
Malvern	0-77	14.7- 27.3	1566	23020.2- 42751.8
Manod	0-95	23- 42.8	11449	263327- 490017.2
Alun	0-127	20.7- 38.3	165	3415.5- 6319.5
Crowdy 2	0-100	63.3- 113.6	4878	308777.4- 554140.8
Total			**184706**	**4351647- 8125314.7**

Table 3.3.B: Total soils sensitivity analysis (±50%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t/ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-100	22.2- 66.5	20311	450904.2- 1350851.8
Hallsworth 1	0-100	12.9- 38.6	13895	179245.5- 536347
Hallsworth 2	0-100	12.9- 38.6	6450	83205- 248970
Denbigh 2	0-100	16.9- 50.7	11499	194333.1- 582999.3
Denbigh 1	0-100	16.9- 50.7	67774	1145380.6- 3436142
Parc	0-100	10.6- 31.8	801	8490.6- 25471.8
Hafren	0-54	15.9- 47.6	1739	27650.1- 82776.4
Moor Gate	0-120	19.1- 57.2	3085	58923.5- 176462
Winter Hill	0-63	5.9- 17.7	200	1180- 3540
Hexworthy	0-87	18- 53.9	4892	88056- 263678.8
Wilcocks 2	0-74	20.1- 60.3	1265	25426.5- 76279.5
Powys	0-102	12.1- 36.3	1950	23595- 70785
Yeollandpark	0-63	9.2- 27.6	1232	11334.4- 34003.2
Princetown	0-120	10.8- 32.3	4708	50846.4-152068.4
Larkbarrow	0-77	10.7- 32.1	914	9779.8- 29339.4
Trusham	0-120	11.9- 35.7	10309	122677.1- 368031.3
Laployd	0-71	40.7- 122.2	129	5250.3- 15763.8
Nordrach	0-85	13- 39.1	951	12363- 37184.1
Moretonhampstead	0-58	20.5- 61.4	2656	54448- 163078.4
Raw china clay spoil	0	0	872	0- 0
Onecote	0-92	8.8- 26.4	119	1047.2- 3141.6
Sportsmans	0-90	9.6- 28.8	2723	26140.8- 78422.4
Halstow	0-130	7.6- 22.7	5785	43966- 131319.5
Teme	0-127	13.2- 39.5	1486	19615.2- 58697
Conway	0-91	39.6- 118.8	903	35758.8- 107276.4
Malvern	0-77	10.5- 31.4	1566	16443- 49172.4
Manod	0-95	16.5- 49.4	11449	188908.5- 565580.6
Alun	0-127	14.7- 44.2	165	2425.5- 7293
Crowdy 2	0-100	43.7- 131.1	4878	213168.6- 639505.8
Total			**184706**	**3100562.7- 9294010**

