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EFFECT OF LAND USE LAND COVER CHANGES ON CARBON SEQUESTRATION IN GERMANY

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DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

[Lisboa], [17/02/2020]

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ABSTRACT

Using carbon sequestration as an indicator for environmental health, it is possible to assess whether a country is on its way to achieving carbon neutrality in the Land Use, Land-Use Change and Forestry (LULUCF) sector. A great deal of research has been conducted to find out whether there is a relationship between LULC and carbon sequestration. In this paper we explore several scenarios and compare how much carbon would be stored under each of them. In addition, this research aims to find out how best the LULUCF sector can contribute towards a country’s goals in achieving carbon neutrality. This was conducted using two models; Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, which calculates the amount of carbon stored in a landscape and TerrSet’s Land Change Modeller, which uses a combination of neural networks and CA Markov to project future Land Use Land Cover (LULC) scenarios. From the documentation of the carbon trend over the 28-year period using the InVEST model, the study finds that between the years of 1990 and 2018, the amount of carbon stored increased by 0.15%. Under the Business as Usual scenario projection there is an increase of 0.22% by the year 2048. In the development scenario we see a decrease of 0.96% and finally in the two conservation scenarios the carbon stock increases by 4.16% and 0.41% respectively. These results suggest that the scenario which would be most beneficial to Germany would be the first conservation scenario. The results of this study highlight the importance of the LULUCF sector in mitigating climate change. Therefore, they can be used to provide informed decision making to spatial planners and land management stakeholders during the development of future land use planning policies.

KEY WORDS:

Carbon sequestration

InVEST model

Geographic Information Systems

TerrSet’s Land Change Modeller

ACRONYMS

BAU	Business as Usual
CAP	Climate Action Plan
CLC	Corine Land Cover
DEM	Digital Elevation Model
ES	Ecosystem Services
FAO	Food Aid Organization
GDP	Gross Domestic Product
GHG	Greenhouse Gases
InVEST	Integrated Valuation of Environmental Services and Trade-offs
IPCC	International Panel of Climate Change
Kt of C	Kilotons of Carbon
LCM	Land Change Modeller
LULC	Land Use Land Change
LULUCF	Land Use, Land-Use Change and Forestry
MLP	Multi-layer Perceptron
Mg of C	Megagrams of Carbon
PPP	Purchasing Power Party
REDD+	Reducing of Emissions from Forest Degradation and Deforestation
UK	United Kingdom
UNFCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WEC	World Economic Forum

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1. Introduction

Carbon flows naturally in the Earth System through the atmosphere, biosphere and lithosphere in an ensemble of processes known as the carbon cycle (Ciais et al., 2013). Over time, carbon emissions in the form of carbon dioxide have tremendously increased (Le Quéré et al., 2009; Meinshausen et al., 2017). This is as a result of an increase in the use of fossil fuels as well as historical land use and land cover changes which have in turn contributed to climate change and increased the likelihood of environmental and economic losses in the future (Ciais et al., 2013). Ecosystems regulate the Earth's climate naturally by adding and removing Greenhouse Gases (GHG), carbon dioxide being the most produced greenhouse gas, from the atmosphere.

One of the measures used to combat climate change is carbon sequestration. According to the United States Geological Survey (USGS) website, this is the process of capturing and storing atmospheric carbon dioxide ("What is carbon sequestration?," n.d.). Carbon sequestration reduces the amount of carbon in the atmosphere by storing it in carbon sinks. A carbon sink is anything that absorbs more carbon than it releases as carbon dioxide (IPPC, 2014). The main natural carbon sinks are plants, the ocean and soil. Many of these carbon sinks may however be losing their effectiveness due to human-induced climate change. This is resulting in them losing their ability to sequester carbon and therefore leaving a lot of carbon trapped in the atmosphere. In addition to storing carbon, many systems also continuously accumulate it in plants and soil, thereby "sequestering" additional carbon each year (FAO, 2016).

In order to manage landscapes for carbon storage and sequestration, information about how much carbon and where it is stored is necessary (Ciais et al., 2013; FAO, 2016). In addition, we need to know how much carbon is lost to the atmosphere as carbon dioxide over time and how land use shifts affect these processes ("Carbon Storage and Sequestration — InVEST 3.8.0 documentation," n.d.). Carbon storage potential has become an important consideration for land management and planning all over Europe ("Forests and Agriculture," n.d.). The ability to assess ecosystem carbon balance can help land managers understand the benefits and trade-offs between different management strategies ("Carbon Storage and Sequestration — InVEST 3.8.0 documentation," n.d.).

According to the World Economic Forum (WEC), Germany ranks 6th globally in carbon footprints ("Annual Report 2018–2019 | World Economic Forum," n.d.) and as a result, they are a major contributor to human-induced climate change. Since 1990, Greenhouse Gas (GHG) emissions in Germany have fallen by about 31% from 1,251 million tonnes of CO_2 equivalents in 1990 to an estimated 866 million tonnes in 2018 ("Indicator: Greenhouse gas emissions | Umweltbundesamt," n.d.). However, this decrease was not achieved strategically but was partly due to the economic crisis in 2009 which led to many companies cutting down on production. According to the Clean Energy Wire website, in 2007 Germany put in place targets to reduce GHG emissions by 40% by 2020, by 55% by 2030 and up to 95% in 2050, compared to the 1990 levels ("Germany's greenhouse gas emissions and climate targets | Clean Energy Wire," n.d.). From this, Germany is going to miss its 2020 target by about 8-9%. As a result, more measures need to be put in place in order to cut even more emissions.

There is a need for enhanced strategic reduction of Germany's GHG emissions. For environmental planning committees in Germany to be able to formulate better policies to achieve the GHG emissions reduction targets, knowledge of where carbon is being stored the most and the least in the landscape is imperative. Corine Land Cover (CLC) maps show the changes in land use over time, therefore they can pinpoint the general changes that have been occurring in each of the individual classes throughout the 28-year period from 1990-2018. In addition, we can also gauge whether these changes have had any effect on the carbon stock levels. All this would prove to be very instrumental towards achieving the set targets, as they would enable the land management committees to formulate policies that emphasize on the need to preserve the existing carbons sinks and replenish any deteriorating ones. This is especially because the necessary energy and infrastructural transformations that were suggested in the Climate Action Plan (CAP) 2050 will likely take a while to implement and for the effects to be felt (Ministry, Conservation, & Bmu, 2018).

Research has been carried out to estimate carbon stock in tree biomass and soil of German forests (Wellbrock, Grüneberg, Riedel, & Polley, 2017). According to this study, carbon stocks in the living biomass increased at a rate of approximately 1.0 t C Ha per year and an estimated 58 million tonnes of CO_2 were sequestered in the vegetation in the year 2012. This study estimated carbon stock using three of the five carbon pools outlined in (Unfccc, 2015) which were; aboveground, belowground and deadwood biomass. Another study explored the role of Land Use Land Cover (LULC) in determining the ability of soil in the UK to sequester carbon. The research concluded that while gains in soil organic carbon accrue at a slower rate, this can be improved when cropland is converted into grassland (Ostle, Levy, Evans, & Smith, 2009). Nevertheless, this research still had a focus in soil carbon.

In China, a study was carried out whereby the InVEST model was used to examine the relationship between carbon sequestration and urbanization level (Wang, Zhan, Chu, Liu, & Zhang, 2019). The total carbon stock of the region reduced from 1990-2015 and soil organic carbon was responsible for 60% of the total carbon stock. Still in China, another study combined the InVEST model with the CA Markov model to investigate the effects of ecological engineering on carbon storage (Zhao et al., 2019). The results of the study indicated an increase in carbon storage by increasing the area of the land cover types with a higher carbon storage ability. In addition to this study, the TerrSet model has been used in a number of studies to model LULC changes. One such paper mapped changes in Ecosystem Services (ES) and biodiversity in Mozambique over a period of 4 years from 2005-2009. Then using the Land Change Modeller (LCM) embedded in the IDRISI/TerrSet software, the study projected LULC changes over a 16-year period (Niquisse, Cabral, Rodrigues, & Augusto, 2017). Thereafter, the study used the projected land cover changes to assess impacts of land cover changes on Ecosystem Services and biodiversity between 2009 and 2025 using the InVEST model.

A study in Iran used the LCM module in IDRISI/TerrSet to analyse land use changes for a 2015 land use status prediction(Ansari & Golabi, 2019). The drivers of change used in the model consisted of distance from the road, distance from manmade areas, distance from land changed edge, distance from stream, elevation and finally slope. The aim of the study was to monitor and predict land use changes. While considerable research has been carried out on the effects of LULC on carbon sequestration and other Ecosystem Services, there is still a debate on whether or not the effects are significant enough that the Land Use, Land Use Change and Forestry (LULUCF) sector can be considered as a major solution to climate change.

Germany, being one of the major economic powers in Europe and in the world, has one of the highest GHG emissions due to the heavy industrialization. According to the Clean Energy Wire website, the country was also once a global leader in environmental policies to combat climate change ("Germany's Climate Action Programme 2030 | Clean Energy Wire," n.d.). However, Germany finds itself unable to meet its 2020 goals. Even with all the measures outlined in the Climate Action Programme, the LULUCF sector has been omitted from the total greenhouse reduction figure ("Germany's greenhouse gas emissions and climate targets | Clean Energy Wire," n.d.). This is because it currently does not count towards the national or European climate protection targets. This sector is also to a great extent excluded from the current international policy framework to address climate change (Murphy, 2009) . Even though the management of forest carbon sinks has been proven to provide negative emissions (Bellassen & Luyssaert, 2014; FAO, 2016), land managers and policy makers seem to be unsuccessful in emphasizing the need to consider land use management as a part of the solutions to climate change.

The aim of this research is to conduct an analysis on the LULC of Germany over the period of 1990-2048 and explore how each CLC class contributes to the loss or storage of carbon. This will in turn assist in finding out whether the LULUCF sector in Germany can sink carbon in significant enough amounts that it aids the country in fast-tracking its achievement of carbon neutrality. Specifically, the aim is to be carried out by:

i. Detailing the progression of LULC changes in Germany from 1990-2018;

ii. Documenting the trend observed in carbon sequestration in Germany over the years from 1990-2018 and;

iii. Projecting future scenarios in order to estimate how much carbon is likely to be sequestered in the landscape for each scenario.

