Modelling the Impact of Agri-Environmental Policy on Land Use in Northern Ireland

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Abstract

Agriculture is an important industry for the Northern Ireland economy. The sector, in facing the challenges posed by Brexit, is shifting its focus to balance economic development and environmental sustainability. The existing Common Agricultural Policy will be phased out and replaced by a new policy framework. Future agriculture policy will need to manage a new long-term vision of profitability, sustainability and resiliency for the industry. Policies within the new framework require clearly defined target outcomes they should aim to deliver

Policymakers now must consider a complex range of factors when designing a sustainable agriculture policy. Future Policy intervention can be supported by utilising modelling techniques. Modelling can explore the economic, environmental and land-use impacts of policy scenarios. Successful models can evaluate the impacts of policies before real-world implementation to avoid any unintended consequences.

This project aims to utilise modelling in this way to help understand the impact of policies on land use. A spatially explicit agent-based model will be developed to help resolve the complexity of designing a new policy framework. The model will primarily focus on introducing environmental schemes targeted at reducing greenhouse gas emissions. Land-use conversions are outcomes of an agent-based decision-making framework that explores the decisions of individual farmers in response to different policy scenarios. The cumulative effect of these decisions impacts the land use at the spatial scale. The model is intended to serve as a tool to be used by policymakers to assist in the policy design stage.

Policymakers, by simulating the impact of future scenarios on land use, can determine the optimal implementation of policies according to defined target outcomes for emissions, financial costs and land-use impacts.

The model uses GIS land-use data for Northern Ireland to evaluate the impacts of sustainable policy on land use. Key results from the simulation suggest increasing the payment rate on policies increases the total hectares in schemes and decreases greenhouse gas emissions. The model is divided into 5 sub-models: spatial model, economic model, social model, ecological model and network model. The sub-models incorporate the processes by which land-use conversions are made and outcomes are monitored.

The model achieves most of its success in formalising and implementing a conceptual idea. To serve as a useful tool for policymakers would require greater knowledge of local farmer behaviour, a deeper understanding of policy design and more available data. If this information was obtained the model could be adjusted to more accurately analyse the potential impacts of policy on land use.

Attestation

I understand the nature of plagiarism, and I am aware of the University's academic misconduct policy.

I certify that this dissertation reports original work by me during my University project.

Signature *John Poole* **Date** **15/04/21**

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1 Introduction

Agriculture is an important industry for the Northern Ireland economy. The sector, in facing the challenges posed by Brexit, is shifting its focus to balance economic development and environmental sustainability. The existing Common Agricultural Policy will be phased out and replaced by a new policy framework. Policymakers are in the process of consulting on the structure and content of the future framework. Modelling can be utilised to offer predictive evaluation of policies within the new framework, helping policy designers understand the impacts on land use and other measured outcomes.

1.1 Background and Context

Around 1.35 million hectares (78%) of the Northern Irish countryside is managed for agricultural purposes with a further 8.4% used for forestry [1]. The industry contributes 1.3% of Northern Ireland's Gross Value Added (contribution to GDP made by an individual sector) and 2.8% of total employment. When compared with values of 0.5% and 1.0% respectively for the rest of the UK, it highlights the vital contribution of the sector to the economy [2].

With Northern Ireland's exit from the European Union, the sector inevitably faces many challenges, none more pressing than the transition from the current Common Agriculture Policy (CAP) to a new policy framework. As the sector competes to increase productivity and improve resilience, it is made clear that any future policy framework should recognise entirely the environmental impacts of farming [3]. These outcomes are part of a long-term vision for the industry set out by DAERA (The Department of Agriculture, Environment and Rural Affairs) in conjunction with various other sector stakeholders.

At approximately 27% of Northern Ireland's total greenhouse gas (GHG) emissions [1], the agriculture sector emits more than any other single sector with emissions increasing by 2% between 2017 and the 1990 baseline (*Figure 1*). This is a result of Northern Ireland's dominant livestock sector with cattle and/or sheep present on 94% of farms [1]. Northern Ireland is also one of the least wooded areas in Europe with tree planting rates declining steadily since 1990 (*Figure 2*). This limits the capacity for carbon sequestration ensuring mitigating GHG emissions remains a vital challenge [4]. It has been argued that the current agricultural policy has significantly contributed to both these problems over time.

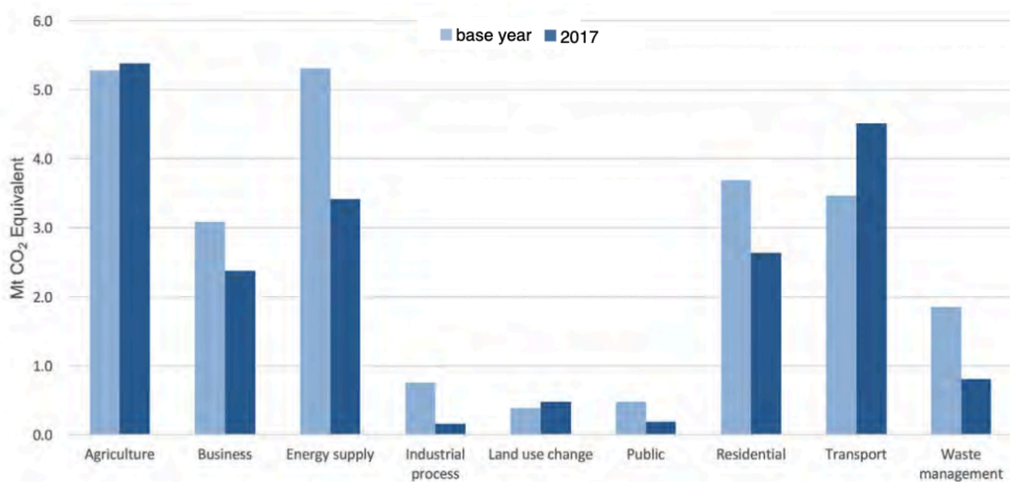

Figure 1. Total GHG emissions in Northern Ireland by sector, 1990 and 2017 [1]

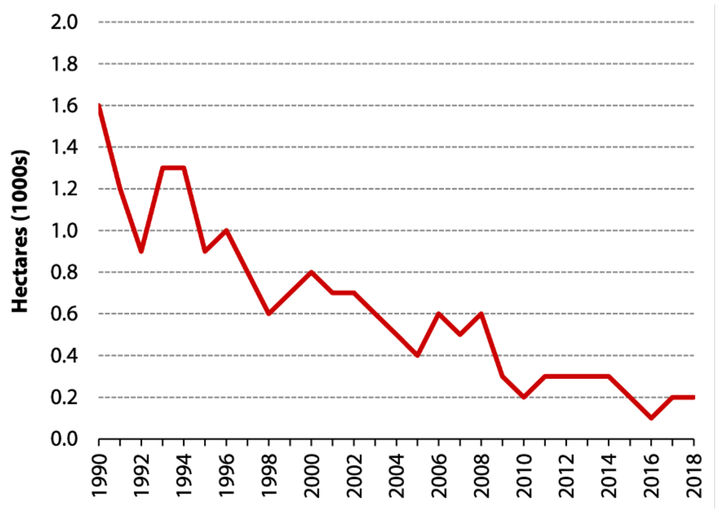

Figure 2. New tree planting in Northern Ireland (1990-2018) [5]

Under the current CAP framework over 90% of funding was allocated under 'Pillar 1' in the form of direct income support payments to farmers. The data presented in *Table 1* highlights the importance of direct payments to farmers. Over the 6 years from 2013 to 2019 single farm payments averaged 57% of total farm revenue. The obvious reliance on subsidy support raises significant challenges when designing a new policy framework that looks to phase out these direct payments.

	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19
Net Income	24,153	19,899	10,082	16,387	28,550	21,925
EU Payments	25,826	25,582	24,972	27,648	26,645	25,840
Revenue	49,979	45,481	35,054	44,305	55,195	47,765
Ratio	52%	56%	71%	62%	48%	54%

Table 1. Comparing average net farm incomes and EU payments over 6 years

The remaining CAP funding is allocated as 'Pillar 2' payments which are tied to rural development through agri-environmental schemes [5]. They are managed in Northern Ireland through the Rural Development Programme (RDP). In 2017 DAERA launched the Environmental Farming Scheme (EFS), a voluntary scheme under the RDP offering a 5-year agreement to deliver a range of environmental measures. These included measures aimed at reducing GHG emissions and sequestrating carbon in the soil. In 2019, 38,000 hectares were managed under the EFS and when combined with other existing RDP measures brings the total land under agri-environmental schemes to 46,000 hectares [1]. The data in *Table 2* shows that during 2016 the area of agricultural land managed through these schemes was reduced by 85%. This signifies the expiration of 10-year agreements tied to older countryside management schemes. Newer schemes like the EFS haven't achieved the same successes with other schemes such as the Organic Farming Scheme ineffective in their impact. Factors that determine the uptake of these schemes including the agreement length and farmer participation require greater understanding in any new policy framework.

The sector is falling short of emission targets and the schemes designed at mitigating these emissions only manage around 3-5 % of NI farmland. Policymakers must consider re-structuring these schemes in any future policy framework to maximise the impact they have. These schemes are a natural first step in transitioning towards a more sustainable agriculture sector.

						thousand hectares
	2014	2015	2016	2017	2018	2019
Environmental Farming Scheme	-	-	-	3	20	38
Organic Farming Scheme	0	0	0	0	0	0
Countryside Management Scheme	280	246	46	46	46	8
Environmentally Sensitive Area Scheme	84	59	0	0	0	0

Table 2. Area of farmland in Northern Ireland under environmental schemes

Future schemes should be targeted, based on evidence [6] and increasingly outcome-based. These criteria can be achieved through an appropriate balance of regulation, incentivisation and clearly defined target outcomes for the environment [3]. Policies to reduce GHG emissions should focus on releasing agricultural land for alternative uses and using land effectively to increase carbon sequestration [7]. These measures are required to meet the UK's net-zero emissions target and require agriculture to act as a significant carbon sink. Changes to agricultural practices have the potential to deliver these reductions but should go beyond a voluntary approach as current mitigation schemes have failed to make any significant reductions in emissions [5].

Understanding the impact of policy scenarios on land use is critical in recognising the wider interactions of driving forces (policy), actors (farmers) and land change. Modelling is used to explore the effects of future changes to policy on land use while providing an assessment of the policy scenarios simulated [8]. The factors that determine land-use choices are highly complex [9] so modelling can also help to represent part of the complexity of these systems [10]. Modelling is, therefore, a powerful tool that can be utilised by policymakers when designing policy before implementation. This can greatly enhance the cost-effectiveness of policies and avoid any unintended consequences.

1.2 Scope and Objectives

This project aims to use modelling to enable DAERA and other relevant stakeholders to observe the impact of potential schemes on land use. Through interacting with the model, they will better understand policy options while evaluating if the measures go far enough to achieve the desired outcomes being incentivised. The model will provide a predictive analytical tool for future policy thinking. Policy schemes introduced into the model will focus on identifying decarbonising pathways to reflect the sector placing sustainability at the centre of its new policy framework. As a result, modelling will be used to explore future policy scenarios that mitigate GHG emissions and increase carbon sequestration in the long term.

Policymakers are increasingly looking at outcome-based schemes, giving greater freedom to farmers and land managers on how to achieve environmental outcomes [11]. Modelling will provide a process through which individual farmers respond and decide on different policy schemes. The cumulative effects of farmer decisions and their impacts on land use will allow policymakers to better understand the factors that determine the uptake of schemes.

The project will produce a spatially explicit agent-based model of land-use change. The model is written in version 6.1.1 of NetLogo and uses the GIS and R extensions.

The landscape holds spatial information about the area under study – Northern Ireland. Initially, county boundary data and a land-use map that defines the land-cover classifications for each parcel of land are imported using the GIS (Geographic Information System) extension. This represents the underlying data used to define the spatial environment. Data specific to farm location and boundary lines was not obtained. If available, the model could be updated to better reflect real-world data. R is preferred for statistical analysis of the results obtained from monitoring emission reductions, financial costs and land-use impacts of policy scenarios. Modelling and the resulting data visualisation are important processes used to convey the impacts of these schemes providing an opportunity to design better policy.

1.2.1 Objectives

The core objectives of the project are summarised below:

- Learn about the problem and design a conceptual model
- Formalise the conceptual model
- Implement the spatial environment using the GIS extension
- Implement the decision-making framework of the individual farmers
- Implement the agri-environmental schemes aimed at reducing emissions
- Implement processes that monitor costs, emissions and land-use conversions
- Design experiments to simulate different combinations of input factors.
- Evaluate and visualise the results of the simulation using the R extension.

1.3 Achievements

The final model implementation matches mostly the ideas outlined in the conceptual model. It provides users with a reasonable exploration of the impacts of policy schemes on land use in Northern Ireland. It also monitors the financial costs involved in policy intervention while updating any reductions in greenhouse gas emissions. The following was achieved according to the core objectives outlined in *Section 1.2.1:*

- The problem was reviewed using existing agent-based and land-use research. After assessing the techniques, a conceptual model to solve the problem was designed.
- The initial concept model was formalised using diagrams which divided the problem into separate sub-models. The spatial, social, economic, ecological and network models combine to enable land-use conversions and monitor outputs like GHG emission reductions.
- County boundary data and a land-use map for Northern Ireland were imported through the GIS extension. This provides the spatial environment on which agents can make land-use decisions. Improvements to the landscape generation process are possible if greater underlying data, specific farm locations, for example, was made available.
- The combined methods of the social and network models form the farmers' decision-making process. The current approach to decision-making is successful in allowing individualised agent choices on policy schemes that impact land use. However, this process certainly could be improved to provide a better depiction of farmer behaviour.
- The final model introduces two policy schemes aimed at sequestrating carbon to reduce GHG emissions. Farmer agents can make decisions on adopting an agroforestry or bioenergy scheme. Users can run the simulation deploying both, none or one of the policies. The schemes can be introduced at varying payment rates. Policy adoption and the ensuing land-use changes will depend significantly on the payment rates set.
- Four separate plots were created to monitor and display the outputs of the simulation. Using inputs selected in the ecological model users can run the simulation to determine if emission targets were achieved by analysing the GHG plot. The other plots observe the total hectares in environmental schemes and the financial impact of each scheme.
- Using embedded NetLogo tools smaller experiments were first set up to validate the model. This ensures the model implementation matches the ideas of the conceptual model. Next, a larger experiment was hypothesised and performed to demonstrate how the model could be used as a tool in policy design. A detailed report of the experiment and its results are presented in *Chapter 5.*
- The results of the example study were exported into R for data visualisation. This provided an accurate visualisation of how different policy scenarios impact land use in Northern Ireland.