Table 3.4.B: Total soils sensitivity analysis (±70%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t/ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-100	13.30- 75.38	20311	270136.3- 1531043
Hallsworth 1	0-100	7.71- 43.71	13895	107130.5- 607350.5
Hallsworth 2	0-100	7.71- 43.71	6450	49729.5- 281929.5
Denbigh 2	0-100	10.14- 57.48	11499	116599.9- 660962.5
Denbigh 1	0-100	10.14- 57.48	67774	687228.4- 3895650
Parc	0-100	6.37- 36.09	801	5102.37- 28908.09
Hafren	0-54	9.53- 53.99	1739	16572.67- 93888.61
Moor Gate	0-120	11.44- 64.84	3085	35292.4- 200031.4
Winter Hill	0-63	3.54- 20.06	200	708- 4012
Hexworthy	0-87	10.78- 61.06	4892	52735.76- 298705.5
Wilcocks 2	0-74	12.05- 68.29	1265	15243.25- 86386.85
Powys	0-102	7.25- 41.11	1950	14137.5- 80164.5
Yeollandpark	0-63	5.52- 31.26	1232	6800.64- 38512.32
Princetown	0-120	6.45- 36.55	4708	30366.6- 172077.4
Larkbarrow	0-77	6.42- 36.40	914	5867.88- 33269.6
Trusham	0-120	7.15- 40.51	10309	73709.35- 417617.6
Laployd	0-71	24.43- 138.45	129	3151.47- 17860.05
Nordrach	0-85	7.82- 44.30	951	7436.82- 42129.3
Moretonhampstead	0-58	12.29- 69.63	2656	32642.24- 184937.3
Raw china clay spoil	0	0.0- 0.00	872	0- 0
Onecote	0-92	5.28- 29.90	119	628.32- 3558.1
Sportsmans	0-90	5.76- 32.62	2723	15684.48- 88824.26
Halstow	0-130	4.55- 25.76	5785	26321.75- 149021.6
Teme	0-127	7.89- 44.73	1486	11724.54- 66468.78
Conway	0-91	23.76- 134.62	903	21455.28- 121561.9
Malvern	0-77	6.28- 35.60	1566	9834.48- 55749.6
Manod	0-95	9.87- 55.95	11449	113001.6- 640571.6
Alun	0-127	8.84- 50.08	165	1458.6- 8263.2
Crowdy 2	0-100	26.22- 148.58	4878	127901.2- 724773.2
Total			**184706**	**1858602- 10534228**

Table 3.5.B: Total soils sensitivity analysis (±90%) in the Tamar Valley catchment.

Soils Types	Depth (cm)	Density of C (t/ha^{-1})	Area (ha)	Total Carbon (t)
Neath	0-100	4.43- 84.25	20311	89977.73- 1711202
Hallsworth 1	0-100	2.57- 48.85	13895	35710.15- 678770.8
Hallsworth 2	0-100	2.57- 48.85	6450	16576.5- 315082.5
Denbigh 2	0-100	3.38- 64.24	11499	38866.62- 738695.8
Denbigh 1	0-100	3.38- 64.24	67774	229076.1- 4353802
Parc	0-100	2.12- 40.34	801	1698.12- 32312.34
Hafren	0-54	3.18- 60.34	1739	5530.02- 104931.3
Moor Gate	0-120	3.81- 72.47	3085	11753.85- 223570
Winter Hill	0-63	1.18- 22.42	200	236-4484
Hexworthy	0-87	3.59-68.25	4892	17562.28- 333879
Wilcocks 2	0-74	4.02- 76.32	1265	5085.3- 96544.8
Powys	0-102	2.42-45.94	1950	4719- 89583
Yeollandpark	0-63	1.84- 34.94	1232	2266.88- 43046.08
Princetown	0-120	2.15- 40.85	4708	10122.2- 192321.8
Larkbarrow	0-77	2.14- 40.68	914	1955.96- 37181.52
Trusham	0-120	2.38- 45.28	10309	24535.42- 466791.5
Laployd	0-71	8.14- 154.74	129	1050.06- 19961.46
Nordrach	0-85	2.61-49.51	951	2482.11- 47084.01
Moretonhampstead	0-58	4.10-77.82	2656	10889.6- 206689.9
Raw china clay spoil	0	0.0- 0.00	872	0.00- 0.00
Onecote	0-92	1.76- 33.42	119	209.44- 3976.98
Sportsmans	0-90	1.92- 36.46	2723	5228.16- 99280.58
Halstow	0-130	1.52- 28.79	5785	8793.2- 166550.2
Teme	0-127	2.63- 49.99	1486	3908.18- 74285.14
Conway	0-91	7.92- 150.46	903	7151.76- 135865.4
Malvern	0-77	2.09- 39.79	1566	3272.94- 62311.14
Manod	0-95	3.29- 62.53	11449	37667.21- 715906
Alun	0-127	2.95- 55.97	165	486.75- 9235.05
Crowdy 2	0-100	8.74- 166.1	4878	42633.72- 810235.8
Total			**184706**	**619445.3- 11773579**