2. Study area

Germany, formally known as the Federal Republic of Germany has a total area of 357, 386 square kilometres (35.7386 million ha) and is located in Central Western Europe at 51°N and 9°E. The country borders Denmark to the north, Luxembourg, Belgium and the Netherlands to the west, Poland and Czech Republic to the east, Austria and Switzerland to the south, and lastly, France to the southwest. it is governed by a federal parliamentary republic

Germany has a population of 83,686,264 making it the most populous state in the European Union. Nearly half of the population is concentrated between the working-class population (25-54 years) and the senior population (65 years+) at 38.58% and 22.99% respectively ("Germany Population (2020) - Worldometer," n.d.).

It has a coastline of 2,389 kilometres and a mean elevation of 263 metres. Germany's major rivers are the Rhine, Weser, Oder, and Elbe which flow northward, and the Danube which has its source in the Black forest and flows eastward. Most of the country experiences a temperate seasonal climate that is dominated by humid westerly winds.

Economically, Germany is the world's third largest exporter of goods; their main exports are vehicles, machinery, chemical goods, electronic products, electrical equipment, pharmaceuticals, transport equipment, basic metals, food products, and rubber and plastics. Germany is the world's fifth largest economy by PPP (purchasing power parity) and fourth by nominal GDP (gross domestic product) ("Europe :: Germany — The World Factbook - Central Intelligence Agency," n.d.).

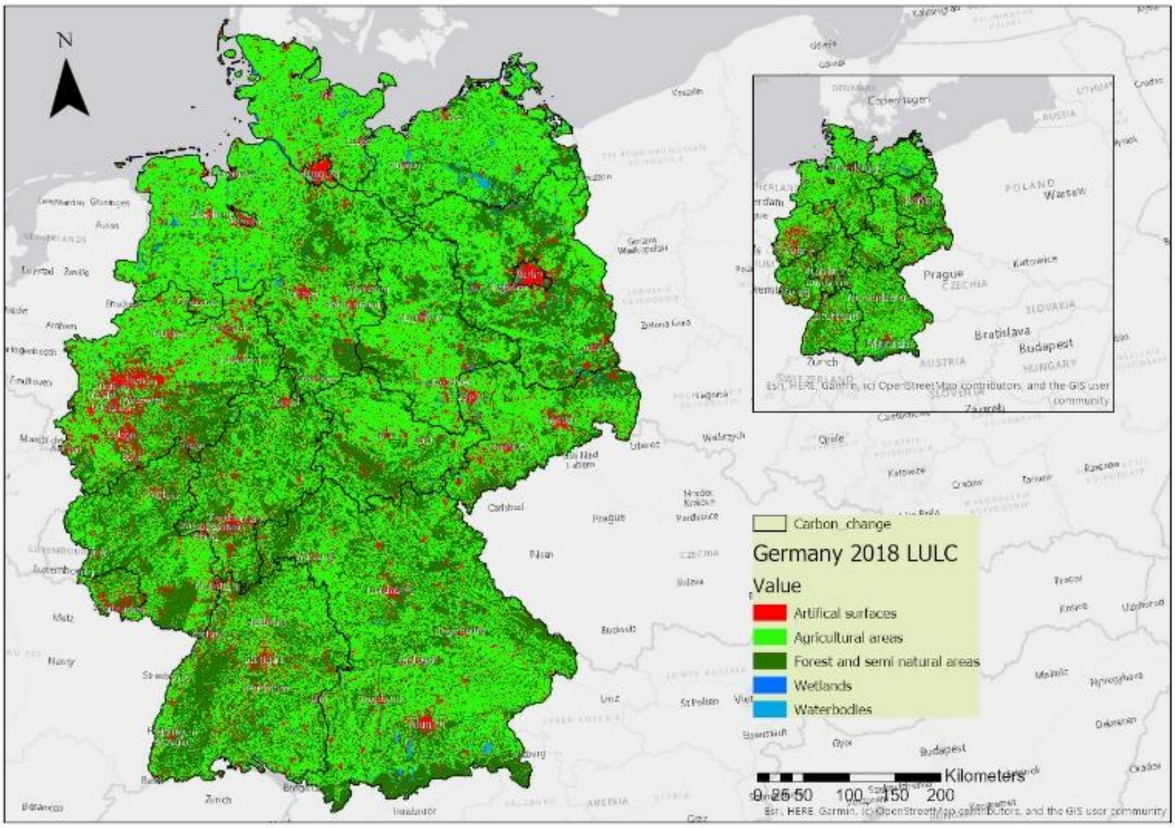


Figure 1: Study area

3. Data and methods

The main dataset used for this research consisted of five CLC maps sourced from the Copernicus Land Monitoring Service website ("CORINE Land Cover — Copernicus Land Monitoring Service," n.d.). These maps cover five different time periods of: 1990, 2000, 2006, 2012 and 2018. They have a resolution of 100 metres, a scale of 1:100,000 and a thematic accuracy of above 85% with a minimum mapping unit of 25ha/100m.

The maps were first reclassified from the original 44 classes to the 5 basic classes of Land Use Land Cover (LULC) maps which are: artificial surfaces, agricultural areas, forest and semi natural areas, wetlands and waterbodies. This is done because the carbon pool table, which is the second input to the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model, contains the 5 basic classes. In order for the model to run and produce valid results, the classes must match.

The carbon pool table is a table containing values of carbon stored in each of the essential pools for each LULC class. The four carbon pools are defined by: aboveground biomass which consists of all living biomass occurring above the soil, belowground biomass which is all the living biomass in live roots, dead wood which is all non-living woody biomass that is not contained in litter, soil organic carbon which is organic carbon found in mineral and organic soils (Unfccc, 2015). The sizes of these pools are responsible for carbon storage on land (Unfccc, 2015). For the purposes of this study, only the aboveground biomass was considered because the study aims to analyse carbon stored in the landscape.

The table used must contain the following five columns: lucode (unique identifier for each LULC class in the CLC maps), LULC_name (the names of the five classes), C_above (the carbon density contained in aboveground biomass for example, vegetation and forests), C_below (carbon density contained in belowground biomass; these are plant and tree roots), C_soil (carbon density in soil) and C_dead (carbon density in decaying matter). They must be written in the same way or else the model will return an error and fail to calculate the carbon stock. The table should look as shown below. The values in this table were consolidated from the annex of a paper assessing the impact of land cover changes in ecosystem services in Bordeaux (Cabral, Feger, Levrel, Chambolle, & Basque, 2016). Since the C_below, C_soil and C_dead pools were not being used, they were not included in the table.

lucode	LULC_name	C_above
1	Artificial surfaces	1.13
2	Agricultural areas	8.12
3	Forest and semi natural areas	19.78
4	Wetlands	1.17
5	Waterbodies	0

Table 1: Carbon pool values for above ground (Cabral et al., 2016)

3.1 Detailing the progression of LULC changes in Germany from 1990-2018

This process was carried out in the change analysis tab of the LCM in TerrSet model. The current and future LULC maps were entered in the model and then it would calculate the area converting from one LULC type to the other. Additionally, the model was able to calculate the net change taking place in each LULC type, the gains and losses occurring and finally the interactions between the LULC types. That is, contribution to change in one LULC type by other LULC types; how much area of land in Hectares a certain LULC type was gaining or losing to the other LULC types. The aim of cataloguing the LULC changes taking place over the 28 years is to be able to draw relationships between the LULC changes and amount of carbon stock in the vegetation.

3.2 Carbon stock trend calculation

In order for policymakers to adequately make decisions concerning landscape management, information about how much and where carbon is stored is essential. After reclassification of the original CLC maps, the resulting maps were clipped using the Germany administrative boundaries shapefile (“Download data by country | DIVA-GIS,” n.d.) in order to be left with the study area. The Germany LULC maps were then loaded onto InVEST model two at a time, the current map which is the year the model begins the calculations from, and the future map which is the year the model uses to calculate the net change in carbon sequestration over the set period. The resulting values can either be negative, which signifies the loss of carbon into the atmosphere as carbon dioxide, or positive, which will indicate that carbon was sequestered. The model works by estimating the net amount of carbon stored in the landscape over the duration of time set by the two land covers. It approximates a value by aggregating the amount of carbon stored in the carbon pools, (or in the case of this study, the aboveground biomass) based on the land use maps and the new classes after reclassification ("Carbon Storage and Sequestration — InVEST 3.8.0 documentation," n.d.). Calculations done by the model are carried out pixel by pixel and the results are displayed as raster outputs of storage, sequestration and value, as well as aggregate totals, measured in Megagrams of carbon per pixel.

The final maps produced from this process are carbon stock for each of the five years, illustrating the variation in carbon stock throughout the country. The other maps showed carbon change from one year to the other, for example, the amount of carbon stored in the landscape or lost to the atmosphere between 2000-2006. This aided in showing the carbon stock change trend observed over the 28-year period. From the carbon stock changes it is then possible to analyse how any LULC changes which may have occurred over the years could have affected the changes in amount of carbon stock: thus, proving or disproving the fact that LULC changes have an effect on carbon sequestration.

3.3 Projecting future scenarios of carbon sequestration.

Scenarios enable policy makers to envision the future in a controlled environment where they are also able to make necessary adjustments and corrections without any effect on the real world. They are able to do this using assumptions and following patterns of data to produce visual representations (Sharma et al., 2018). Simple scenarios only require information about the new policy to be implemented or a new plan/project under consideration. Complex scenarios on the other hand require information on drivers of change on the landscape e.g., new policies, infrastructural development or climate change data. The scenarios modelled for this study are examples of complex scenarios (Carter, La Rovere, Jones, Leemans, & Nakicenovic, 2001).

Having analysed the previous years' CLC maps and carbon stock/change maps, we now need to come up with future land cover maps. The goal of this is to be able to calculate how much carbon is likely to be stored in the landscape or lost to the atmosphere in the future. Several approaches have been used to model LULC change including machine learning approaches, cellular approaches, economic approaches, agent-based approaches and hybrid approaches (Megahed, Cabral, Silva, & Caetano, 2015). This study featured a hybrid approach that combined a cellular approach which is the CA Markov technique in the Land Change Modeller (LCM) embedded in the TerrSet software and a machine learning approach using Multi-Layer Perceptron under the same software (Yirsaw, Wu, Shi, Temesgen, & Bekele, 2017). The methodology that was followed in order to get the future LULC maps can be summarised in Figure 2 below.