1.4 Overview of Dissertation

Chapter 2 – 'State-of-The-Art, examines existing modelling techniques, such as agent-based modelling, to understand the benefits and drawbacks in selecting a particular technique as part of the problem solution. This section explains why the final decision was made and proceeds to investigate existing land-use research in greater depth. From this, specific land-use models related to the problem will be detailed showing some of the figures and outputs of each example. This chapter will conclude by comparing potential simulation tools used to program the model before discussing the final choice of NetLogo.

Chapter 3 – 'Requirements', provides a section detailing a list of requirements for the project. This section provides a grounded understanding of potential user requirements for the model, and what features they would find useful. Although it wasn't possible to carry out requirements capture from policy designers, this section aims to frame this discussion from the perspective of what policymakers would want.

Chapter 4 – 'Design and Implementation', explains how the model is structured to solve the problem outlined in the 'Scope and Objectives'. It examines the methods and processes within each sub-model providing sound reasoning for the choices made. The spatial, social, economic, ecological and network models are discussed at length to explain how they are designed to influence land-use choices.

Chapter 5 – 'Model experimentation and results', allows users (policymakers) to see how the model can be used to contribute to policy design. The experiment aims to find the optimal payment rates that have the most hectares in environmental schemes while keeping costs to a minimum.

Chapter 6 – 'User Evaluation', discusses the feedback obtained from a testing questionnaire completed by a number of fellow students. The questionnaire details several tasks for the tester to complete using the model interface. The information obtained from a single round of testing showed aspects to improve upon in any future implementation work.

Chapter 7 – 'Conclusion', provides a summary of the project achievements which is repeated for the convenience of the reader. This chapter also contains a critical evaluation of the project, its successes and failures, and how it might be improved or extended in the future. Also discussed is how the model could be adapted if another project, similar in design, was to be developed.

2 State-of-The-Art

In developing a solution to the problem outlined, there are several areas of research to analyse and review. System Dynamics and agent-based modelling are the two main approaches implemented to solve the complexity of real-world systems. Reviewing these techniques and forming comparisons between them will determine the methodology used in the model implementation. Exploring other models related to land-use change will also give greater insight into the final model solution. Next, a comprehensive analysis of the tools used to implement the model will be detailed. From this comparison, we can infer the best programming environment to develop the model.

2.1 Agent-Based Modelling

Agent-based modelling (ABM) utilises a bottom-up computational approach that is highly decentralised [11]. In ABM, a complex system is modelled as a collection of entities called agents that make decisions based on a set of rules [12]. Despite a definitive definition for agents, it is widely recognised that there exists in agents features of autonomy, social ability, reactivity and pro-activeness [13]. They make decisions and influence the environment with their actions and can represent different individuals, agencies and institutions [8]. ABMs are particularly well suited for representing spatial interactions under heterogeneous conditions [14]. Modelling with heterogeneity distinguishes ABM from other modelling techniques. Classically used in social science, ABM's have become increasingly popular for studying emergent behaviour [15]. The emergence of patterns, structures and behaviours arise from agent interactions and not through any explicit model process [16]. Due to its popularity in recent years applications of ABM now span a range of research areas. Applications range from modelling agent behaviour in ecological and environmental systems to space-related topics in geospatial and urban studies. Typical agent-based models are structured by introducing a set of agents, defined by attributes and an underlying typology, into an environment on which they can interact with other agents in addition to the environment itself [16].

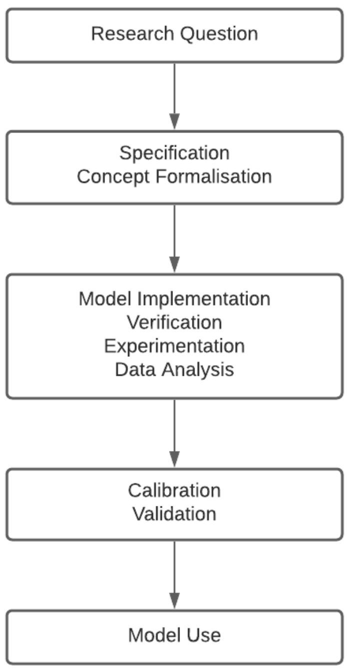

Figure 3. Agent-based Modelling Process

2.2 System Dynamics

Developed in the 1950s, Jay W Forrester, defined System Dynamics (SD) as "the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise" [17]. System Dynamics is a methodology and mathematical modelling technique used to study complex feedback systems [18]. Mathematically, a System Dynamics model is a system of differential equations [19]; they are dynamic as they describe how system properties change over time [20]. The core concept of System Dynamics is that problems exist due to the interactions, feedback loops and information delays among component parts within a system [21]. Systemic structures, therefore, focus on the intricate relationships that exist in complex systems [22]. The concept of endogeneity is fundamental to the System Dynamics approach. From this endogenous point of view System Dynamics attempts to understand sources of system behaviour that exist within the structure [23].

In SD the real-world processes are represented in terms of stocks, flows between these stocks and information regarding the values of the flows [19]. Stocks are the foundation of any system [24]; they characterise the state of the system, providing information upon which decisions and actions are based [25]. Stocks are a representation of different real-world processes such as people, money and knowledge [26]. Flows measure the rate at which the stock is changing at any point in time, inflowing and outflowing to initiate stock change. This forms the overall structure of SD; system behaviour is described using many feedback loops. More specifically, these feedback loops are closed sequences of causes and effects, that is, closed paths of actions and information [27]. System Dynamics has been utilised as a tool in a wide range of fields, from social and economic to ecological systems.

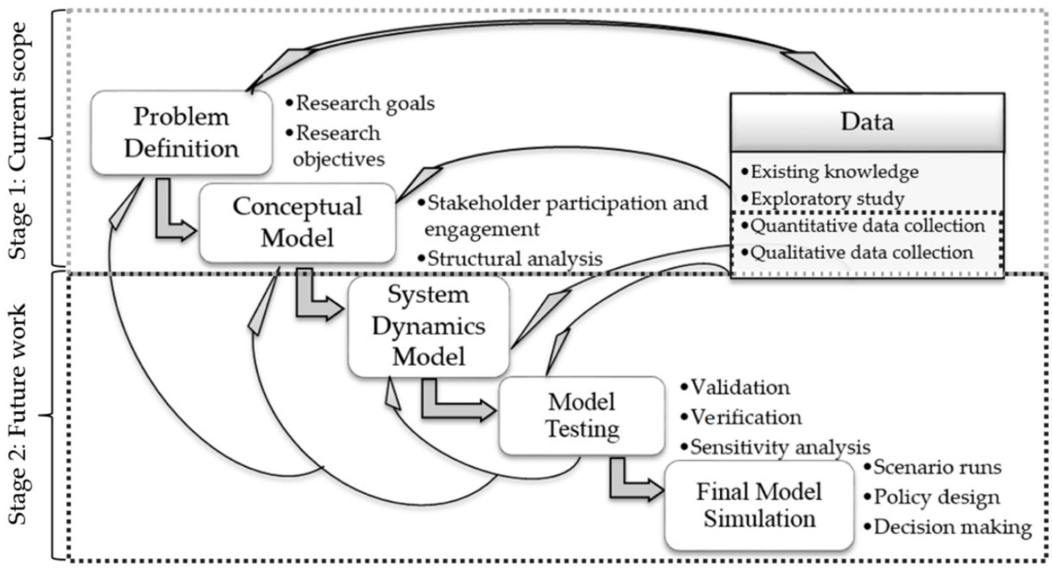

Figure 4. System Dynamics Modelling Process [28]

2.3 Comparison and Decision on Modelling Technique

Both System Dynamics (SD) and agent-based modelling (ABM) can be utilised to explore complex real-world systems. SD and ABM each have their strengths and limitations in modelling these systems; they are applicable in different situations. A detailed comparison of the methodologies will follow before a final decision on the technique to be incorporated into the project solution is made. The objectives of the simulation will ultimately dictate the method used to model it.

- An Agent-based modelling approach allows agents following a simple ruleset to simulate a complex, non-linear, dynamic system from the ‘bottom up’ [29]. ABM is an effective methodology that combines time and space dimensions while emphasising heterogenous and discrete state characteristics [30]. The ability to incorporate heterogeneity into ABM gives rise to agents with varying degrees of rationality. This offers advantages over a SD approach that assumes all individuals are perfectly rational [31].
- In general, less information is necessary when considering parameters and relationships between variables in ABM than in SD [29]. Therefore, in considering a solution to a problem where little is known about the system, ABM can be particularly useful.
- When attempting to capture emergent behaviour, agent-based models are preferred over SD if the interaction between agents is complex, non-linear or discrete. In SD, describing the discontinuity of individual behaviour is difficult [31].
- Most social processes consider physical space or social networks necessary. These aspects are difficult to account for mathematically in SD; agent-based models readily allows for agent interactions meditated by these networks [32].
- SD models do not capture the variability in outcomes caused by stochastic events. By contrast, the distribution of outcomes generated through these random interactions among individuals can be quantified in agent-based modelling [33].
- However, assumptions necessary for verification and validation, such as linearity and normality, can be difficult to achieve for agent-based models [14]. Another limitation of ABM’s is abstracting the real world based on theoretical assumptions to mirror those same real-world processes and observations. While serving as a proof of concept, the model cannot be considered conclusive evidence of a process or system [34]. Agent-based toolkits can also experience performance limitations when simulating a large agent-set [35].
- Alternatively, a System Dynamics approach utilises holistic simulation to understand the non-linear dynamics of complex systems from the ‘top down’ [36]. SD avoids the limitations of modelling from a micro perspective and ignoring the interactions of macro factors seen in agent-based modelling [30].
- Systemic structures provide a better understanding of how variables may be mutually influential. From SD modelling, a sound analysis of the system in terms of possible feedbacks and outcomes is obtained while ensuring a robust and logical method of coupling models [37].
- SD is best implemented to examine aggregate flows, trends and sub-system behaviours [38]. Criticisms of SD centre on its application, including the role of historical data in the model building confidence. System Dynamics also needs to better address how it considers hierarchy [39].

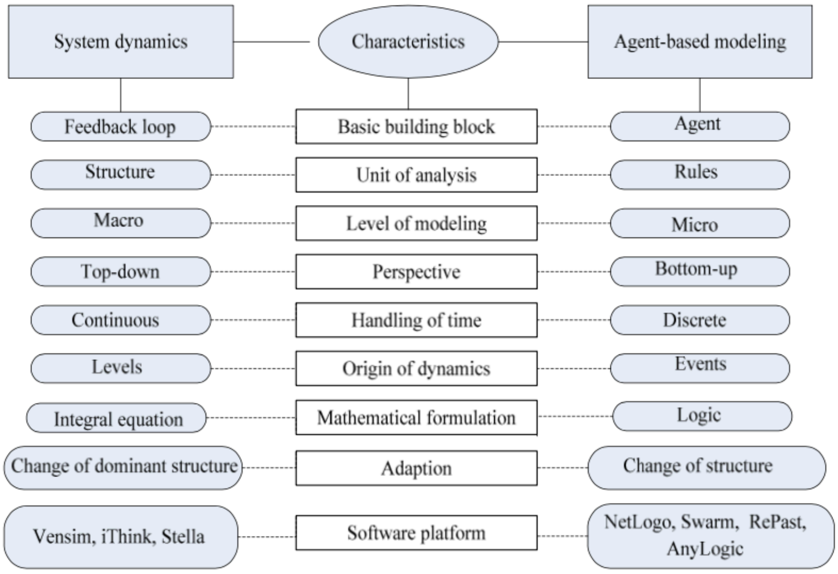

Figure 5. Comparison Between SD and ABM [30]

In summary, ABM and SD methodologies both have their advantages and limitations in analysing complex systems. After considering each technique, it was decided agent-based modelling was the best methodology to help model the impact of agri-environmental schemes on land use in Northern Ireland. The agent-based approach: 1) captures emergent phenomena; 2) provides a natural environment for the study of certain systems; and 3) is flexible, particularly in relation to the development of geospatial models [12]. These three reasons form the basis of why ABM was chosen to represent part of the solution to the problem. Particular drawbacks of SD include not incorporating spatial factors or heterogeneity into its process. These characteristics are in complete contrast to the objectives defined as part of the model specification. System Dynamics lack of flexibility regarding these characteristics made agent-based modelling the obvious choice capable of fulfilling the model objectives. ABM will facilitate the creation of individual farmer agents with an associated decision-making framework. The individual agents form networks of interactions with other agents and the spatial environment. Internal farmer characteristics in combination with external network and economic influences will alter policy adoption rates, thus impacting land use in Northern Ireland.

2.4 Land-Use Change Models

The characteristics of agent-based methods make it a commonly implemented modelling technique utilised to support land-use change research [40]. Land change refers to the conversion of land use from one purpose to another. Examples include the conversion of land from cropland to grassland. Land change is measured by comparing land use at two or more points in time [8]. Changes are usually the result of human interference with the natural world. The intensification of land-use changes in recent times is driving unprecedented changes in environmental processes at local, regional and global scales [41]. The study and monitoring of land-use change have been given greater attention by researchers and policymakers around the world in recent times. Changes in the way humans use land are causes of either land cover conversion or land cover modification. While land cover conversion refers to the replacement of one cover type by another, land cover modification is a small change that affects the land cover without changing its overall classification [42].

Due to the necessity to understand the process of land-use changes, land-use change (LUC) modelling has often been used as a solution to the complexity of these systems. LUC models are tools to understand the multitude of complex factors that influence the pattern of land-use change [42]. Many LUC models have been proposed despite the existence of a definitive theory for constructing these models [43]. The models predominately consist of three central components: driving forces, actors and land change [8]. Driving forces interact with various actors to shape land change and are grouped into five major types: socioeconomic, political, technological, natural and cultural [44]. Changes to any of these factors at any scale, regional or local, will usually trigger land-use changes.

Within LUC models, ABM'S are often implemented because they are well adjusted in modelling spatial interactions under heterogeneous conditions and decision making [9]. Combining ABM and LUC models creates an integrated system that includes both the landscape over which actors make decisions and the decision-making framework of key actors [14]. Although ABMs are used to understand LUC processes, they are limited by the complexity of the systems they try to address. As a result, ABMs are typically used to simulate local scale LUC processes [45].

To overcome this complexity aspect many current LUC models adopt a multi-agent approach that incorporates the use of feedback and interdependencies into the overall framework. Interdependencies exist both spatially and temporally with land-use decisions influenced by the decisions of other land managers and by the attributes of the surrounding environment. The resulting web of interdependencies consolidates to form a complex network of feedback loops [42].

This is a general overview of how agent-based and land-use change models are implemented to study land-use changes. In the next section, two specific examples of how land-use changes are modelled using agent-based and land-use change methods will be detailed. Each will be related in some way to aspects of my conceptual model.

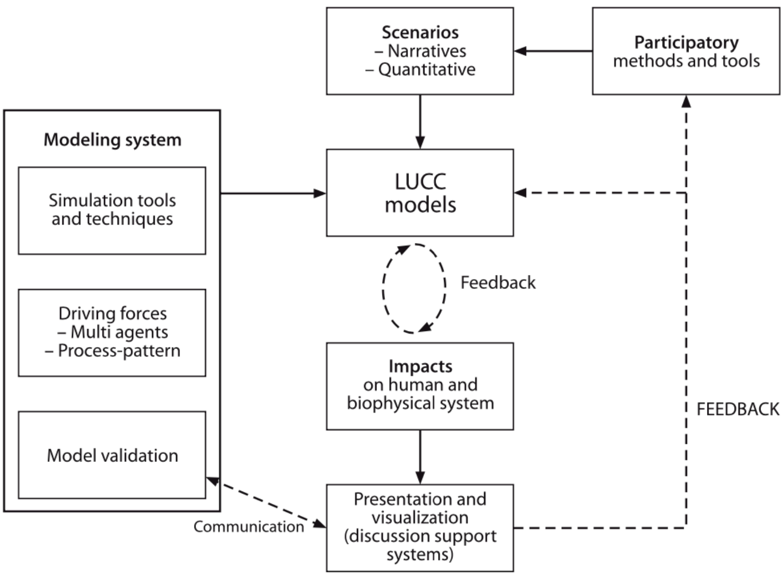

Figure 6. Example Overview of LUC Model Process [46]

2.4.1 An Agent-Based Model of Mediterranean Agricultural Land-Use/Cover Change for Examining Wildfire Risk [47]

The model simulates a traditional Spanish agricultural landscape that is undergoing social, demographic and cultural change. Agricultural location theory is combined with agent behaviour specific to the study region to provide the decision-making framework. Maps of land-cover composition that emerge from the interaction of farmers' land-use decisions are then used to assess potential impacts on wildfire risk. For research purposes related to the structure of my model, this section will focus on the spatial and decision-making processes of the model rather than its examination of the impacts on wildfire risk.

The model approach is process-based and considers the behavioural aspects of agents in making decisions that influence land use. By considering agent actions as spatially explicit, the model also allows a dynamic representation of interactions between socio-economic and biophysical processes. Thus, the model offers improvements in the representation of the impacts of individualised heterogeneous spatial decision-making over classical approaches.

In developing a model structure representative of real-world behavioural patterns, interviews were undertaken with local stakeholders. Responses from the interviews were used to form the decision-making framework and highlighted two distinct 'types' of farmers: commercial and traditional farmers. These farmer groups make land-use decisions to establish an area of land as one of three possible land uses crops, pasture or non-agricultural land. Agents perceive the landscape as a grid of pixels on a seasonal basis. The distinction between commercial agents that operate in an economically rational, profit-maximising manner and traditional agents that seek to maintain classical practices and landscape aesthetics is an important observation of the model. Different attributes and rules within the model are used to characterise commercial and traditional farmer groups to accurately represent the decision-making process of both.

Attribute	*Traditional Agent*	*Commercial Agent*
Commitment	'Part-time' or 'Hobby' farmer	'Full-time' businessman
Age	Any, greater than 19 years	Maximum 65 years (retirement age)
Land Exchange	Will not exchange land	Will buy/sell land to achieve profit
Land Uses	Maintains land in 'traditional' uses	Whatever land use maximises profit
Financial	Profit is not primary determinant	Aims to maximise profit

Figure 7. Attribute comparison of different agent groups [47]

The model was developed in the NetLogo modelling environment and considers two state variables that agents make decisions about - the proportion of land used for crops and the proportion of land used for pasture. To examine the impacts of land use, maps with random land-use configuration were generated using a modified random cluster method. This method specifies a probability parameter P to generate landscapes with pixel clusters of varying size. As P increases the number of patches decreases with mean and maximum patch size increasing. Land-use maps generated with $P < Pc$ (critical threshold $Pc = 0.59$) are similar in composition to existing land-use maps of the region from 1999. Maps with P values above the threshold are not comparable with original land-use maps for the area. Once the value approaches 1.0 the landscape is composed entirely of pastoral and arable farming.

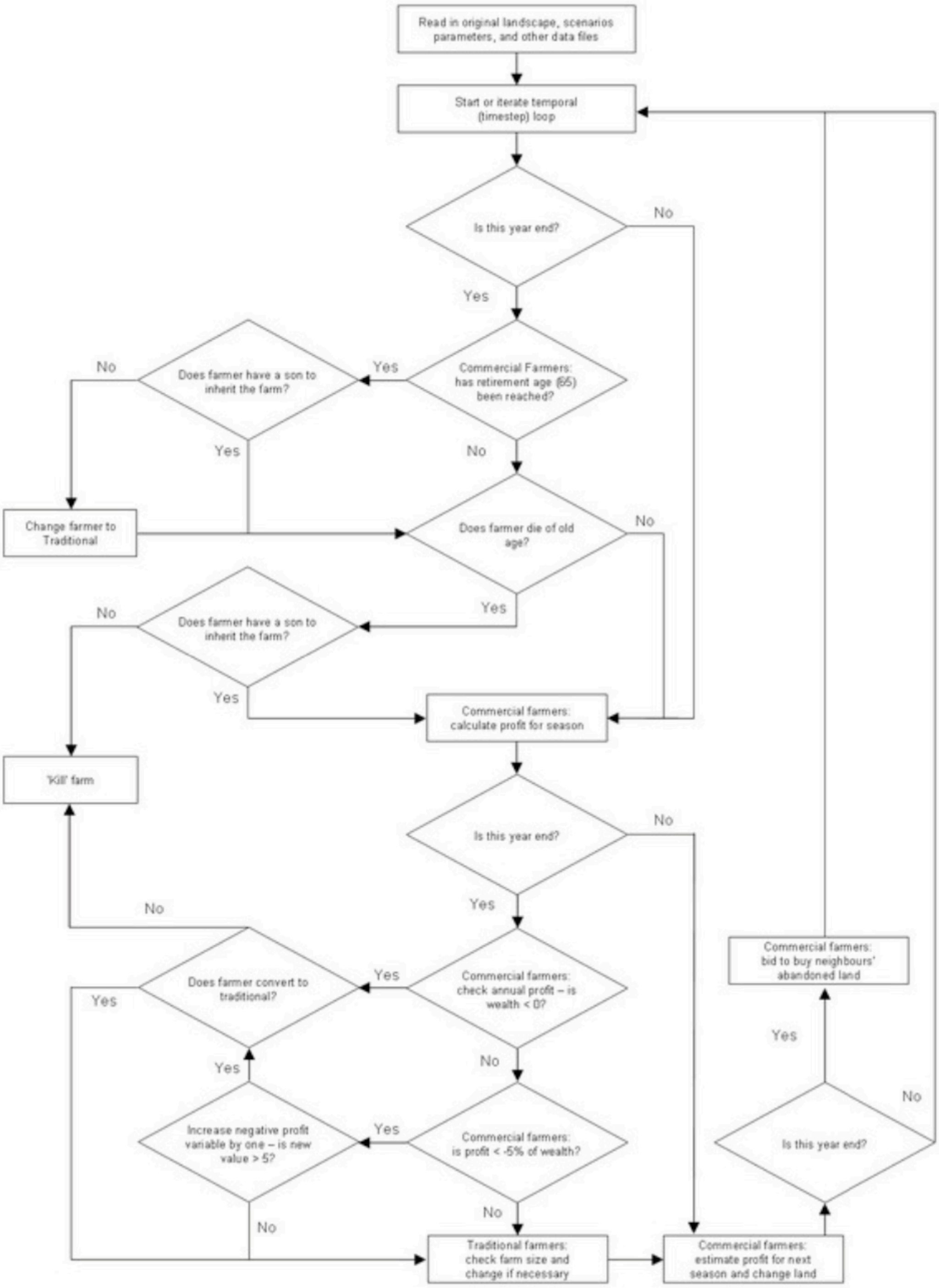

Figure 8. Process of the agent-based model of land-use decision-making [47]

Results show land-use scenarios tend towards a similar final land-use configuration but differ in their compositions. Parameter values in *Figure 9* span the parameter space of the model. This facilitates the examination and investigation of the range of possible model states and important input data. Scenarios LU1-LU3 differ least from results for the model initiated with the original land-use map. By contrast, LU4-LU7 scenarios are driven by dominant land-uses initially, resulting in markedly different land-use compositions (*Figure 10*).

Scenario	*Variable*	*Distribution of Values*
LU1	Land use	*P* = 0.2 (SPA land-tenure, 509 LU patches)
LU2	Land use	*P* = 0.4 (SPA land-tenure, 291 LU patches)
LU3	Land use	*P* = 0.5 (SPA land-tenure, 198 LU patches)
LU4	Land use	*P* = 0.6 (SPA land-tenure, 94 LU patches, predominantly pasture)
LU5	Land use	*P* = 0.6 (SPA land-tenure, 83 LU patches, predominantly crops)
LU6	Land use	*P* = 0.8 (SPA land-tenure, 1 pasture patch)
LU7	Land use	*P* = 0.8 (SPA land-tenure, 1 crops patch)

Figure 9. Parameter values for ABM/LUCC testing [47]

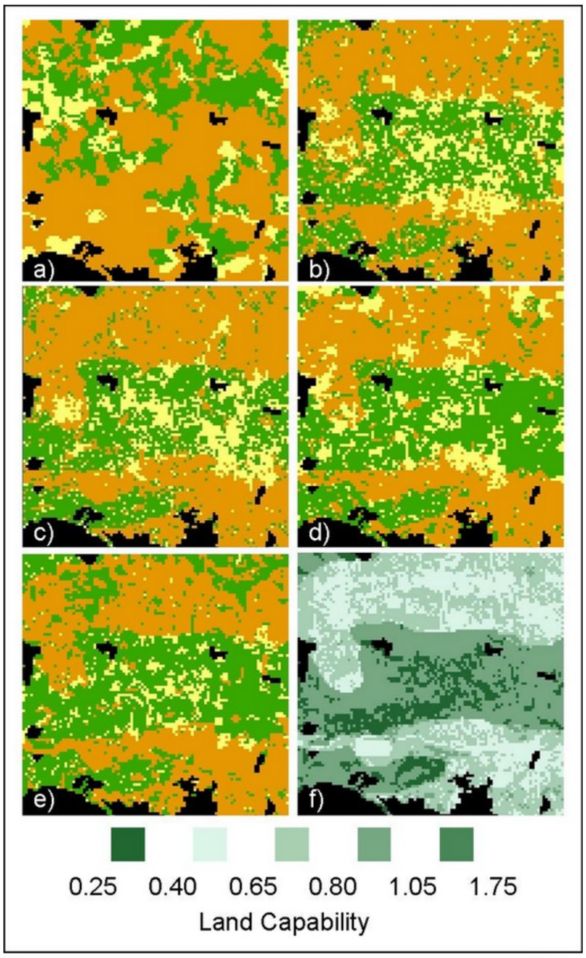

Figure 10. Land-use maps from land-use scenarios [47]
a) original land-use map for the region, b) LU1, c) LU2, d), LU5, e) LU7 and f) land capability

The structure of this model provides several useful ideas in implementing an agent-based land-use change model. In particular, the depiction of agents' decision-making process is something to consider when designing and implementing the decision framework of my agents. Also, as interviews of farmers in Northern Ireland was not possible in this project the concepts proposed in this model for defining an agent typology may be also useful.

2.4.2 An Agent-Based Approach to Modelling Impacts of Agricultural Policy on Land-use, Biodiversity and Ecosystem Services [48]

This model simulates the consequences of agricultural policy reform on farmers land-use decisions while evaluating impacts on biodiversity and ecosystem services. The focus of this section will lean on the impacts of policy on land use as it closely relates to the type of problem this project seeks to examine. The policy scenarios examined are three possible alternatives for the Common Agricultural Policy (CAP). The impacts of changes in agriculture policy on land use are simulated by this model up to 25 years in the future. Agricultural decisions are modelled annually hence the model time-step is 1 year.

The purpose of the model is to understand how the income-maximising behaviour of individual farm agents competing for land in a finite landscape affects change within a region depending on agricultural policy. The model also incorporates changes in farm size, farm exits and changes in production into its overall framework. The main entities within the model are farms, production, investment, plots, markets and the political environment. The key state variables attached to each farm agent are fixed-assets, area of land owned and rented, equity capital, family labour, farmer age and managerial ability. Plots are the gird elements that represent the landscape with each land unit defined by its size, location, soil type, ownership, rental price and rental contract.

The model features a two-phase process; the model structure is created in the initialisation phase. This facilitates the creation of the landscape and farm agents. The simulation phase represents the decision-making process repeated in each simulation. Changes in the level of policy payments and conditions for receiving payments are the only input during a simulation. The overall model structure is comprised of several sub-models that include the landscape initialisation, landscape indicators and biodiversity indicator processes. For the simulation, the counties of Jönköping and Västerbotton in southern and northern Sweden were selected because they are marginal agricultural regions. Changes in agricultural policy are more likely to have landscape impacts in these regions.

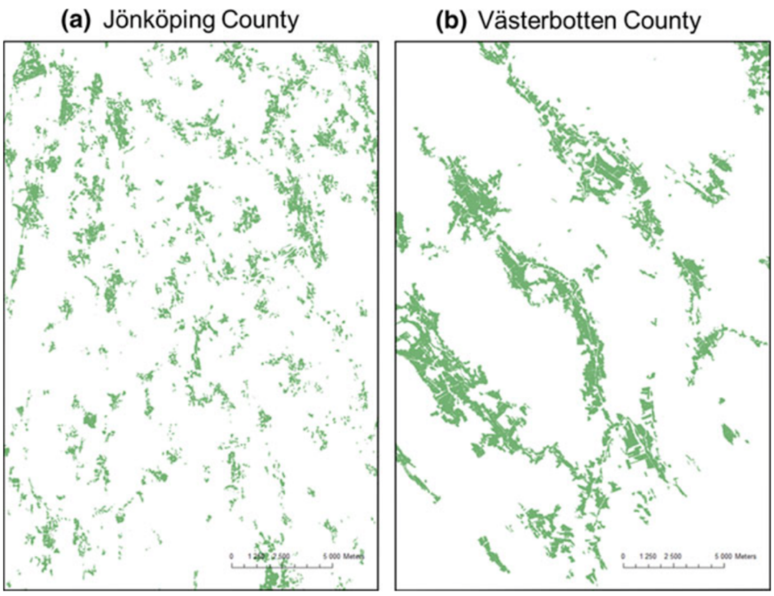

Figure 11. Landscape structure of the two regions

The model assesses the impacts of three alternative schemes on landscape values in the study areas. Only the direct payment support is varied in each scheme; existing environmental payments allocated under the CAP budget are held constant. Two of the scenarios are existing real-world policy schemes: the AGENDA and DECOUP scheme. The third scheme, FUTURE, is hypothetical and is designed to illustrate the implication of reducing direct income support.