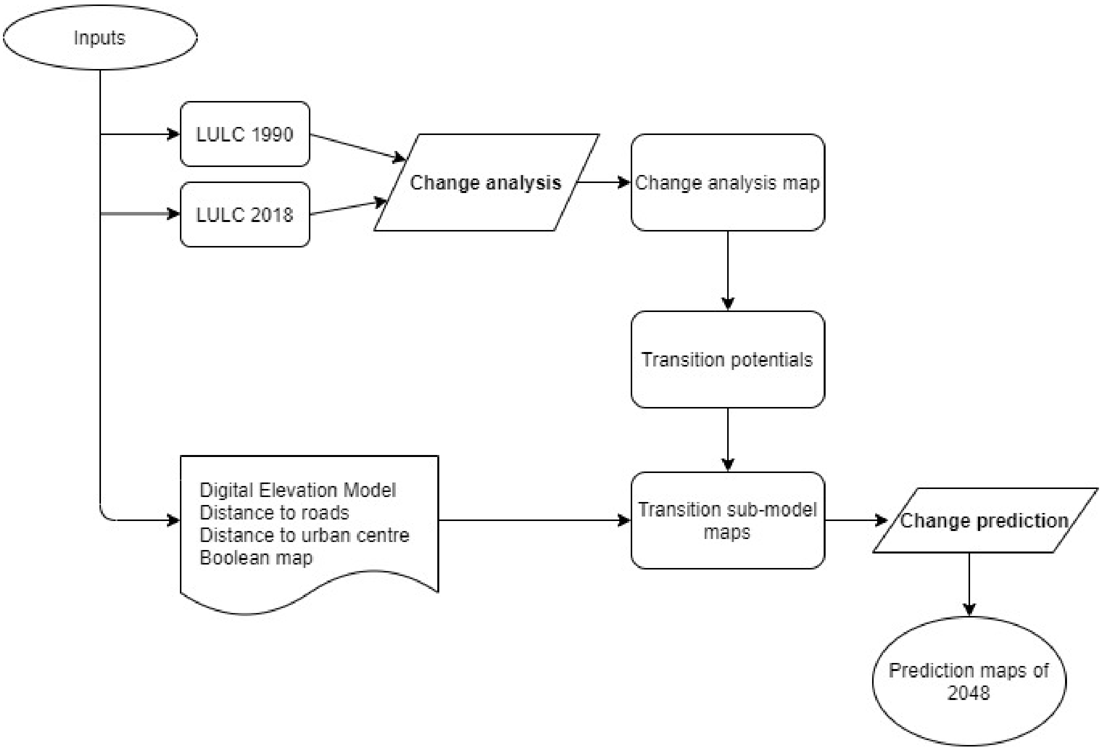


Figure 2: Land Change Modeller methodology

The first step involved in this process was carrying out change analysis to explore the interaction within the land uses between the years 1990-2018. This is where we are able to tell what percentage of one land use was converted into another land use or which land uses persisted, i.e., did not experience any change (Voight, Hernandez-Aguilar, Garcia, & Gutierrez, 2019). The model was instructed to ignore transitions under 50,000 Ha in order to be left with the most significant transitions that occurred in the 28-year period. The following step is to model the transition potentials (Berg, Rogers, & Mineau, 2016). The scenarios to answer the research question are modelled in this step. To do this, four different scenarios were modelled:

- In the first one which was the **baseline** scenario, otherwise called Business as Usual (BAU), no changes were made. All the six transition potentials that resulted from the change analysis stage were used to project the 2048 LULC map with no restrictions put in place.
- The second scenario was the **development** scenario, in this case, artificial surfaces were not allowed to convert to any other land use. This is because in a case where a country prioritises development, more and more land is needed to allow for the construction of new infrastructure. Therefore, four different transition potentials were outlined; agricultural areas to artificial surfaces, agricultural areas to forest and semi natural areas, forest and semi natural areas to artificial surfaces and finally, forest and semi natural areas to agricultural surfaces. These were all modelled under one sub-model.
- In the third scenario, which will be referred to as **conservation 1** hereafter, three transitions were modelled. These are artificial surfaces to agricultural areas, artificial surfaces to forest and semi natural areas, and agricultural areas to forest and semi natural areas. In this scenario, forest and semi natural areas were restricted from undergoing any conversion since we are trying to maximise the amount of carbon being sequestered into the landscape.
- The final scenario, **conservation 2**, is a modification of scenario 3. The point here is to come up with a more achievable conservation scenario. Therefore, the transitions modelled were artificial surfaces to forest and semi natural areas, artificial surfaces to agricultural areas, agriculture to forest and semi natural areas, and finally, agricultural areas to artificial surfaces. This last transition was not included in the conservation 1 scenario.

It is important to note that the four different scenarios were modelled one by one, I.e. the sub-models for transition potential in each scenario were run as one model, but this process was done separately for each scenario. Following the modelling of the scenarios, the independent variables are now added to the model. For this research, the independent variables used were;

- a Boolean constraint map showing areas where development was restricted from taking place as 0 and the rest as 1;
- a Digital Elevation Model (DEM) for Germany;
- a raster map of distance to roads in Germany and;
- distance from German urban areas, all of which were gotten from the same source ("Download data by country | DIVA-GIS," n.d.).

Independent variables used during land change modelling are factors that are likely to influence LULC changes. They were all prepared in ArcGIS using the Euclidean distance tool. Before using the independent variables, they can be tested for their potential explanatory power using Cramer's V test. This is a quantitative measure of association on a scale of 0.0 which suggests that there is no association, to 1 which suggests perfect correlation (Eastman, 2009). However, this does not mean that the performance of the model is automatically improved. This is because the relationship between the variables and the model is complex and the mathematical requirements cannot be corroborated (Eastman, 2009).

The (LCM) embedded in TerrSet has three modelling options namely, the Multi-layer Perceptron (MLP) Network, Similarity-Weighted Instance-based Machine Learning (SimWeight) and Logistic Regression. Of these, only the MLP allows modelling of more than one transition at the same time. While both the MLP and SimWeight produce the best results in transition modelling (TerrSet Tutorial 1987, n.d.), the MLP was preferred for this study due to its ability to run more than one transition at the same time. Transitions should only be modelled together if the underlying drivers of change are believed to be similar.

After modelling one scenario and inputting the independent variables, the model is run in order to get the transition potential maps. These are generated by extracting samples from the LULC maps, provided in the beginning, that went through the transitions being modelled, in addition to those that had the potential to undergo changes but did not. When this step is completed, the model aggregates the results in html format and produces a number of transition potential maps equivalent to the number of transitions that were initially modelled.

The following stage is the change prediction tab. This is the last step to get the future LULC maps needed for this section of the study. The amount of change taking place per transition can be modelled in two ways. One is to use a Markov Chain analysis embedded in the LCM module in TerrSet, the other is to specify the transition probability matrix from an external source. For this study, the Markov Chain analysis was used. The output of this stage is a hard and a soft prediction model, the latter being optional. The hard prediction model is based on a competitive land allocation model that shares characteristics with multi-criteria decision process. On the other hand, the soft prediction model produces a map indicating the propensity to change for the specified set of transitions (Eastman, 2009). The information used in this tab is dependent upon what was specified in the previous tabs, specifically the transition potential tab. The default method used to determine future occurrences of change is by the use of a Markov Chain. This process involves establishing the state of a system based on its previous condition and the probability of change occurring from one state to the other (Subedi, Subedi, & Thapa, 2013). Therefore, the model deduces the probability of a pixel changing from one land use type to another. The Markov model has been used in quite a number of studies in ecological modelling (Subedi et al., 2013; Yirsaw et al., 2017; Zarandian et al., 2017). It is important to note that since the objective here is to model future LULC maps, there is no way to determine how accurate these maps would be because of the lack of an established LULC map with which to carry out a comparison.

Following the completion of the change prediction stage, the hard prediction maps produced were then exported to ArcGIS, adjustments to the format made and thereafter they were loaded onto the InVEST model. Here, the process carried out to calculate carbon sequestered in the landscape in the past 28 years was repeated. The only difference is that in this case 2018 was used as the current year map and the predicted land cover maps for 2048 used as the future year.

4. Results

4.1 LULC changes in Germany from 1990-2018

According to Figure 3 below, during the time period between 1990 and 2000, Artificial surfaces saw the most gain while agricultural areas faced the most loss. The land lost from agricultural areas transitioned to artificial surfaces. Forest and semi natural areas too gained some land from agricultural areas, and there was more land gained than was lost in this class. From the year 2000 to 2006 agricultural areas and artificial surfaces are still experiencing the most change. Artificial surfaces gained 0.41% of the total land area and lost 0.1% while agricultural areas gained 0.09% and lost 0.47%. During this period forest and semi natural areas lost more land, 0.11% than in the previous 1990-2000 period.

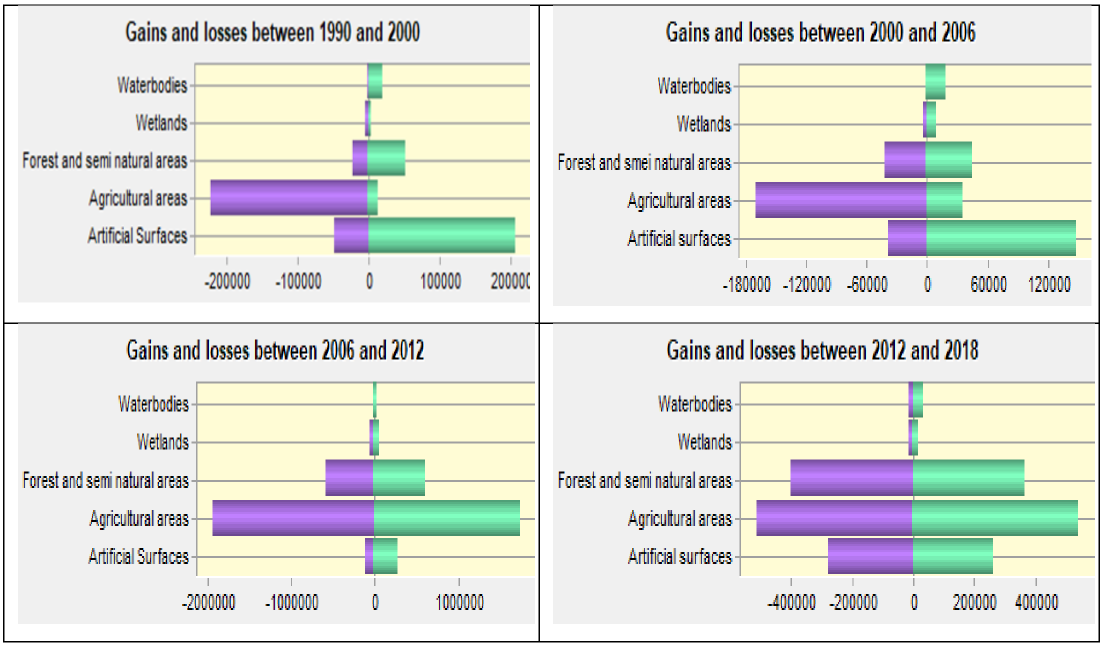


Figure 3: Gains and losses trend for 28 years

Between 2006 and 2012 the land gained by the artificial surfaces does not seem to be as significant as what occurred between 1990 to 2006. On the other hand, agricultural areas appear to have gained even more land than was gained between 1990-2006. In forest and semi natural areas the same seems to be the case, with a slight increase in land gained over land lost. Between the year 2012-2018, agricultural areas have continued to gain more land 1.52% while losing almost just as much, 1.43%. Gains and losses in forest and semi natural areas seem to have remained pretty much the same at 1.02% and 1.12% respectively, in comparison to 2006- 2012. There was also a relatively equal gains and losses in artificial surfaces at 0.77% and 0.73% respectively.