Results from the simulation suggest the strongest structural change is under the FUTURE scheme where more farms exit, and farm-size increases most. This structural change is least under DECOUP and reflects the changes in farm income introduced by each scheme. The choice of policy scheme also has significant impacts on land use. AGENDA results in insignificant changes to land use as the scheme relates closely to the current CAP framework. Due to the decoupling of support particularly in livestock payments, DECOUP sees a significant decline in beef production when compared with AGENDA. The effects of FUTURE are similar to those for DECOUP in that production is more extensive. However, lower payments for maintaining environmental quality of land mean less land is kept in production compared to DECOUP.

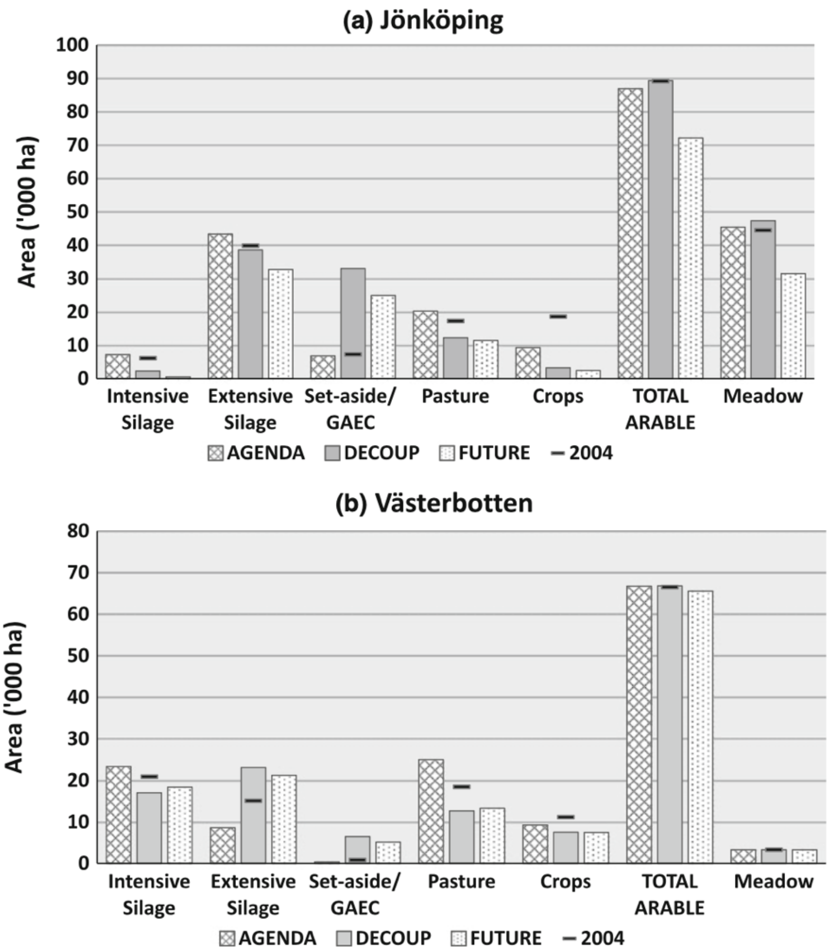

Figure 12. Changes in land use resulting from policy schemes

2.5 Simulation Tools

Over the years, various toolkits have been designed to enable researchers to develop agent-based applications. Each toolkit contains a variety of characteristics that better serve different purposes and objectives in modelling these complex systems. For the most part, these simulation frameworks are widely distributed; they provide detailed documentation and a user interface that simplifies the work. They relieve modellers of programming aspects of the simulation that aren't content specific while increasing the reliability and efficiency of such programs [49]. Naturally, agent-based simulation tools have become popular when implementing a conceptual model design. In the past, conventional programming languages such as C, Smalltalk and Java, were usually employed for such tasks [50]. However, the rise of ABM specific software frameworks means this is no longer the case. The first of these to be widely deployed was Swarm, whose design influenced several successors including Repast and Mason. The Logo family has also developed several popular agent-based software packages, such as NetLogo [51]. Following a survey conducted by Railsback, Lytinen & Jackson, published in 2006 [52], this section looks to compare the four major platforms: NetLogo, Mason, Repast and Swarm. After a review of each software platform is detailed, a decision will be made on the framework best optimised to program my model implementation.

2.5.1 NetLogo

NetLogo is a widely used high-level ABM environment that is freely available online. It was designed by Uri Wilensky in 1999 and is based loosely on the programming language Logo. It is designed to be 'low threshold high ceiling' and makes use of agents in the form of turtles, patches, links and observers [53]. The 'low threshold' aspect means there isn't a steep learning curve when programming with this language; its primary design objective is usability [54]. It is particularly suited for modelling complex systems evolving over time [55]. The platform enables the observation and capture of emergent phenomena in natural and social systems. Despite a simple programming interface, NetLogo is capable of creating sophisticated simulations and supports extensions that allow GIS data and R analysis. NetLogo also comes equipped with comprehensive documentation and an extensive model library. The framework has an active user community online helping it become a popular platform for implementing agent-based models [51].

2.5.2 Swarm

Swarm was the first software tool designed specifically for agent-based modelling [54]. It is an object-orientated platform developed at the Santa Fe Institute in 1994. Swarm was developed to design multi-agent models that simulate complex adaptive systems. The basic unit of simulation within the system is a 'swarm' which is a collection of agents executing a schedule of actions [56]. It supports hierarchical modelling which can be achieved by nesting multiple swarms. Swarm uses its own data structures and memory management to model objects [54]. This gives rise to a prominent concept within Swarm called 'probes' – this allows users to read and set the state of an object at runtime [52]. Swarm remains one of the most powerful and flexible simulation platforms [54]. However, in practice, Swarm has a steep learning curve. Due to its object-orientated nature, experience in Object-C and Java is necessary to simulate ABM with Swarm. This represents a significant barrier in Swarm being chosen as a tool for developing ABM which is especially true today when other powerful and easy-to-use tools such as NetLogo are available. Though additional support is available and events such as SwarmFest are held annually, Swarms' popularity as a tool for modelling complex systems has diminished over the years [51].

2.5.3 Repast

Repast was originally developed by the University of Chicago as one of the toolkits to supersede Swarm. Repast, however, does not implement swarms and was introduced to support the social science domain [54]. A prominent feature of repast models is that they provide a visual tool that makes it easier for inexperienced users to build a model. Repast provides extensive documentation and a series of "How to Documents" that allow new users to familiarise themselves with the software. Repast also maintains a support mailing list where questions and queries are answered promptly [49]. Within the framework, many tools for data visualisation and editing are available as well as extensions that support GIS data. Agent Analyst is an ABM extension that allows Repast models to be integrated with the ArcGIS software for example [51]. Steady improvements to the repast framework mean it has now diverged into a more comprehensive platform maintained by the Argonne National Laboratory. Repast Java, Python and .NET are no longer being developed and have been superseded by Repast Simphony (Repast-S). Although limited to Java implementation, Repast-S is a powerful tool that provides a rich context of functionalities [51]. Repast has since established itself as one of the most popular simulation toolkits for ABM research by supporting a wide range of tools for developing these models [57].

2.5.4 Mason

Mason (Multi-Agent Simulation Of Neighbourhood) is a fast discrete-event multiagent simulation library core written in java [58]. It was developed by the Evolutionary Computation Laboratory and the Center for Social Complexity at George Mason University. It was designed for flexibility of use in a range of systems with special emphasis on swarm multi-agent simulations of many agents. Mason's development focuses on meeting the needs of computationally demanding systems [59]. The design approach appears to centre on maximising execution within a minimal model library. Mason's model contains visualisation and GUI features but is against the concept of supporting domain-specific tools. The Mason framework is most comparable to the Swarm and Repast simulation tools. In summary, the Mason framework creates a small, fast, easily understood and easily modified core. It provides separate, extensible visualisation in 2D and 3D with efficient support for many millions of agents [59].

2.5.5 Comparison and Decision on Simulation Tool

After consideration of the design challenges related to the implementation of my model, I found the NetLogo framework to be best suited to the objectives of the model. A direct comparison of the four major simulation tools can be found in *Table 3*. From a design approach, this table suggests NetLogo is the most well-rounded software toolkits. Allowing inexperienced users to easily implement conceptual models through its 'low threshold' design approach was a significant factor for me personally. As an inexperienced user myself, having no prior knowledge of complex systems, usability was significant when choosing a simulation framework to program with. NetLogo also came with the added benefit of a simple installation and setup process over the other toolkits. Detailed documentation and an active online community meant there were various sources of information from which I could easily build my knowledge of the language. NetLogo is also bundled with numerous extensions, from which the GIS and R extensions were of particular interest. These extensions and the various other characteristics make NetLogo the optimal simulation tool for my model implementation.

	NetLogo	Swarm	Repast	Mason
Developer	Northwestern University	Santa Fe Institute	University of Chicago	George Mason University
Introduction Date	1999	1996	2000	2003
Modelling language	Proprietary scripting	Object-C, Java	Java, Python, Microsoft.NET	Java
Required Programming Skill	Basic	Strong	Strong	Strong
Integrated GIS functionality	Yes	Yes	Yes	No
Integrated graphing/statistics	Yes	Yes	Yes	No
Availability of demonstration models	Yes	Yes	Yes	Yes
Documentation	Good	Patchy	Limited	Limited
User base	Large	Diminishing	Large	Increasing
Speed of execution	Moderate	Moderate	Fast	Fastest
Ease of installation	Very easy	Poor	Moderate	Moderate

Table 3. Comparison of ABM platforms based on Liang Chen (2012) [51]

2.6 GIS Data

Traditional land-use maps are categorical, dividing land into categories of land use and land cover; recent techniques allow mapping of land use as continuous variables [41]. Both, however, may be compared using geographic information systems (GIS) to measure land-use change at given areas of the earth's surface. GIS is a framework that allows the capture and analysis of spatial and geographic data. Attribute data is typically incorporated with geographic information. The combination of these two data types makes GIS an effective problem-solving tool [60]. Along with problem-solving, GIS can be a useful tool for spatial analysis especially in determining the location of features, mapping quantities and analysing how land changes over time.

GIS data is mainly stored as two primary data types: raster and vector. Raster data stores information in a cell-based manner. Rasters consist of a matrix of pixels, also referred to as grid cells, organised into rows and columns. Each cell has a value that represents a feature that is observed and is best used for storing continuous data. Vector data, by contrast, is comprised of vertices and paths that store information in x, y coordinates. This data type represents the world either as points, lines or polygons and is useful for storing data that has discrete boundaries.

During my research, I was able to obtain both raster and vector land use data for Northern Ireland. Both GIS datasets were sourced from *https://digimap.edina.ac.uk/environment* and are imported into NetLogo during the implementation phase of my model through the GIS extension. The two datasets both provide the classification of land-use types for Northern Ireland in 2015. Land use is one of the most common types of raster data and is derived from satellite data collected from Landsat mappers. Due to the nature of its data storage raster data analysis is easy to program and quick to perform. These reasons make using raster land use data in NetLogo a good fit for the objectives of my model. Vector data isn't without its advantages with the accurate geographic location of data being maintained as it can be represented at its original resolution.

GIS is a versatile and powerful medium [43] and when coupled with a model can assist in communicating results to policymakers, offering predictions of future land-use changes as a result of policy scenarios. Therefore, linking GIS with LUC models can enhance the capabilities of the overall system for spatial problems [43] and is a necessary inclusion in my project.

2.7 GIS Extension

NetLogo's GIS extension provides the necessary features to import the raster land use data. The GIS extension is a powerful tool for creating and enhancing models through the use of real-world datasets. This is especially useful in the context of my project as it enables the visualisation of actual land use types for Northern Ireland in the NetLogo environment instead of having to create an abstract land-use allocation process based on real-world classifications. Any policy scenario analysis can be tested upon the GIS framework.

After selecting the appropriate land use map, it is modified through qGIS which is free and open-source software. This application is necessary for converting the dataset into a format compatible with the NetLogo environment. Currently, the extension supports ERSI shapefiles (.shp) for vector data and ERSI ASCII gird files (.grd and .asc) for raster data. Once displayed in the NetLogo space, the land use map can be combined with my model to analyse the impact of agri-environmental policies on land use in Northern Ireland.

3 Requirements

The system's users are intended to be teams within the government bodies responsible for policy decisions. The users should be able to explore policy options focused on mitigating GHG emissions and increasing carbon sequestration over a 30-year timeframe. The model aims to serve as a tool to help understand the consequences of sustainable policy thinking. Although it wasn’t possible to carry out requirements gathering from real policy designers, this section seeks to frame the discussion of requirements from the perspective of what the policymakers would require from this tool. This will be achieved by listing several functional and non-functional requirements and a final use case diagram summarising the key requirements.

3.1 Functional Requirements

- The model should be capable of handling GIS data to generate the spatial environment. This will enable a land-use map to be imported into the simulation. The model will be utilised to simulate land-use impacts in Northern Ireland and therefore must accurately model this study area.
- The model must create a set number of farmer agents belonging to different groups given input parameters set by the user. The location of these farmers and the group they belong to must be shown by the model. This allows users to visually see where and when farmers make land-use conversions.
- The model should allow users to define the likelihood of each farmer group participating in environmental schemes. This allows users to conduct field interviews with real farmers to determine a list of criteria used to calculate the probability a farmer associated with a particular group adopts either scheme.
- The simulation must allow users to manually adjust parameters associated with concepts such as succession, retirement, death and environmental awareness. This allows users to gather empirical data related to Northern Irish farmers and adjust these inputs based on their findings.
- The model needs to allow users to introduce the policies into the simulation at varying payment rates. This enables users to understand the effects of payment rates on the policy adoption rate and determine the optimal price at which policies should be introduced.
- The model needs to monitor the greenhouse gas reductions as a result of policy intervention. This will allow users to compare the GHG emissions at the end of the simulation with pre-defined emission targets to realise if policies achieved the desired environmental outcomes.
- The simulation should allow users to define the number of neighbours in an individual farmers’ social network. The extent that each farmer is influenced by their social network should also be determined by the user. This gives users the ability to observe the impacts of social networks on policy adoption rates.
- The model must be able to obtain the costs incurred in achieving the objectives of the scheme. This will provide policy teams with the opportunity to deliver a better policy that takes into consideration the long-term implications of decisions taken today.
- The model should monitor the total number of hectares in agri-environmental schemes. This allows users to understand the impact of policy intervention on land use in Northern Ireland. Users will gain insight into the amount of agricultural land released to help sequestrate carbon and increase the sustainability of the sector.

3.2 Non-Functional Requirements

3.2.1 Useability

The model must be easy-to-use and should consider this in its design approach. Inexperienced users with no prior knowledge of complex modelling should be able to understand and effectively use the model. A user guide in *Appendix 2* is provided to the user which is encouraged to be reviewed before starting any model runs. After reviewing the guide, the user should easily be able to set up the model based on any combination of input parameters they choose to run the simulation with.

3.2.2 Performance

When simulating a model run, the run must complete in a reasonable time. For the model to serve as an effective policy tool it must allow users to conduct research without delays. If an acceptable model performance is not achieved, policymakers may consider the tool obsolete.

3.2.3 Scalability

The model must be adaptable to changes to the scale and size of the system. It must be designed in a way that allows other researchers to take the model in its current implementation and extend its methods and processes. The design must allow flexibility to account for changes to the study region or policy schemes that other modellers may want to make.

3.2.4 Availability

The model must be available across a wide range of machines and operating systems. When deploying the model to users, the exact specifications of the systems where the model is to be utilised is unknown. Therefore, the model must be available to serve effectively as a tool to support policy design with as few barriers to use as possible.

3.3 Use Case Diagram

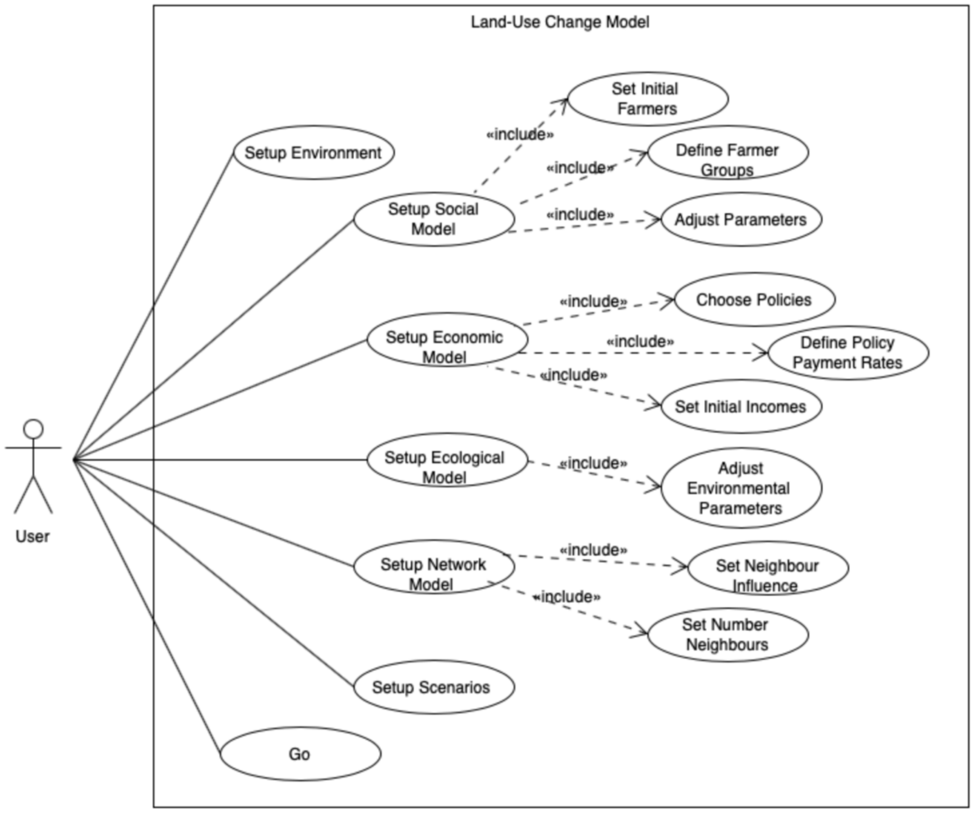

Figure 13. Use case diagram for the model overview

The use case is summarised from the functional requirements stated in the previous section. It details the steps the user is expected to carry out when setting up and running the simulation for a single run. First, the user must generate the spatial landscape from the GIS data. Next, they should adjust the parameters under the four model headings: social, economic, ecological and network. This defines the initial conditions with which the model is run. Different combinations of input parameters can be experimented upon to analyse their impact on land use.

Once these conditions are adjusted, the user presses the '*setup scenario'* button to initialise the parameters into the system. After the necessary steps are complete the simulation can be run for a single run. Not following the correct order in setting up a model run will cause the model not to do anything. When running the simulation, the land-use map will update at each time step and the user can visualise the collective land-use conversions as a result of individual farmer decisions.

4 Design and Implementation

The model design is separated into the spatial, social, economic, ecological and network models. These sub-models define the landscape on which the agents make decisions along with the agents themselves and their associated decision-making framework; also holds the economic and ecological information related to both the landscape and the farmer agents.

The spatial model defines the initial landscape which holds a range of information about the area under study. The generated landscape consists of county boundary data and an initial land-use map that describes the current land-cover classification for each parcel of land. These are imported through the GIS extension and provide the ability to link the spatial environment with the agents' actions and decisions.

The social model provides the ability to generate a set number of randomly distributed farmer agents. The farmer agents incorporate the decision-making framework into their overall design. This provides individual farmers with the ability to make land-use decisions about the land associated with their farm. The diversity of this decision-making ability is, however, simplified by defining an agent typology. Attached to each farmer agent are several social and economic attributes such as age, income, neighbours, etc. Thus, the social model defines the processes linking decision-making with factors internal to each farmer agent.

The economic and network models each introduce external factors that influence an individual farmers' decision-making. The economic model allows attributes relating to the farmer agent's economic status to be defined. The model also provides the framework to introduce agri-environmental schemes at different policy payment rates. Varying the payment rates will directly impact the adoption rates of policy schemes by influencing the agent's decision-making. The network model provides the ability to observe the implications of social networks in influencing agent's decision-making. The model introduces a specific number of neighbours into each farmers' social group. The decisions of other farmer agents within each social group affect the agent's internal factors.

The ecological model contains several environmental parameters related to each policy scheme. These parameters are introduced into the simulation before a model run. The values selected combined with the land-use conversions as a result of agent decisions impact the amount of carbon sequestrated in the soil. These factors are responsible for calculating the GHG emission reductions at each time step.

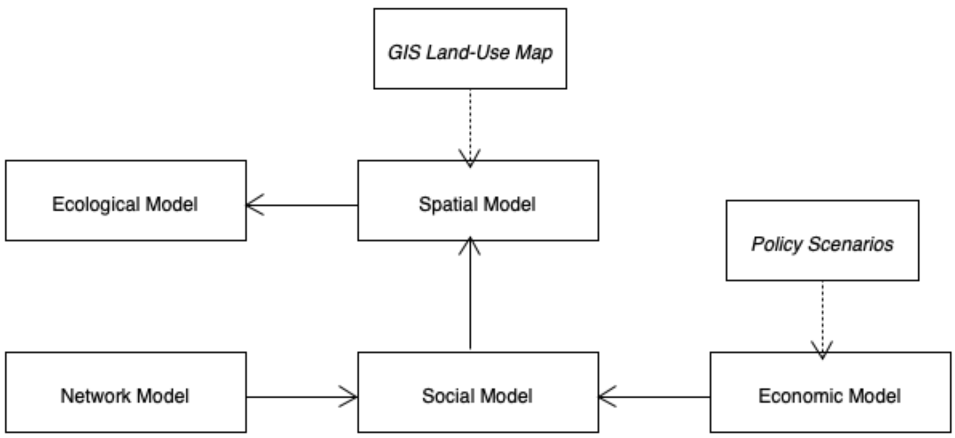

Figure 14. Structure of the Model

4.1 Spatial Model

The spatial model generates the landscape through which farmer agents make decisions on different environmental schemes. This represents the first design stage of the model to be implemented. This subsection details information specific to the study area before reviewing the design and implementation of the spatial model itself.

4.1.1 Study Region

The study area simulated in this model is Northern Ireland. 70% of the agricultural land is described as less-favoured areas (LFA) meaning the agricultural conditions are relatively poor [1]. Due to these conditions, LFA can be considered minimal in terms of productivity. The majority of farmland in the country is under grass with only 12% of farms having arable or horticultural crops [1]. Medium to large scale farm businesses contribute 60% of the total gross output from 30% of the land area [1]. Around half, of the land throughout the country is owner-occupied with the remaining a combination of owned and rented land. The rented land is predominately under the conacre system. This is a system of short-term letting and is a feature distinctive to Ireland. Collectively, this defines a unique set of circumstances that differentiate agriculture in Northern Ireland from the rest of the UK. As a result, attention must be given when implementing policies to ensure they reflect the landscape of Northern Ireland. The model needs to be run at the spatial scale which is relevant to the policy intervention. This will enable a more successful observation of farmers response to policies and the impact they have on land use.

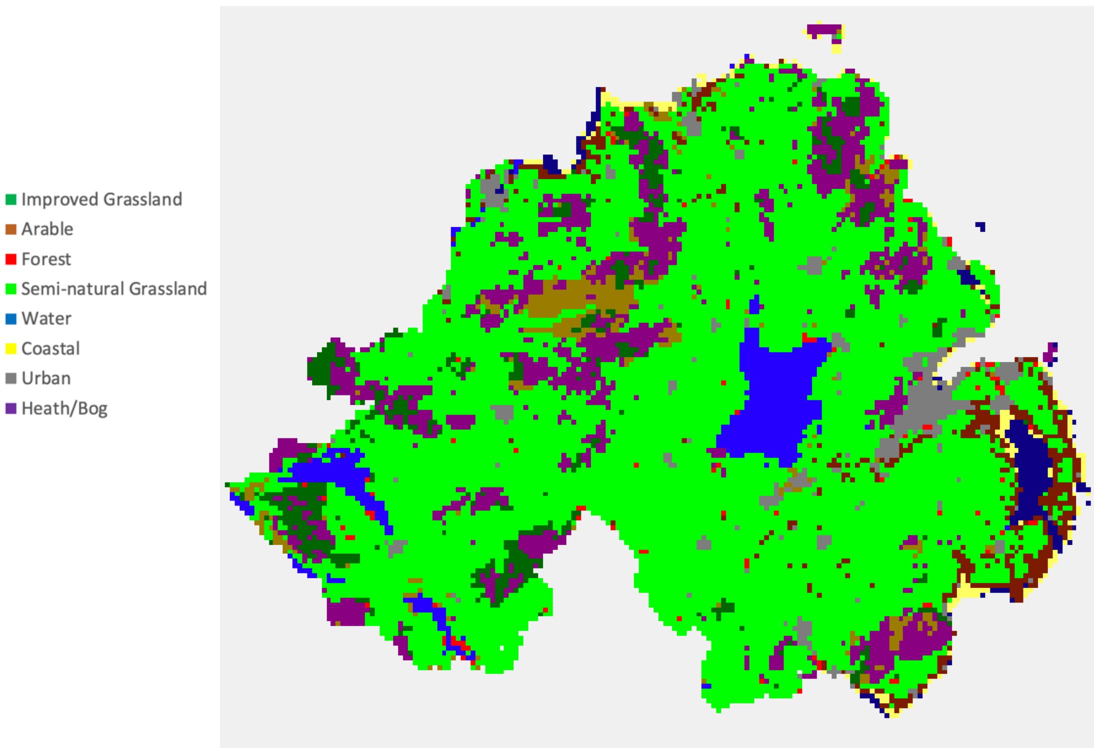

Figure 15. 2015 Land-use map for Northern Ireland

4.1.2 Design

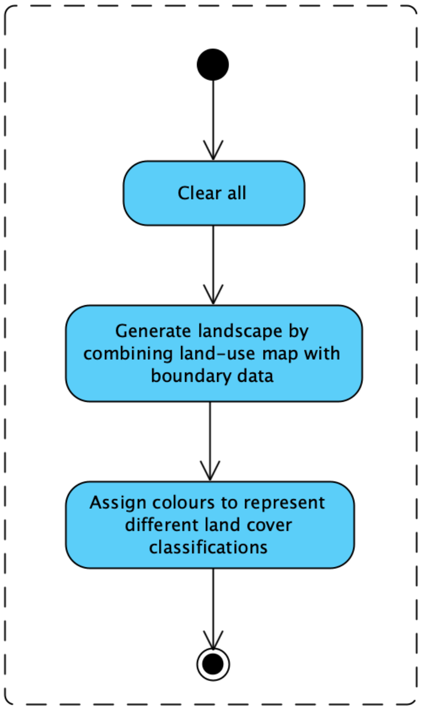

Figure 16. Activity Diagram for setting up the spatial environment

4.1.3 Implementation

The initial land-use map is derived from satellite data collected by the Landsat 5 Thematic Mapper. It was obtained from Digimap which is operated by EDINA at the University of Edinburgh. The raster dataset was clipped using QGIS 3.14 which is a free and open-source GIS application that supports viewing, editing and analysis of geospatial data. This step was necessary to convert the land-use map into a file format supported by the GIS extension. After processing the raster dataset, it is exported as an ASCII file and read directly into NetLogo.

The raster dataset is combined with county boundary data to create the landscape on which the farmer agents' make decisions. The county boundaries are vector datasets obtained from OpenDataNI. The datasets are in a Shapefile format which is compatible with the GIS extension and can therefore be imported directly into NetLogo without any data pre-processing of the data.

The landscape generated by the raster and vector datasets consists of a 220 x 190 patch grid with a bottom left corner location of origin and no vertical or horizontal wrap. Each parcel of land is defined using NetLogo patches; one patch is equal to around 50 hectares. Due to the temporal scale, farms under 50 hectares are not considered in the model. As a result, only medium to large scale farm businesses are modelled. Each patch holds a range of information such as the type of land-use and land-cover classification, the group the patch belongs to, the field owner id and the county (counties) the field is located.

Each patch is next assigned a colour that represents the different land-cover classifications such as forest, arable, urban, etc. The colour is dependent on the land-use value that is associated with the original raster land-use dataset. Once assigned, a map similar to that in *Figure 15* is displayed in the NetLogo interface.

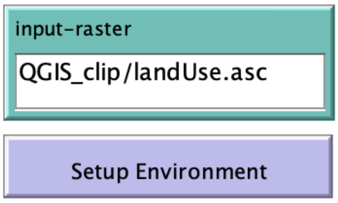

Figure 17. Interface components relating to the landscape generation

Interface Component	Function
Input-raster	A path to the location of the input raster data file which has been clipped in QGIS
Setup Environment	Sets up the spatial environment by triggering the process of displaying the land-use map on the interface

Table 4. Functions of the interface components within the Spatial Model

4.2 Social Model

The social model encompasses the decision-making framework of the farmer agents. The model contains several processes that influence the farmer's likelihood to adopt the policy scenarios. The factors influencing these decisions are internal and don't consider the actions of other agents. This subsection covers the design and implementation of the social model which details the agent typology, the farmer/farm life cycle and the decision-making process of agents.