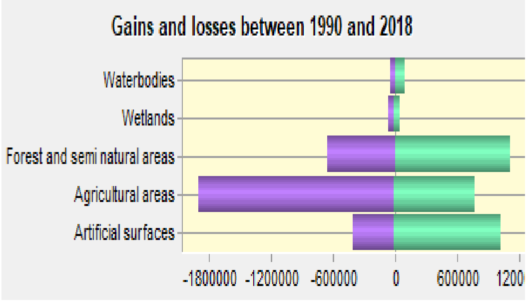


Figure 4: Overall gains and losses 1990-2018

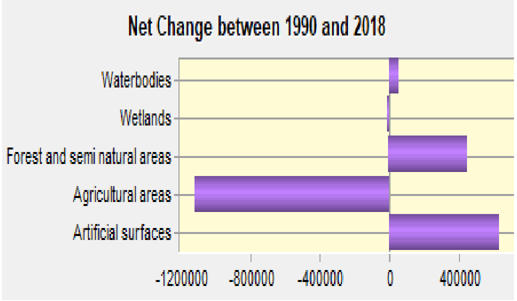


Figure 5: Net change per category 1990-2018

From Figure 4 above, overall, from 1990 to 2018 agricultural areas seems to have faced the most amount of land use change, losing 5.31% of the total land area and gaining 2.18%. This was followed by forest and semi natural areas which lost 1.83% and gained 3.1% and then artificial surfaces which lost 1.14% and gained 2.9%. Over the 28-year period agricultural areas lost the most land, 3.13% while artificial surfaces gained the most, 1.76%. Forest and semi natural areas faced almost negligible amounts of lost land while gaining 1.27% which is a good sign.

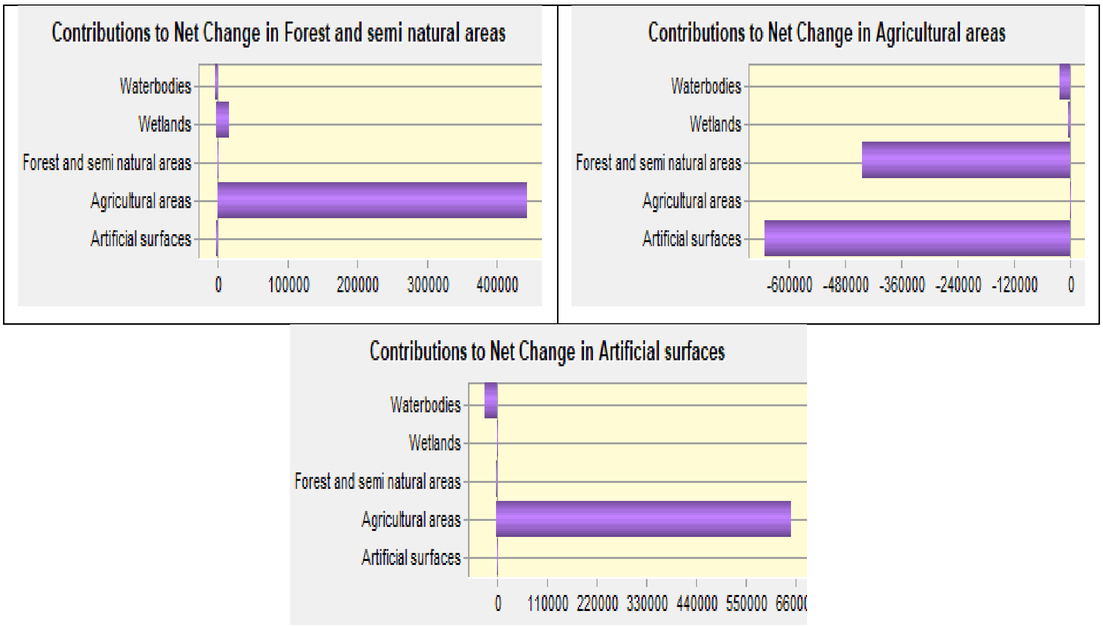


Figure 6: Contributions to change for the three major categories

In reference to Figure 6 above, forest and semi natural areas gained 1.27% of the total land area with 1.24% of it coming from agricultural areas followed by 0.05% from wetlands. As seen in Figure 5 previously, agricultural areas lost a lot of land, 1.82%, to artificial surfaces while the vice versa happened for artificial surfaces. 1.23% was also lost to forest and semi natural areas as well. Artificial surfaces gained 0.5% of land from agricultural land and lost 0.04% to forest and semi natural areas.

4.2 Carbon sequestration in Germany from 1990-2018

Before being added to the InVEST model, the CLC maps for years 1990, 2000, 2006, 2012 and 2018 were reclassified from their original 44 classes to the 5 basic CLC classes. These classes are; artificial surfaces, agricultural areas, forest and semi natural areas, wetlands and waterbodies. The resulting maps from the calculation of carbon sequestration are indicated below.

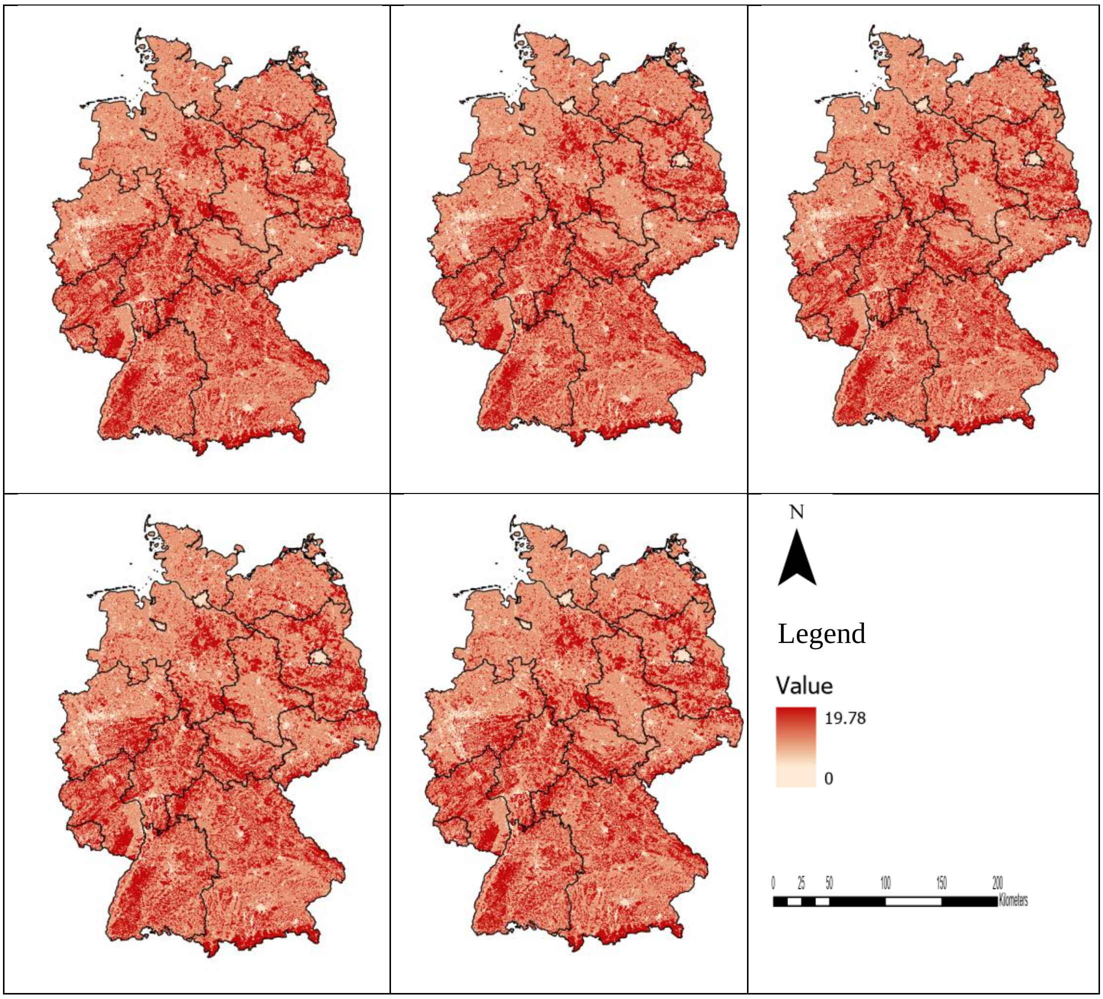


Figure 7: Carbon stock trend 1990-2018

From Figure 7 above, the maps look similar, almost like they have been repeated. This is not the case. The maps appear similar because the difference between the amount of carbon stock in vegetation has not changed by a big percentage from the year 1990-

2018. The amount of carbon stock in 1990 was 393,871,051.92 Mg of C whereas in 2018 it was 394,471,457.69 Mg of C. The total change in amount of carbon stock was 594,252.31 Mg of C which means that there has been an increase of only 0.15% in the amount of carbon stock in the past 28 years. Figure 8 indicates the amount of Mg of C sequestered for each time period. Two bar graphs were also produced; one showing the change in amount of carbon during the 28-year period and another showing the carbon stock documented per year in Germany over the same period. The graphs provide a great visual of the trend observed in sequestration or loss of carbon throughout the 28-year duration.

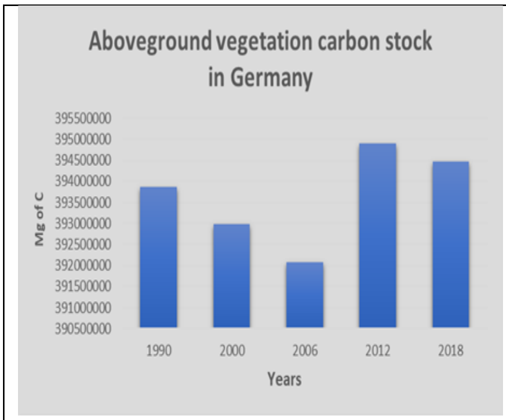


Figure 8: Carbon stock trend in Germany from 1990-2018

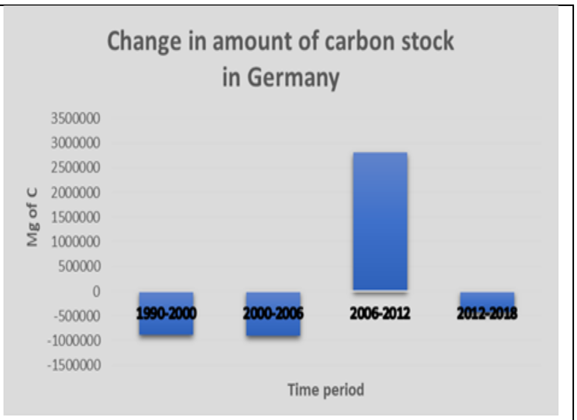


Figure 9: Change in carbon stock

As shown in Figure 8 above, there was a steady decline in the amount of carbon stock between the years 1990-2006. However, we can see a change in the positive direction from the year 2006-2012, then a slight drop from 2012-2018. According to Figure 9, these results show that the only time when there was sequestering of carbon in the landscape was between the years 2006-2012. In all the other years more carbon was being lost to the atmosphere than being stored from one year to the other.

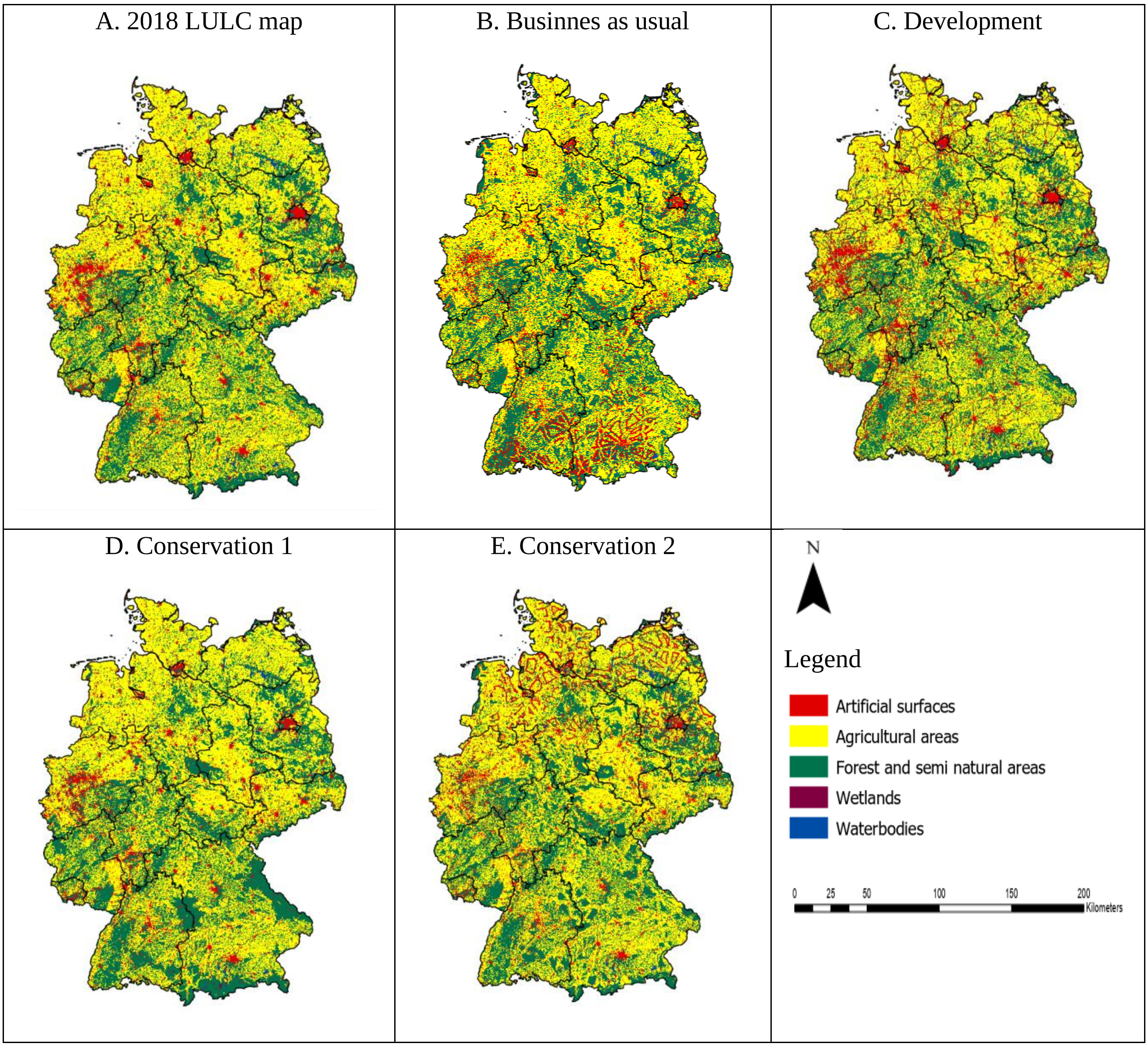
4.3 Modelling of future scenarios

As mentioned in the methodology section, the first step involved in this process was to perform a change analysis between the land covers of 1990 and 2018. The results yielded showed there was a lot of interaction between agricultural areas and artificial areas. The transitions observed in the 28 years are shown below.

Category	Hectares	Legend
0	58046255	Total area of Germany
1	897708	Agricultural areas to Artificial surfaces
2	129286	Forest and semi natural areas to Artificial surfaces
3	246845	Artificial surfaces to Agricultural areas
4	487860	Forest and semi natural areas to Agricultural areas
5	126604	Artificial surfaces to Forest and semi natural areas
6	930680	Agricultural areas to Forest and semi natural areas

Table 2:Division of the land area in Hectares among the transition potentials

After the modelling of the four different scenarios, the hard prediction LULC maps were generated.


A. 2018 LULC map

B. Businnes as usual

C. Development

D. Conservation 1

E. Conservation 2

Figure 10: Hard prediction LULC maps for the four modelled scenarios

These were then loaded onto InVEST model to calculate amount of carbon stored. In the first scenario, which is the BAU scenario, all the six categories in **Error! Reference source not found.** above were added to the model. After calculation of carbon stock, the result was that by the year 2048, 885,024.82 Mg of C will be sequestered at a rate of 29,500.82 Mg of C per year. This indicates a 0.15% increase in the amount of carbon stock in the next 30 years (from 2018). In the development scenario, categories 1, 2, 4 and 6 in table 4.1 above were. A change of -3,810,876.74

Mg of C was observed, which means that carbon will be lost to the atmosphere at a rate of -127,029.22 Mg of C per year. This will be a decrease by 0.96% from 2018 levels.

In the conservation 1 scenario, categories 3, 5, and 6 were modelled. From the conservation 1 scenario, a change of 16,421,638.46 Mg of C is expected, which indicates that carbon will be sequestered in the landscape at a rate of 547,387.95 Mg of C per year. This will be an increase from 2018 levels by 4.16%. Lastly, in the conservation 2 scenario, where categories 1, 3, 5 and 6 were modelled a change of 1,635,183.95 Mg of C which translates to 54,506.13 Mg of C per year was observed. This will cause an increase in the amount of carbon sequestered by 0.41% from 2018 carbon stock. The rates are summarised in the bar graph below.

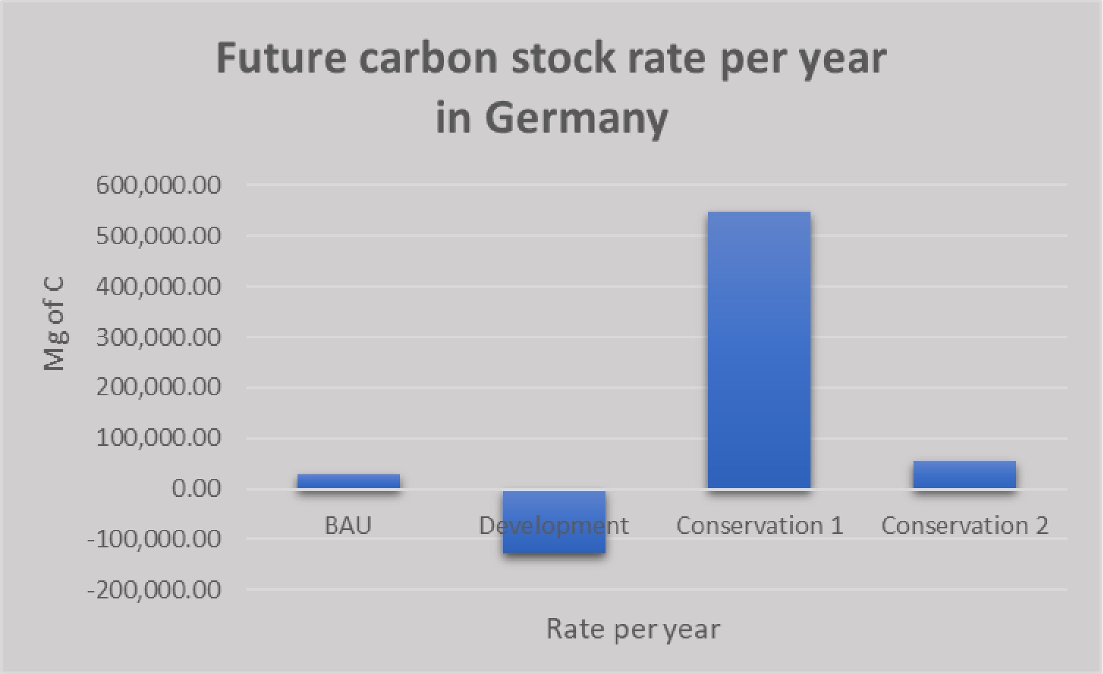


Figure 11: Estimated carbon stock rate per year in the modelled future LULC scenarios

5. Discussion

Before reviewing the results of the study and providing an analysis, it is essential to point out that the models used while useful and relatively easy to use, had a few limitations, as all models do. The InVEST model for example, assumes that the land use classes are not gaining or losing carbon over time within the classes themselves. This is not the case, especially when it comes to forests and semi natural areas. The amount of carbon stored in forests reduces with their age. As they become more mature, the carbon they store levels out (Zhu, Song, & Qin, 2019), and this cannot currently be captured by the model. Due to this assumption, the only changes considered by the model are those that occur as a result of changes from LULC type to another ("Carbon Storage and Sequestration — InVEST 3.8.0 documentation," n.d.). The LCM in TerrSet model on the other hand only deals with physical factors. Socio-economic and demographic factors cannot be added to the model, this means that change can only be modelled with variables such as distance to roads and urban centres, elevation, slope and not population or economic data, both of which have been known to affect change in LULC. In addition, it is not possible to specialise the parameters e.g., specifying by how much percentage one would like a particular land cover to change when modelling the scenarios. Therefore, one is stuck only modelling the probability of the pixels in one LULC type changing to another, but not by what percentage. This puts a limit on how much change can be modelled. Nevertheless, the models provided information that will aid in answering the research questions brought up by this study.