4.2.1 Design

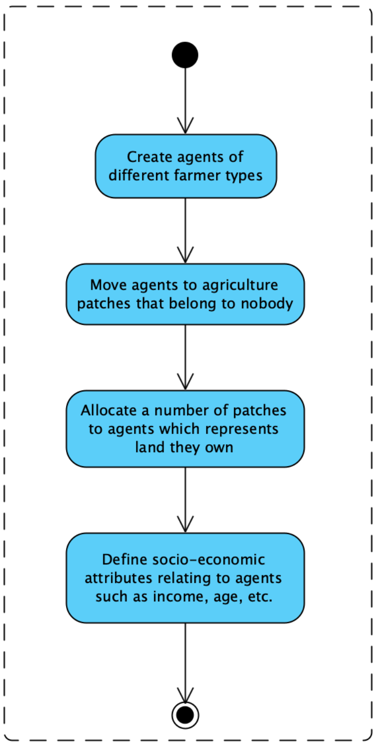

Figure 18. Activity Diagram for the Social Model

4.2.2 Farmer Agent Typology

An agent typology is proposed to simplify the diversity of farmers' decision-making. A typology is an approach deployed to represent general farmer types based on specific farmer characteristics; farmer agents can be categorised depending on their willingness to change. This is of particular use to the model implementation as we look to analyse the impact of environmental schemes on land use. Through carrying out detailed surveys of a sample farmer population, empirical evidence is gathered that indicates farmers' willingness to partake in various policy scenarios. As the required data from local farmers was unable to be captured, the agent typology defined in this model will be based on previous typology research. Using the farmer characteristics described in *Table 5,* an agent typology is constructed with three different farmer types to be deployed in the model.

'Traditional' farmers are full-time owners of small to medium-sized farms. They only operate on land that they own - no rented land. As farming is their primary occupation, they depend almost entirely on income generated by the farm business. Most farmers within this group prefer to keep farming and are more likely to have a successor to the farm business. They are generally against farm expansion and while financially motivated, they also place value in preserving a conventional lifestyle. These agents prefer not to participate in agri-environmental schemes as they are discouraged by the initial investment in converting to different farm practices. However, if the payoff from policy payments reaches a certain threshold or conventional farming does not generate enough income they may participate in environmental schemes.

'Supplementary' farmers generally operate medium-sized farmers and have substantial off-farm incomes. They represent part-time or retired farmers and because of these off-farm earnings aren't solely dependent on income generated from the farm business. These factors significantly affect their policy adoption decisions, especially when compared with traditional and commercial farmer agents. Supplementary farmers are more in favour of adopting environmental schemes as they are less concerned with the profitability of the farm; they have a lower threshold than traditional agents for making policy decisions.

'Commercial' farmers operate large farm businesses and usually rent some portion of their land. Like traditional agents, they are fully dependent on income from farming since it represents their primary occupation and source of earnings. Commercial agents tend to focus more on the profitability and economic viability of their farm business. As a result, land-use decisions are solely based on the profit maximising land-use option. They are willing to adopt environmental schemes if the financial pay-out is greater than the income they currently generate on that land.

The model allows the user to select the initial number of farmers to introduce into the simulation. From this, they can define the percentage of farmers that belong to either the traditional, supplementary or commercial farmer types. Incorporating this agent typology into the model ensures the impacts of policy intervention of land use is better assessed. Gaining a greater knowledge of farmer types in Northern Ireland would allow this typology to be improved to serve more accurately in assessing land-use impacts.

	Traditional	Supplementary	Commercial
Land tenure	Full owner	Full/Part-owner	Part-owner
Farm Size	Small/Medium	Medium	Large
Source of Income	On-farm	Off-farm	On-farm
Social Networks	Moderately connected	Least connected	Highley connected
Farm Expansion	Low	Medium/Low	High
Participation in environmental schemes	Low	Medium/High	Medium

Table 5. Characteristics of different farmer groups based on Daloglu (2014) [61]

4.2.3 Farmer Agents

Once the initial number of agents and the portion of agents that belong to each farmer group (traditional, supplementary, commercial) is defined by the user, the model creates and introduces them into the simulation. Any land cover classified as agriculture is specified as belonging to 'nobody' in preparation for the land allocation process that randomly distributes the farmer agents and assigns them a random number of patches. Patches represent the fields owned by the farmer agents. Each field is assigned two variables that detail the farmer group the owner belongs to and the specific id that uniquely defines the farm owner. The land allocation process is the same for each of the three agent groups.

Before a model run, all agents are assigned several socio-economic attributes such as age, income, business type (e.g., dairy, arable, poultry), production type (medium, large) as well as attributes relating to the farmer/farm life cycle. These attributes are static and don't update at each time step. The values associated with each of the attributes influence the decisions of the agents when considering policy scenarios that result in land-use conversions.

4.2.4 Decision-Making Process

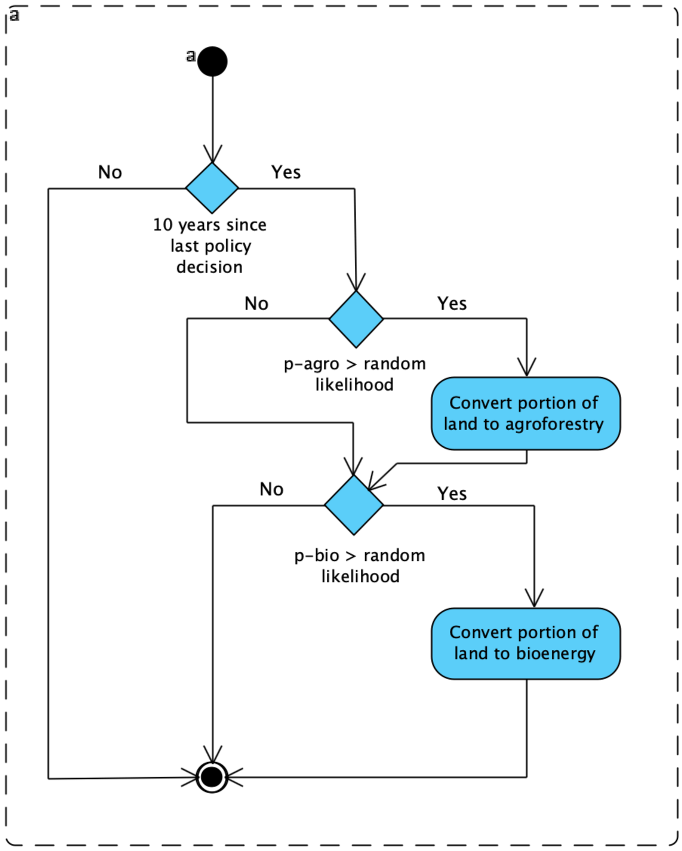

Figure 19. Activity diagram for the decision-making process

Any action or decision within the model is made entirely by the farmer agents. The main process agents make decisions on is whether to adopt different policy schemes. The user can select a probability between 0 and 1 that represents the willingness of each farmer group to participate in either of the two policy scenarios. Agents belonging to different farmer groups -traditional, supplementary or commercial- therefore have different likelihoods that determine if they participate in the policy scenarios.

To simulate diversity in the decision-making of agents within the same farmer group, a random probability is assigned to each farmer agent. This value is evaluated against the willingness value of the group the agent is associated with. While the willingness value is initially set at a specific value in the interface it is subject to change as internal and external decisions influence the farmers' decision to partake in the schemes. The random probability number represents the threshold at which agents participate in the schemes. Depending on the threshold values between agents, different numbers lead to different decisions on policy scenarios. For example, if the random number for one traditional agent, t1 is 0.20, 0.60 for another traditional agent, t2, and the willingness value of the group set to 0.4, t1 will participate in the policy whereas t2 will not.

Decision-making within the model is therefore determined through a probabilistic approach. The outcome of the example is determined by comparing the numbers, if the willingness value is greater than the random number assigned to individual agents, the agent participates in the policy. In the case that this is true for both schemes the farmer agent will adopt both.

The contract length of the schemes is 10 years which is typical for schemes of this nature. Once an agent decides to adopt a policy, they cannot make another policy decision until 10 years have passed. The agents are assigned a random number between 1 and 10 before the model run that represents the years since they last adopted an environmental scheme. This prevents the agents from making land-use decisions at the same time. Once this random number is greater than or equal to 10, agents are free to make policy decisions provided all the other conditions are met.

Once these conditions are satisfied the agent is said to have adopted the policy and a percentage of their land is converted to either agroforestry or bioenergy crops. The land-use map is updated to reflect this land-use change. After the farmer agents have assessed their conditions for policy adoption, the variables relating to the farmer are updated. If they decided to participate in a scheme the willingness value associated with that policy scenario is reduced, as after another 10 years they are less likely to place more land under the same scheme. In contrast, depending on the conditions of the other scheme, it may become slightly more attractive to the farmer agent, so the willingness value is increased by a small amount. Other variables associated with the age of the farmer and the years since their last decision are incremented by one.

The farms whose agents have reached the end of their farming life cycle through death or retirement are inherited by a successor. However, if a successor is not found the farm is sold. The implementation of succession and the method of selling a farm is explained in greater depth in *Section 4.2.5*. After the completion of these conditions, one time step in the model is concluded. The model is run repeatedly for 30-time steps in which each time step represents 1 year. The timeframe for the model is 30 years between the years 2020 and 2050. 2050 represents the year the UK expects to achieve net-zero emissions so any agri-environmental policy should aim to take effect by this time. Once the time step limit is reached the simulation is halted and the outputs of the model are reported which include changes in land use, the financial impact of policy intervention and the total reductions in GHG emissions

4.2.5 Succession

The model incorporates the dynamics of succession within the model. The succession process is instigated when the current farm owner either retires or dies. The user can choose the average age at which these occur. They can also select a value between 0 and 1 that determines the number of farmers that retire and the number of farmers with successors chosen. Once the farmer agent reaches these stages in the life cycle the transition of the farm to the successor is completed. However, if the farmer has no successor in place by this stage there is a process through which the farm is sold. The model only considers the sale of farms to existing farmer agents.

If the farmer agent selects the successor that inherits the farm, it is assumed the new farm head shares similar ideas and will operate the farm in a similar manner to the previous owner. The existing farm agents age is reset, and the takeover of the farm is complete. All other farm/farmer attributes remain the same; there is no significant change in the decisions made by the new owner compared with the previous owner. Internal and external influences will have the same impact on the new farm owner’s decision to partake in policy scenarios.

If the farm takeover is not completed by a chosen successor the farm is sold. The process of selling a farm considers many factors before deciding on the existing farmer agent that acquires the land for sale. If land is available only those agents close to the farm can purchase it. This is based on the assumption that farmers wishing to expand their business generally look to acquire land that is as close as possible to the land they already own. Agents with farms larger than that for sale are also considered to be more likely to purchase any farms for sale within a certain proximity. This assumes that larger farms generate more earnings and are better placed to expand their business. Other factors that increase the likelihood of an agent purchasing more land is the age of the farmer, the group the farmer belongs to and the amount of savings the farmer has in the bank. Younger farmers are more ambitious and as a result more willing to consider expanding the farm. Also, agents within the commercial group are most likely to be interested in acquiring more land. Supplementary agents are next most likely with traditional farmers least willing to expand their business. The interface provides users with the ability to select the average savings of the farmer agents. This value follows a normal distribution and agents with higher savings are considered to be more likely to purchase land. Each of these 5 factors is assigned a numerical value with factors considered to be of greater importance in the buying process attributed a higher value. A random value is also used to incorporate stochasticity into the buying process. The more of these factors the interested farmer agent meets the higher buyer total value they will attain. The agent with the highest buyer total value acquires the land for sale. The previous agent is removed from the simulation and the information associated with the field ownership is updated with the buyer's details. The farmer agents' details are also updated to reflect the increase in the farm size through the acquisition of the new farmland.

This represents the process of how farms without successors are sold within the model. The new landowner also provides the opportunity for a shift in the decision-making process that impacts land use. The farmer agent may belong to a different group from the previous owner and may have different willingness values and thresholds that affect policy adoption. Incorporating succession within the model, therefore, represents a process through which land use is impacted differently depending on input parameters and the randomness involved with the sale of farms. The succession process also enables a more realistic simulation as farm cessation and expansion are prominent in real-world agriculture systems.

4.2.6 Environmental Education

This process is another example of an internal agent factor within the model that influences the decision of the farmer agents on whether to adopt policy scenarios. It enables policymakers to analyse the effects of educating the farming population about the impacts of agriculture on the environment. The user can select the percentage of farmer agents that are educated and aware of environmental issues. Agents with environmental education have a higher willingness value that increases the likelihood of participating in the schemes.

The environmental awareness process alters the willingness value initially assigned to each agent depending on which group they belong to – different value for different groups. The increase from this process may push the willingness value above the threshold for policy adoption and therefore represents an important internal factor that influences decision-making.

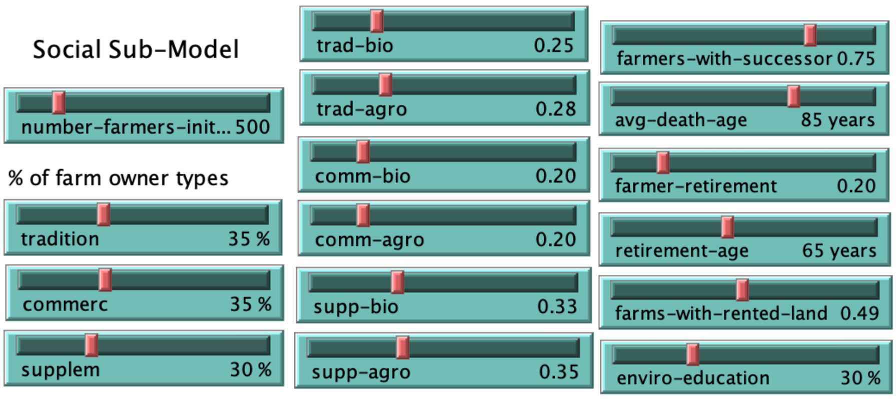

Figure 20. Interface components relating to the Social Model

Interface Component	Function
Number-farmers-initial	Sets the number of farmer agents to be introduced into the simulation
Tradition	Sets the percentage of farmer agents that belong to the traditionalists
Commerc	Sets the percentage of farmer agents that belong to the commercials
Supplem	Sets the percentage of farmer agents that belong to the supplementaries
Trad-bio	Value that determines the likelihood traditionalists adopt the bioenergy policy
Trad-agro	Value that determines the likelihood traditionalists adopt the agroforestry policy
Comm-bio	Value that determines the likelihood commercials adopt the bioenergy policy
Comm-agro	Value that determines the likelihood commercials adopt the agroforestry policy
Supp-bio	Value that determines the likelihood supplementaries adopt the bioenergy policy
Supp-agro	Value that determines the likelihood supplementaries adopt the agroforestry policy
Farmers-with-successors	Sets the number of farmer agents with successors to inherit the farm
Avg-death-age	Sets the average life expectancy of the farmer agents
Farmer-retirement	Sets the number of farmer agents that will retire
Retirement-age	Sets the age at which farmer agents will retire
Farms-with-rented-land	Sets the number of farms with rented land
Enviro-education	Sets the percentage of farmers who are educated about the environmental impacts of farming

Table 6. Functions of the interface components within the Social Model

4.3 Economic Model

The economic model introduces external factors that affect the agent's decisions by changing the likelihood that they participate in the policy scenarios. The model introduced two policies that encourage farmers to adopt sustainable practices that mitigate GHG emissions. Policies are imposed with varying payment rates to provide a range of land-use outcomes based on the policy pay-out. This section considers the design of the two schemes, how they are introduced into the model and how they affect the farming groups differently.