5.1 LULC changes and carbon stock in Germany from 1990-2018

The decision on which of the four major carbon pools specified in the IPCC report to use for this study was based on the research design and availability of data. Since the focus of the research is to explore the relationship between LULC and carbon sequestration, it makes sense to use aboveground biomass. Adding the other three carbon pools would have probably yielded better results in terms of the amount of carbon stock (Unfccc, 2015). However, it would have proven difficult afterwards to know exactly what percentage of the carbon stock was as a direct result of LULC changes with the tools available at the study's disposal.

While calculating carbon sequestration from 1990-2018, the changes observed from one year to the other were almost negligible in comparison to the total amount of carbon stock. In 1990, 393,871,051.9 Mg of C was stored in aboveground vegetation. By 2018 the total amount had increased to 394,471,457.7 Mg of C (11.04 MgC per Ha) therefore indicating an increase of only 0.15%. This is supported by the fact that the changes occurring in forest and semi natural areas were very small. Majority of the changes were occurring between agricultural and artificial surfaces. However, in one time period, between 2006-2012, there was a notable increase in the amount of carbon stock as seen in Figure 8. At the same time, agricultural areas gained even more land than in the previous time period, 2000-2006 as seen in Figure 3.

This could mean that there is more potential for carbon sequestration in the agriculture sector that needs to be exploited. This can be used in conjunction with measures applied to forest and semi natural areas in order to ensure that all the avenues for carbon sequestration are maximised. According to (Unfccc, 2008), harmony between agriculture-related climate change policies and sustainable development is necessary if there is hope to entice farmers, policymakers and land managers to adopt agricultural mitigating practices.

5.2 Modelling of future scenarios

It is important to note that scenarios are “neither predictions nor forecasts” (IPPC, 2014). Instead, they paint a picture of probabilities, events that are likely to happen if certain variables are applied. It was challenging to model scenarios following the IPCC guidelines on scenarios as emissions from land use change have not been as well documented as their counterparts, energy-related emissions. Therefore, the scenarios modelled in this study followed a simple path of;

a) Business as Usual, i.e., what would happen if no form of intervention happened. There was an increase in carbon stock by 0.22%. In this scenario, LULC is allowed to develop without any interference or restrictions. This provides policymakers with a glimpse of what areas could use some improvement if they hope to tap into the ability of the LULUCF sector to aid in climate change mitigation.

b) Development, what is likely to happen if a country focuses on development and fails to prioritise conservation. This is a state in which the government seeks to maximise economic growth by expanding land uses which can be exploited for example, more industrialization, more roads, more agriculture. After the modelling and calculation of future carbon stock, a decrease in carbon stock levels by 0.96% from 2018 was observed. Since this scenario depicts what is likely to happen if a country decided to prioritise development over conservation, more land is needed to ensure more development. In most cases this land ends up being taken from the forest sector. This is a scenario that is not likely to happen in Germany seeing as it is already a developed country therefore negating the need to prioritise development. It was however modelled in order to serve as a caution by illustrating what could happen should a country decide to go in that direction.

c) Conservation. What kind of results would we expect if conservation was considered a top priority? Around 430 million tonnes of atmospheric carbon dioxide is sequestered in forest cover in Europe (Schelhaas et al., 2015). It therefore stands to reason that under conservation scenarios the aim would be preserving the existing forest cover as much as possible. The conservation scenarios were split into two to allow for different viewpoints.

    i. Conservation 1: The first one was a scenario whereby no new artificial surfaces were modelled. Germany has been working on reducing the amount of land that is being paved over and they had hoped to reduce this number to 30 Ha per day by 2020 (“Land use reduction | Umweltbundesamt,” n.d.) with the objective of slowing down land use. This allows for natural areas to remain as they are or at the very least to not undergo cementation which effectively curbs any form of sequestration that would occur otherwise. This scenario saw the highest increase in carbon stock by 4.16% from 2018 levels. It would be ideal and could be possible especially since Germany’s population is forecasted to be reduce to 80 million (“Germany Population (2020) - Worldometer,” n.d.). Which ideally would mean that there would be less need for expansion of agricultural land and therefore abandoned parcels could be used for afforestation.

ii. Conservation 2: The second conservation scenario had the same 3 transitions modelled in conservation 1 but with an additional transition whereby agricultural areas could potentially be converted to artificial surfaces. This saw an increase of 0.41% of carbon stock from 2018 levels. This is slightly more than what would be sequestered under the BAU scenario, but it is barely enough to make a significant difference. However, this is the more probable scenario between the two conservation scenarios. Even with a projected decrease in population it is highly likely that artificial surfaces will continue to grow as more people continue to move to the urban centres thereby increasing the need for more artificial surfaces. This would in turn then mean that there is less land available to grow more forests.

Of the four scenarios modelled, three of them feature an increase in carbon stock, this is mainly driven by the increase in forest cover. This is evidenced by the fact that the conservation 1 scenario, which had the most area of land being occupied by forest and semi natural areas, had the highest increase in carbon stock at 4.16% with a rate of 547,387.95 Mg of C (0.153 MgC per Ha) per year from 2018 levels. The amount of carbon stock from 1990 to 2048 is summarised in Figure 12 below.

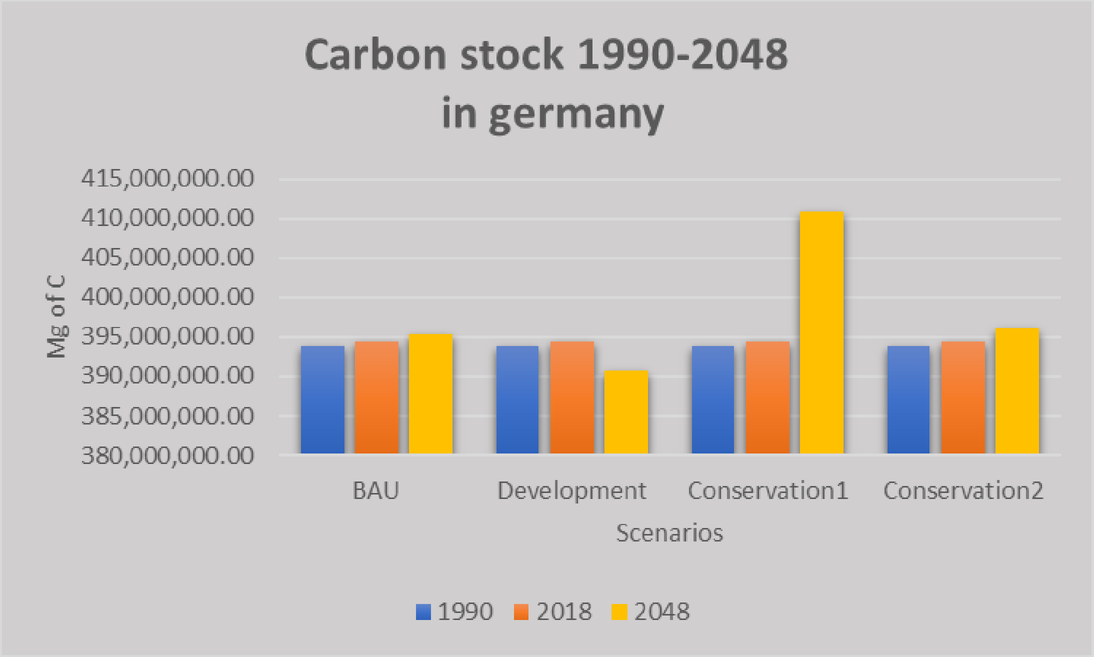


Figure 12: Carbon stock summary from 1990-2048

As reported by (Bondeau et al., 2007), the future of terrestrial carbon balance in Europe is quite unclear. Despite it being known that conservation and replenishing of forests translates to an increase in carbon uptake, it is not known whether this trend is set to continue to be the case in the future. With the modelled scenarios, policymakers are able to get a glimpse of what can be expected if certain paths are taken. As a result, they can intervene and add more stringent measures or modify the existing ones if they hope to curb climate change before it is too late.

After exploring all these different scenarios, it is evident that in order to secure Germany’s ability to sequester more carbon in the LULUCF sector, more policies that target the conservation and replenishment of forest cover need to be implemented. However, if protective measures are applied to forests without examining drivers of change and suggesting ways of addressing them, these policies would only reduce a small percentage of total emissions from the LULUCF sector. Thus effectively leading to “cross-biome leakage” which will seriously hamper any efforts to mitigate against climate change (Strassburg, Latawiec, Creed, & Nguyen, 2014). As a result, this calls for more measures to be applied in the agriculture sector as well. Figure 14 below was consolidated by converting the carbon stock values gotten from the four modelled scenarios, which are measured in Mg of C (Megagrams of Carbon) to Kilotonnes of

CO_2. The conversion of 1 gigatonne of C = 3.664 billion tonnes of CO_2 was used. This was done in order to facilitate comparison between how much CO_2 per year would be sunk in each scenario in relation to the total emissions of Germany’s last inventory year which was 2017.

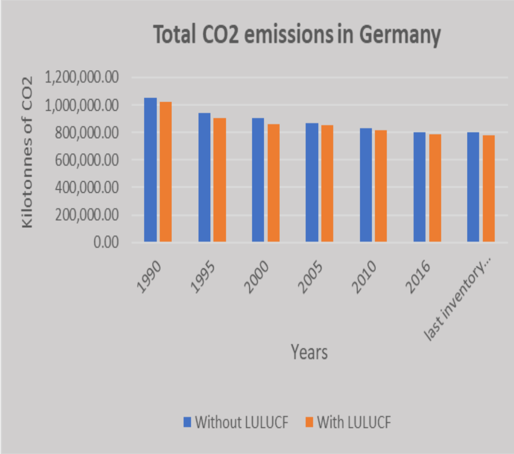


Figure 13: Total Germany CO_2 emissions measured in Kilotonnes of CO_2 (“Greenhouse Gas Inventory Data - Time Series - Annex I,” n.d.)