4.3.1 Design

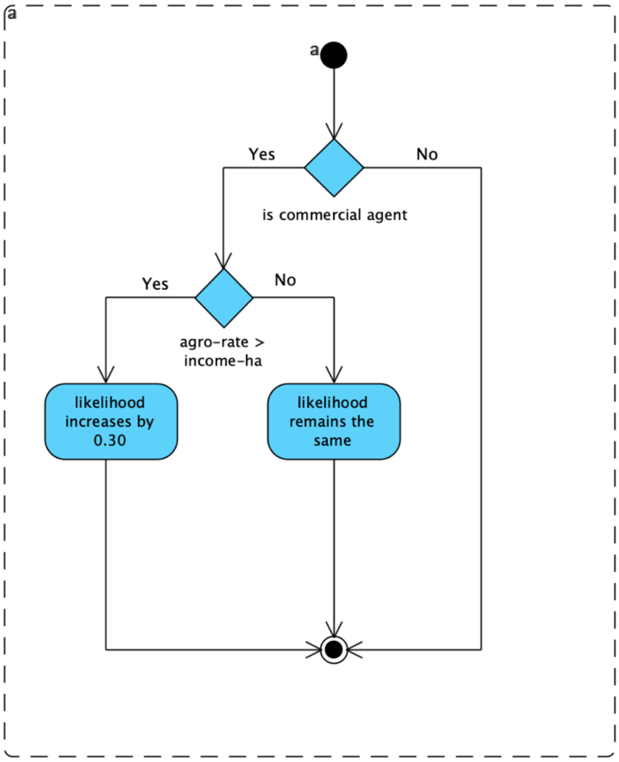

Figure 21. Activity diagram for the Economic Model

4.3.2 Policy Scenarios

The model is an exploration of the impact of agri-environmental policies on land use in Northern Ireland. Policy analysis will focus solely on scenarios that mitigate GHG emissions and increase carbon sequestration. The design approach for the policies introduced is accredited to a report on 'Reducing emissions in Northern Ireland' by the Committee on Climate Change published in February 2019. They outline scenarios that have significant potential for land-use changes in Northern Ireland. The two scenarios most appropriate to the objectives of this project were:

- **High biomass/natural peatland**: Agricultural land released through higher agricultural productivity and some changes in behaviour on diets and food waste. Focus on high tree and bioenergy crops planting rates and productivity and peatland restoration [5].
- **Multi-functional land use**: Medium levels of ambition on innovation and behaviour to release agricultural land for other uses. High levels of hedgerows and trees on farms and areas of afforestation leading to a more diverse agricultural landscape [5].

These scenarios are simplified in the model implementation and only contain aspects that have a direct impact on land use. The first scenario will focus on sequestrating carbon through bioenergy crop planting. The second scenario will introduce agroforestry as a policy option that is targeted at reducing GHG emissions. These scenarios will provide the farmer agents with incentives to adopt these carbon sequestration measures.

4.3.3 Implementation

The interface allows the user to select which policy scenarios to run the simulation with. The model can simulate the impacts of both the bioenergy and agroforestry policies on land use. The simulation can also be run with only one policy or none of the policies. In the case that the impacts of one or both policies aren't being simulated, a base scenario is run. The base scenario is intended to represent changes in land use in the absence of policy intervention. It uses current agroforestry and bioenergy planting rate data and updates land use at each time step based on this information.

The introduction of policy scenarios and the subsequent land-use changes are the result of decisions made by individual farmer agents. The agroforestry and bioenergy policies can be introduced at varying payment rates chosen by the user. The two interface sliders allow these rates to be adjusted; the payment rates are measured in hectares per year. The user can also adjust the average net income of the farmer agents depending on their farm business type. Income was chosen as it represents a good metric for gauging the profitability of a farm business.

The incomes of agents are important economic attributes used to calculate the net income per hectare which is used for comparison with the policy payment rate. If the payment rate reaches a certain level the farmer agents' likelihood to adopt a policy scheme increases. At this payment level, the policy is seen to be economically viable and more profitable than the agent's current enterprise. From this, greater land-use changes are expected as the payment rate has incentivised a significant portion of agents.

The threshold for when this increased likelihood occurs depends on the farmer group the agent belongs to. For commercial agents, if the rate is greater than their current income per hectare that are immediately more likely to adopt the policy. Since they are financially motivated when the policy becomes a viable enterprise, they are more willing to convert part of their land to the schemes. Supplementary farmers will increase their likelihood of policy adoption by only a small amount if the payment rate is greater than their net income per hectare; this reflects their lack of dependence on income generated by the farm business. Despite their dependence on earnings from the farm, traditional agents are modelled to only increase their likelihood of policy adoption if the payment rate is double their income per hectare. This process reflects the traditionalists' resistance to change with a significantly higher payment rate required to cover the initial investment to convert land to agroforestry or bioenergy crops.

Policy payments rates for the agroforestry and bioenergy scenarios represent external factors that can be directly influenced by policymakers. Changing the payment rate provides varying degrees of incentivisation that agents within each farmer group respond to differently.

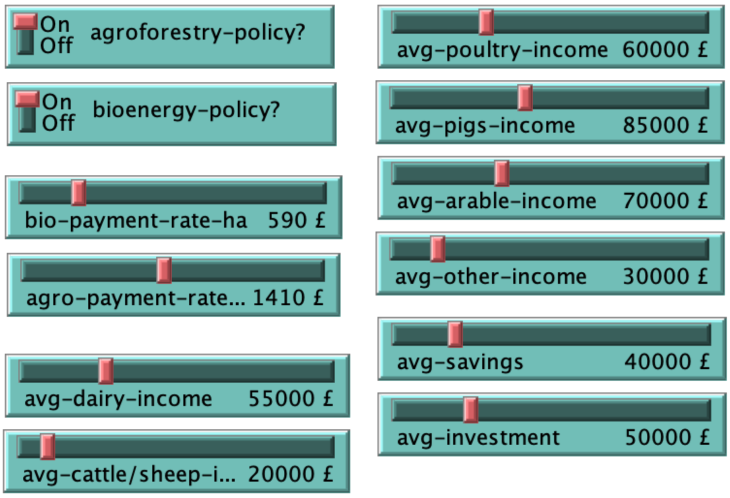

Figure 22. Interface components relating to the Economic Model

Interface Component	Function
Agroforestry-policy?	This switch allows the user to run the simulation with or without the agroforestry policy
Bioenergy-policy?	This switch allows the user to run the simulation with or without the bioenergy policy
Bio-payment-rate-ha	Sets the payment rate per hectare for the bioenergy policy
Agro-payment-rate-ha	Sets the payment rate per hectare for the agroforestry policy
Avg-cattle/sheep-income	Sets the average income for cattle and/or sheep farmers
Avg-poultry-income	Sets the average income for poultry farmers
Avg-dairy-income	Sets the average income for dairy farmers
Avg-pigs-income	Sets the average income for pig farmers
Avg-arable-income	Sets the average income for arable farmers
Avg-other-income	Sets the average income for other farmers
Avg-savings	Sets the average farmer savings
Avg-investment	Sets the average farmer investment

Table 7. Functions of the interface components within the Economic Model

4.4 Ecological Model

The climate change outputs that result from policy intervention is another focus of the model. The land use converted to agroforestry and bioenergy crops sequestrates carbon in the soil. From this, emissions can be monitored over a model run and the total GHG reductions can be calculated. Users can then evaluate if policy intervention achieved the desired climate targets defined before running the simulation.

4.4.1 Design

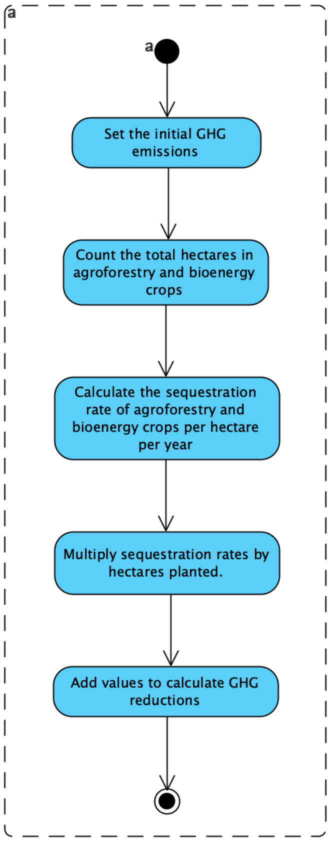

Figure 23. Activity diagram for the Ecological Model

4.4.2 Implementation

The interface provides users with the ability to adjust several environmental parameters relating to agroforestry and bioenergy policies. The inputs these parameters provide along with the total hectares of land in agri-environmental schemes are used to calculate the carbon dioxide sequestrated at each time step.

The first two parameters in *Table 8* relate to the agroforestry policy. Users can select the planting density of trees per hectare; values range from 0 to 300 trees planted on agricultural land per hectare. Next users adjust the sequestration rate of one tree depending on the species planted. The multiplication of the number of trees per hectare and the sequestration rate of one tree is used to calculate the sequestration rate of agroforestry per hectare measured in MtCO2e (million tonnes of carbon dioxide equivalent). Multiplying this sequestration rate per hectare by the total hectares in agroforestry at each time step gives the total carbon dioxide sequestrated by the agroforestry policy per year.

The remaining parameters in *Table 8* relate to the bioenergy policy where the percentage of bioenergy crops planted as either miscanthus or short rotation coppice willow is first defined by the user. Next, the sequestration rates of miscanthus and willow per hectare are defined. The multiplication of the total hectares planted in either bioenergy crop by their sequestration rate is used to calculate the total carbon dioxide sequestrated by miscanthus and willow crops. Adding these values gives the total carbon dioxide sequestrated by the bioenergy policy at each time step.

Finally, to calculate the GHG reductions at each time step, the carbon sequestrated by the bioenergy and agroforestry policy is summed. This value is plotted against the initial GHG emitted by the agriculture sector. From this, users can visualise the impacts of policy intervention in mitigating climate change.

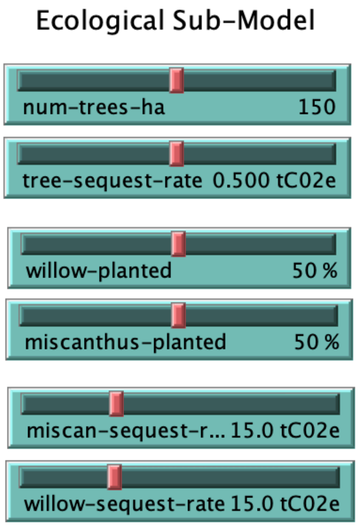

Figure 24. Interface components relating to the Ecological Model

Interface Component	Function
Num-trees-ha	Sets the planting density of trees per hectare of agroforestry
Tree-sequest-rate	Sets the sequestration rate of one tree. Value depends on the tree species planted
Willow-planted	Sets the percentage of bioenergy crops planted as SRC willow
Miscanthus-planted	Sets the percentage of bioenergy crops planted as miscanthus
Miscan-sequest-rate	Sets the sequestration rate of miscanthus per hectare per year
Willow-sequest-rate	Sets the sequestration rate of SRC willow per hectare per year

Table 8. Functions of the interface components within the Ecological Model

4.5 Network Model

The network model introduces another external factor that influences agents land-use decisions by changing the likelihood they adopt the agroforestry and bioenergy schemes. The social interactions of farmers in real-world agriculture systems can have significant impacts on an individual farmers decisions and actions. Incorporating social networks into the model, therefore, enables a more realistic examination of how the interaction between internal and external factors influence the wider land-use changes that occur. This section considers the design approach of the social network and how it is implemented within the model to influence policy decisions.

4.5.1 Design

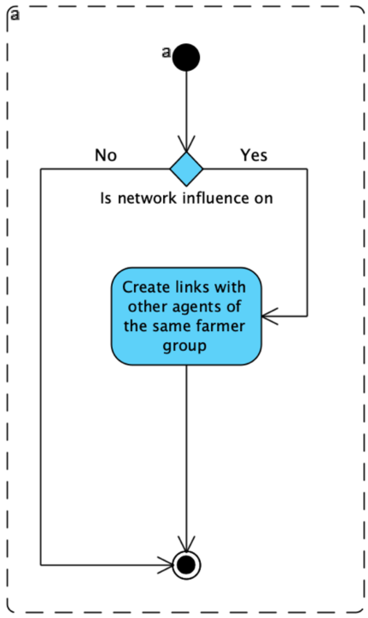

Figure 25. Activity diagram for the Network Model

4.5.2 Implementation

The simulation can be run with or without the influence of social networks. This must be defined before any model run and as a result, social networks cannot be introduced partway through a model run. The reason for implementing this feature was to allow users to examine the impacts of agent's social interactions on policy adoption rates. This can be achieved by first running the model without social networks and then by running the model with social networks turned on. The differences in model outputs observed between the two runs will provide an understanding of the impacts of social networks.

When introduced into the model the conditions relating to farmer agents' social networks can be adjusted. To reflect the different agent groups and their different social interactions as defined in the agent typology, three separate social networks are implemented within the model. The networks consist of a series of links and farmer agents can only interact with agents of the same group. The three sliders can be adjusted to define the number of neighbours in the commercial, traditional and supplementary agent's social network. The networks can be varied to consist of between 1 and 10 neighbour agents. Selecting the number of neighbours in the slider, 4 for example, mean each farmer agent within that group has 4 links to other agents of the same group. This represents the social network that influences the farmer agents.

The links that comprise the social networks are dynamic in that they experience change. Farms without successors are sold and the farm owners are removed from the simulation. Any links associated with the farmer agent are also removed. This reduces the social networks of the farmer agents that were linked with the agent. Farmers whose chosen successor inherit the farm retain the same social connections and the networks remain intact.