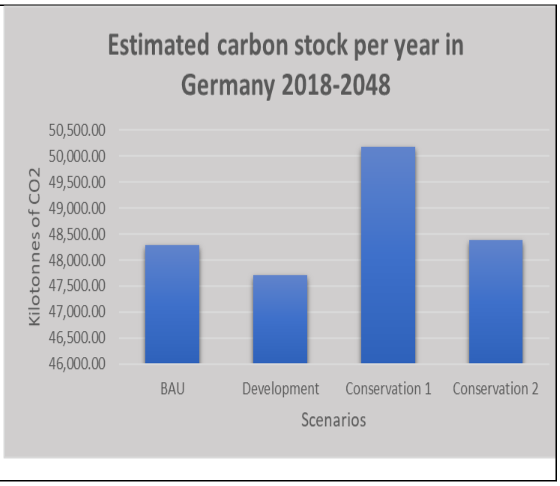
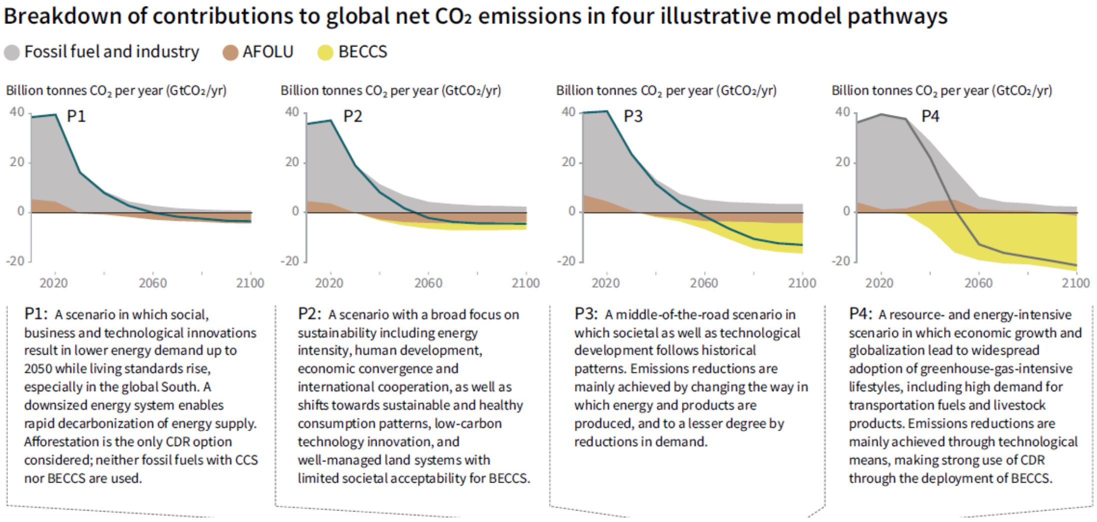


Figure 14: Estimated carbon stock rate per year

In 2016, almost 58 million tonnes of CO_2 equivalents (58,000 kt of CO_2) was stored in the LULUCF sector in Germany (Ministry et al., 2018). 96.5% of this figure was stored in forests. This points to the importance of this sector in climate change mitigation. However, from the Figure 14 above, we see that in the best-case scenario, conservation 1, around 50,000 kt CO_2 equivalents is stored in the landscape per year. When this value is compared to the emissions per year, Figure 13, in which 2017 saw around 800,000 kt $C0_2$ equivalents emitted, it barely makes a dent. Germany’s goal is to have the agriculture sector emitting no more than 61 million tonnes (61,000 kt of CO_2). Going at this rate, Germany is likely to fail to meet its targets again come 2030. Consequently, if there is any chance of salvaging the situation, the best option would be to combine artificial means with natural means of carbon storage in order to be able to achieve carbon neutrality in Germany (Hood, 2007).



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Figure 15: The four illustrative model pathways suggested to manage carbon storage and sequestration (Hood, 2007).

From Figure 15 above, either scenario P2 or P3 would aid in achieving this. Both scenarios combine natural and artificial methods of carbon sequestration whereas in P1 there is no artificial intervention and in P4 there is a heavy reliance on technology for carbon capture. Additionally, the government of Germany plans to exploit the ability of soil to act as a carbon sink by supporting targeted planting of carbon absorbing plant species and encouraging better protection and restoration of moor and wetlands (“Germany’s Climate Action Programme 2030 | Clean Energy Wire,” n.d.).

6. Conclusion

Emissions reduction via implementation of Reducing Emissions from Deforestation and Forest Degradation (REDD+) works very well for climate change mitigation in tropical developing countries. However, developed countries would benefit more from reforestation, forest management and harvested wood products (FAO, 2016). This makes sense in the case of Germany especially because, the country being developed means that there is not a lot of land available for planting more forests. Evidence of this can also be seen from the LULC maps. Therefore, the mitigating potential of Germany’s forests needs to be fully exploited in order to have them sinking more carbon that they emit. This can be done by adopting low-carbon intensity technology and enforcing proper management of the existing forests thereby resulting in the use of forest resources without increasing emissions from them (FAO, 2016).

This therefore means that if Germany hopes to maximise on the ability of the LULUCF sector to aid in climate change mitigation, more research needs to be done in order to find lasting solutions that would encourage more carbon sequestration. However even with this in mind, forests are not immune to climate change impacts for example, storms, human influences and natural disturbances. Therefore, the measures put in place should consider this and make the necessary accommodations. Any further research conducted in this area should consider incorporating stakeholders’ input in the scenario modelling process as that would have proved to be of great benefit to the study. In addition, inclusion of the other three carbon pools i.e., belowground carbon, soil organic carbon and dead matter carbon would certainly greatly improve the results.

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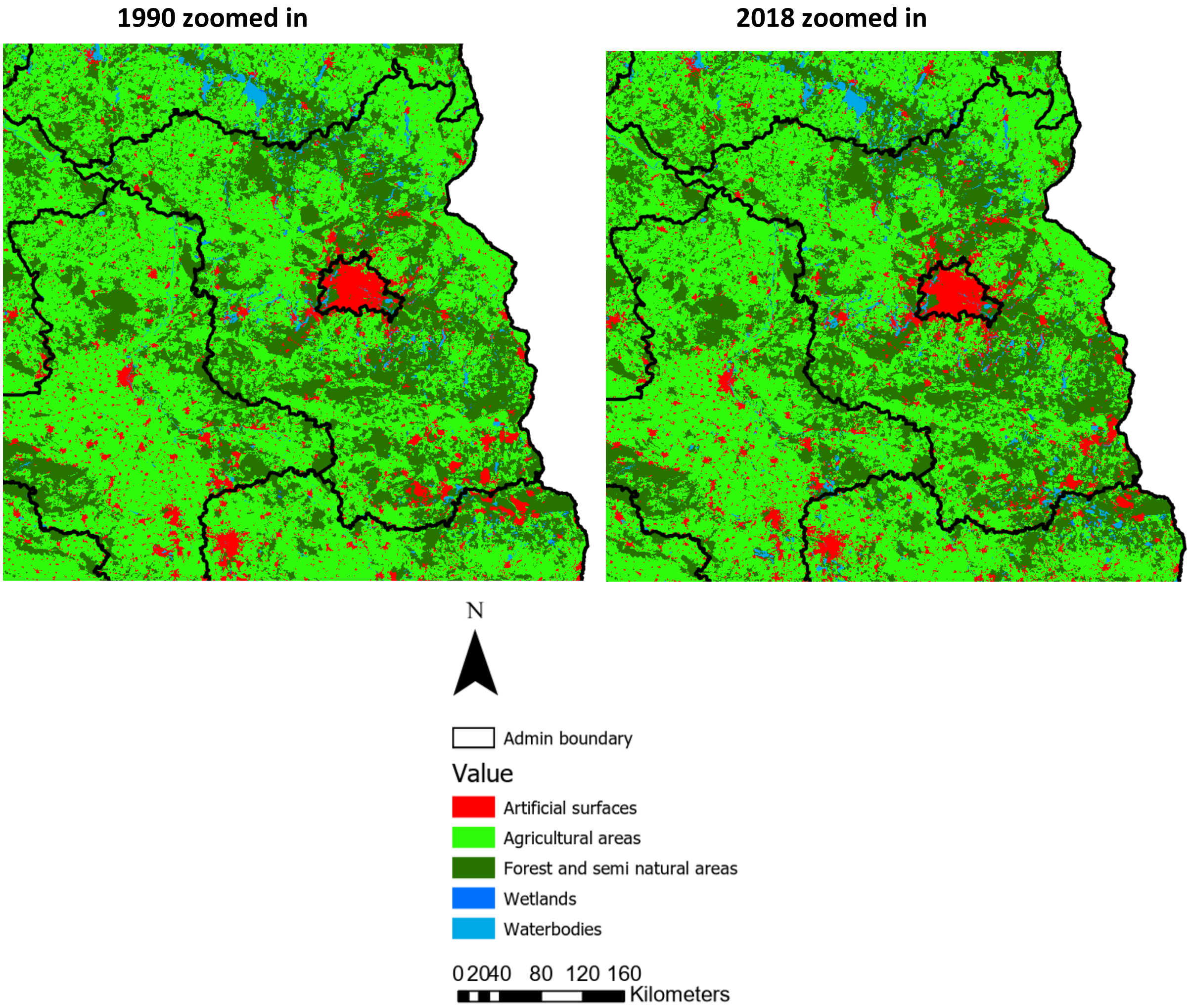
ANNEXES

1. Reclassified LULC maps

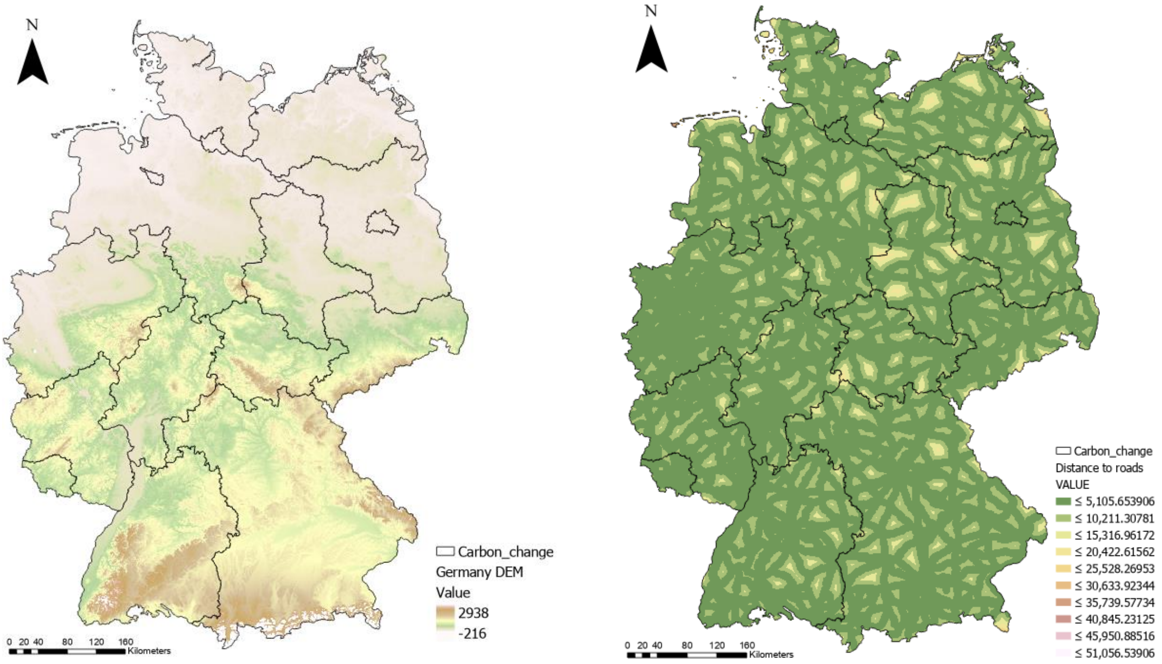


1990 zoomed in

2018 zoomed in

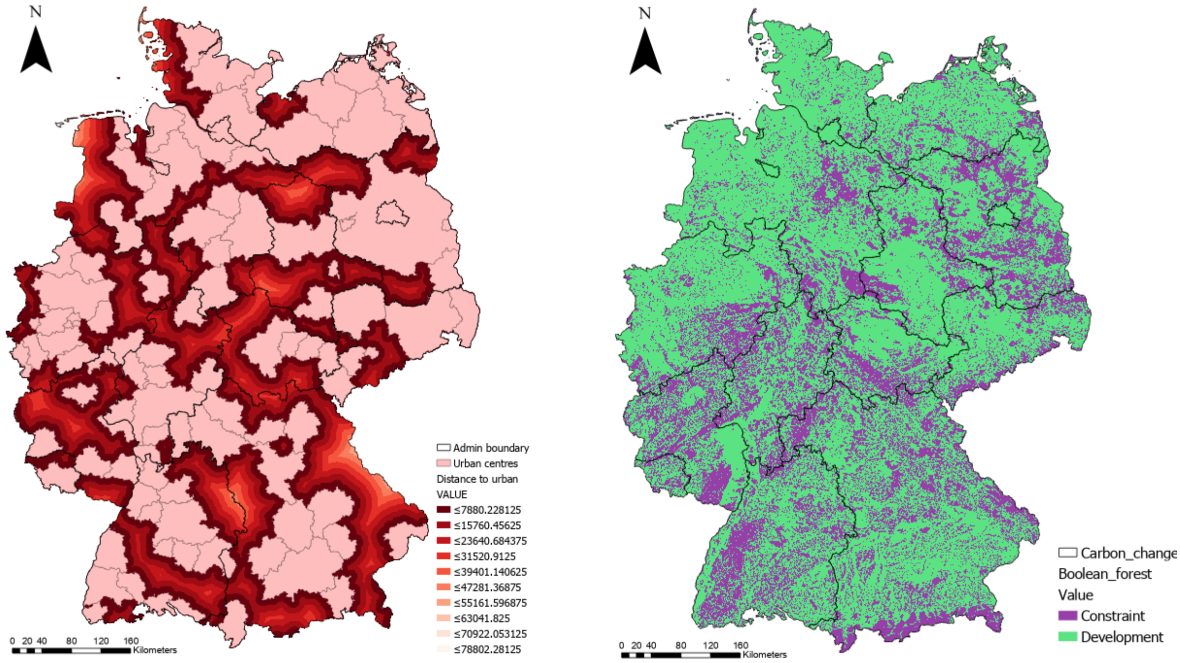
Annex figure 1: Reclassified Germany CLC maps zoomed in to show the subtle changes taking place between 1990-2018. The area predominantly in red is the city state of Berlin.

2. Independent variables



A) Germany Digital Elevation Model

B) Distance to roads, calculated using Euclidean distance

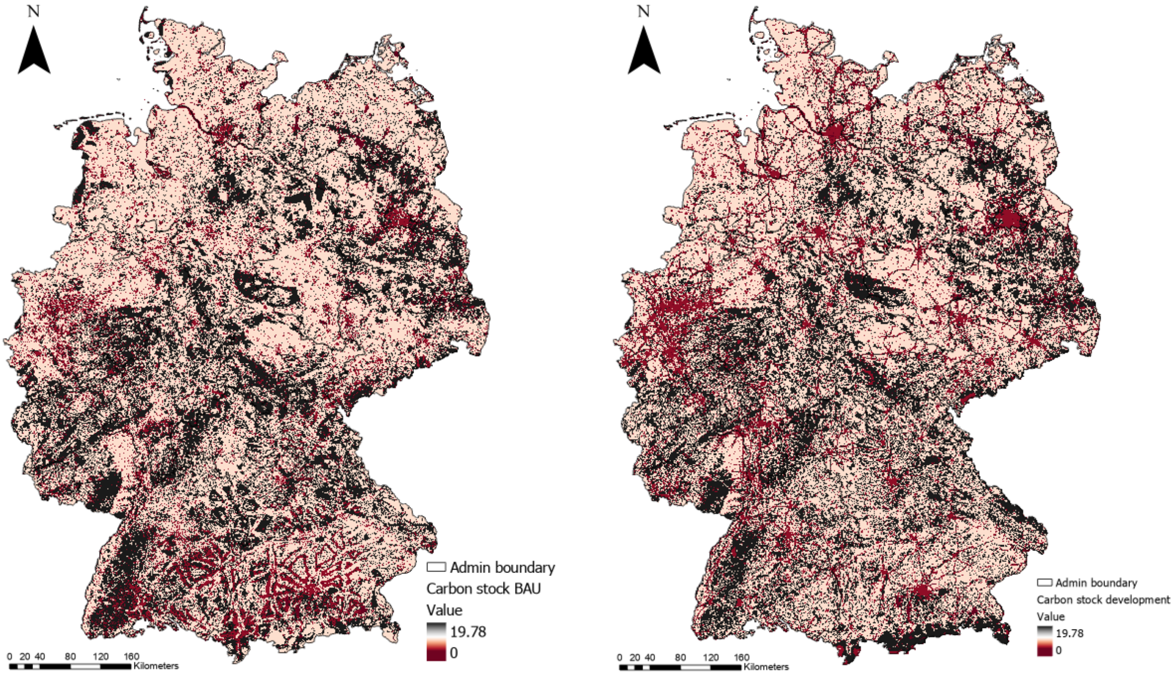


C) Distance from urban centres calculated using Euclidean distance

D) Boolean map showing areas that were restricted from development and those where development was allowed.

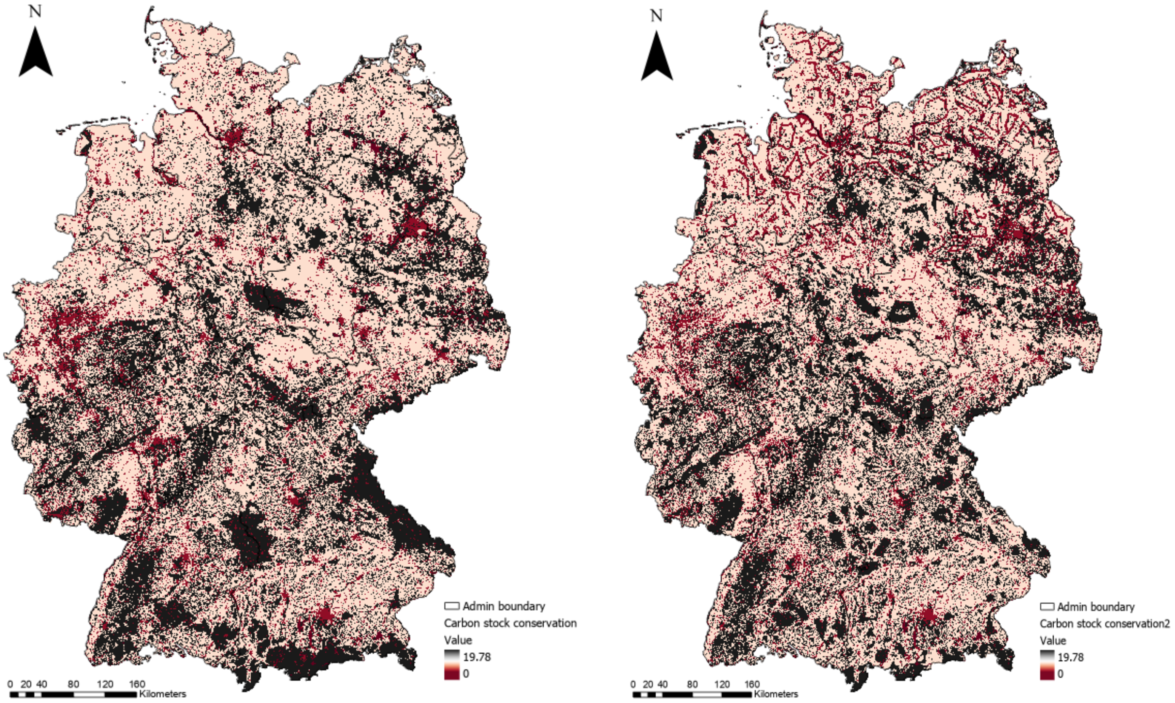
Annex figure 2: Independent variables that were fed into the TerrSet model

3. Carbon stock maps from modelled scenarios



A) Estimated carbon stock contained in the landscape under BAU scenario.

B) Estimated carbon stock contained in the landscape under development scenario



C) Estimated carbon stock contained in the landscape under conservation1 scenario.

D) Estimated carbon stock contained in the landscape under conservation2 scenario.

Annex figure 3: Carbon stock maps for each of the four modelled scenarios. The areas in black show areas that had the highest amounts of carbon stock thus carbon was stored in the landscape while the ones in red show areas which contained the least amount of carbon stock meaning that carbon was lost to the atmosphere.