The extent to which the farmer agents are influenced by their respective social networks can be adjusted using the *neighbour-influence* slider. The value selected increases the agent's willingness to participate in the policy scenarios. This influence value is only applied when the farmer agents have more than 1 neighbour within their network participating in either scheme. The number of neighbours participating in the agroforestry and bioenergy schemes is determined for each farmer agent at each time step. Farmer agents are therefore influenced by the policy decisions made by agents within their social network and increase their likelihood for land-use changes to reflect this.

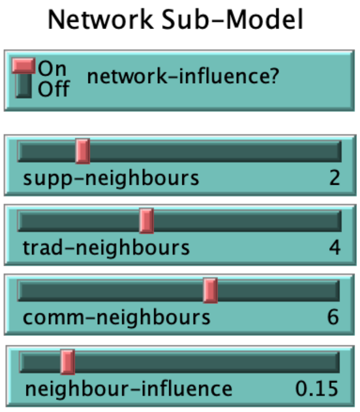

Figure 26. Interface components relating to the Network Model

Interface Component	Function
Network-influence?	This switch allows the user to run the simulation with or without social networks
Supp-neighbours	Sets the number of links in each supplementary farmers' social network
Trad-neighbours	Sets the number of links in each traditional farmers' social network
Comm-neighbours	Sets the number of links in each commercial farmers' social network
Neighbour-influence	A value between 0 and 1 that determines the extent each farmer agent is affected by other agents

Table 9. Functions of the interface components within the Network Model

4.6 Model Outputs

The main outputs of the simulation after a single model run are the total hectares in agroforestry and bioenergy schemes, the total costs related to introducing both policy scenarios and the reductions in greenhouse gas emissions as a result of agri-environmental policy intervention. These outputs are plotted using 4 graphs that allow users to easily visualise the results of the simulation.

The two graphs in *Figure 27* plot the total hectares of agroforestry and bioenergy crops planted by the commercial, traditional and supplementary farmer agent groups over 30 years. It is calculated by counting the patches with land cover in bioenergy crops and agroforestry that belong to each of the three agent types. The total patches are multiplied by 50, 1 patch is equal to 50 hectares, to give the total hectares under bioenergy and agroforestry schemes for commercial, traditional and supplementary agents. These values are updated at each time step to reflect the land-use changes made each year. The graph is updated with each time step and the value is plotted repeatedly until the model halts.

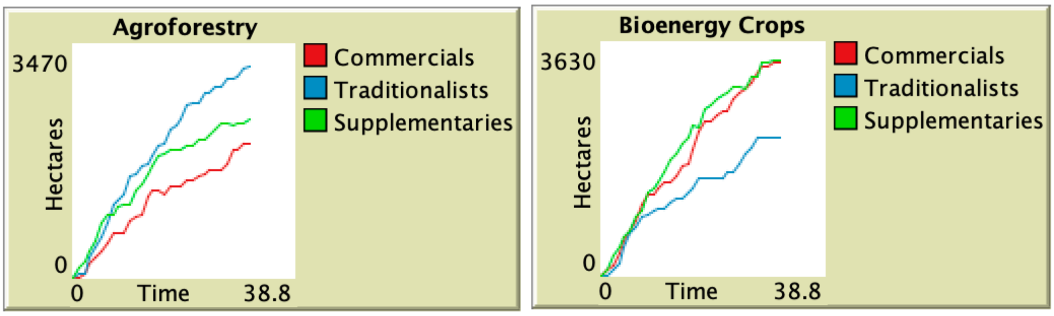

Figure 27. Graphs plotting total hectares in environmental schemes

Figure 28 plots the total GHG emissions at each time step of the simulation. The reduction in emissions is a result of carbon dioxide sequestrated by the policy scenarios. The value is calculated by subtracting the initial GHG emissions by the GHG reductions from land-use changes. This calculation is made at each time step while the model is running. The initial GHG emissions are gathered from emission data for Northern Ireland measured in 2020. It shows the agriculture sector emits around 8 MtC02e (million tonnes of carbon dioxide equivalent). The process of how the values for GHG reductions are calculated is detailed in *Section 4.4.*

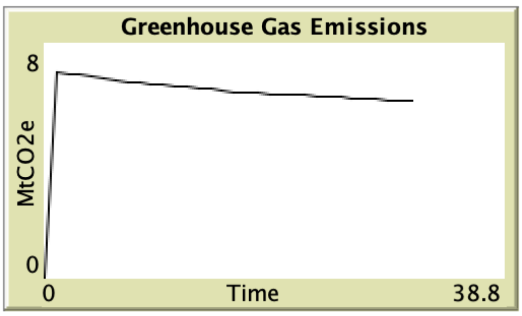

Figure 28. Graph plotting GHG emissions

Figure 29 plots the financial costs involved in introducing the agroforestry and bioenergy schemes. Two separate lines calculate the specific costs of either policy scenario. The value is calculated by multiplying the policy payment rate defined in the interface by the total hectares in agroforestry and bioenergy schemes. Over the course of a model run, the plot is updated to reflect changes in the cost value as a result of land-use changes made at each time step.

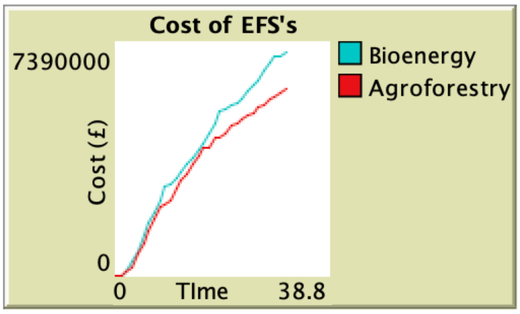

Figure 29. Graph plotting the cost of the policy scenarios

The model interface also provides users with the option to save the model results to an output file. The user specifies the location where they wish to save the output file using the '*Choose* File' button. The save file location is placed in the *plotfile* box for a final review before saving the output using the '*Export Output'* button. The results are saved as a graph in jpeg format; the R extension is used to achieve this. It uses two lists that contain the total hectares of agroforestry and bioenergy crops planted at each time step. This represents the plot data that the R extension will utilise. This particular output data was chosen for graphical representation in R because the land-use change as a result of policy intervention is the main focus of the model. R assigns the plot data to the attributes 'xs1' and 'xs2' and plots two lines that represent the total land converted to agroforestry and bioenergy crops. An example of the graphical output using the R extension can be seen in *Figure 31*.

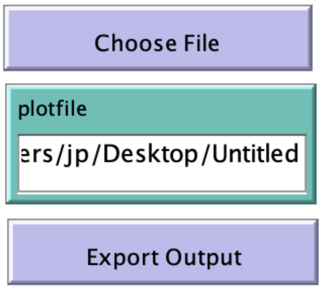

Figure 30. Export model output Using R Extension

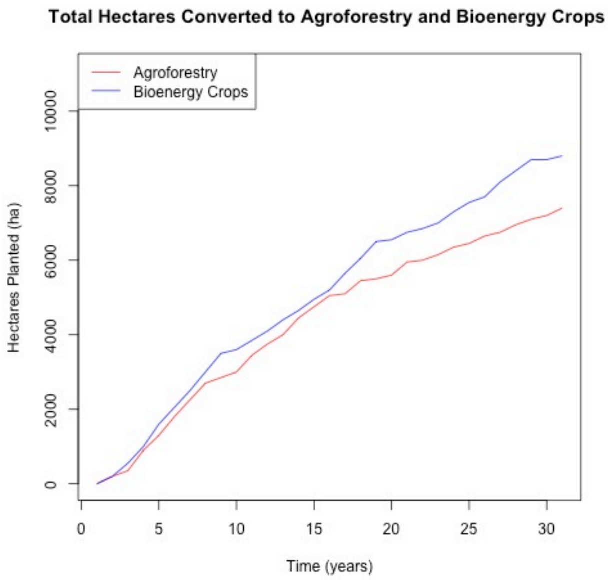

Figure 31. Graph of land-use changes

4.7 Other Interface Components

The model interface contains several other options and methods that the user can interact with. This includes different options for running the simulation and several features that interact with the spatial environment. The model run options allow the simulation to run repeatedly until it halts after 30 ticks using to '*Go'* button. The simulation can also be advanced a single tick by pressing the '*Single Step'* button.

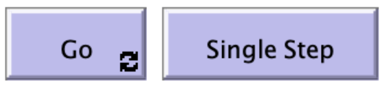

Figure 32. Model run options

The view farmers and links button in *Figure 33* when pressed allow the user to see the location of the farmer agents and the links that exist between the agents. The farmers are represented by a dot shape and are coloured white if they belong to the traditional group, black if they belong to the commercial group and pink if they belong to the supplementary agent type. Since three separate social networks were implemented between the different agent types pressing the buttons allows users to visualise the individual networks. The networks consist of links and are orange for commercial networks, yellow for traditional networks and blue for supplementary networks.

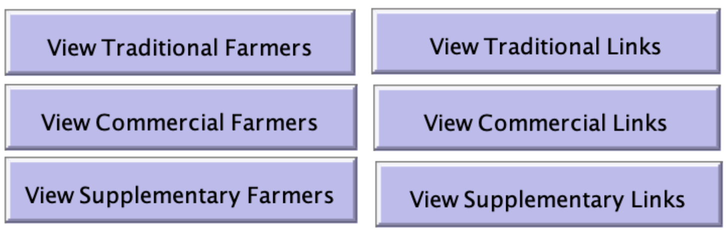

Figure 33. Buttons to view agents and links of different farmer types

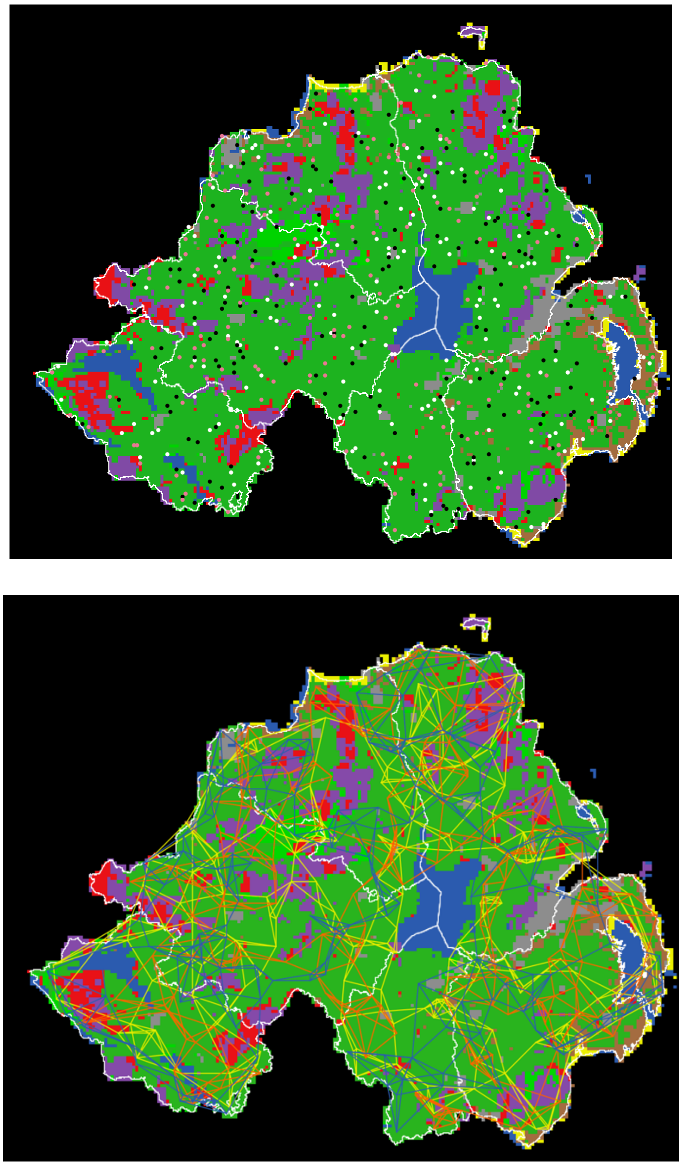

Figure 34. Location and social networks of farmer agents

The ‘*Get Information’* button allows users to mouse-click anywhere on the land-use map. When pressed, the county boundaries the mouse-click was within and the number of farms with land in that specific county will be outputted in the two monitors. The other monitors measure the number of farms in environmental schemes and the amount of land belonging to each farmer agent type.

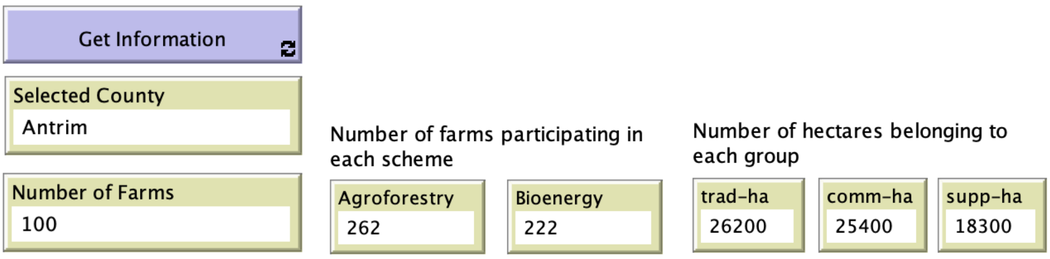

Figure 35. Monitors that measure various aspects of the farmer agents

5 Model Experimentation and Results

Having implemented the conceptual model design the model can now be experimented with. Using NetLogo's BehaviorSpace several smaller experiments were first performed to validate the model, the details and results of which are detailed in *Section 5.1*. After confirming the results validate the model implementation, a larger, more complex experiment was performed to illustrate how the model could potentially be utilised to reinforce policy design. In *Section 5.2* the experiment setup is described with the results presented in *Section 5.3.*

5.1 Model Validation

Validation is the process of ensuring the implemented model performs as expected and conforms to the design objectives initially outlined. The process of validating the model implemented in this project began with hypothesizing several simple experiments. The experiments were designed to vary a single parameter while fixing the other parameters. This micro perspective allows individual results to be collected and analysed to verify that the model functions per its design. The experiments were designed using NetLogo's BehaviorSpace which is a tool integrated within the software framework that facilitates this experimentation. The datasets generated from the model runs are represented graphically to better understand the relationships between different input parameters and the behaviour of the system.

Experiments were performed to validate the function of the social, economic, ecological and network models separately. The spatial model is exempt from experimentation as there are no input parameters to sweep. Only parameters that directly influence the model outputs are considered for experimentation.

Figure 36 is an example of one of the experiments run for the ecological model. The input parameter that was varied in the experiment was *num-trees-ha;* the remaining ecological parameters and all other input parameters were fixed. Through increasing the number of trees per hectare the greenhouse gas emissions should decrease- this is the expected model result. *Figure 36* represents the actual result after running the experiment. The result proves the initial hypothesis, and this parameter is therefore considered to be functioning correctly.

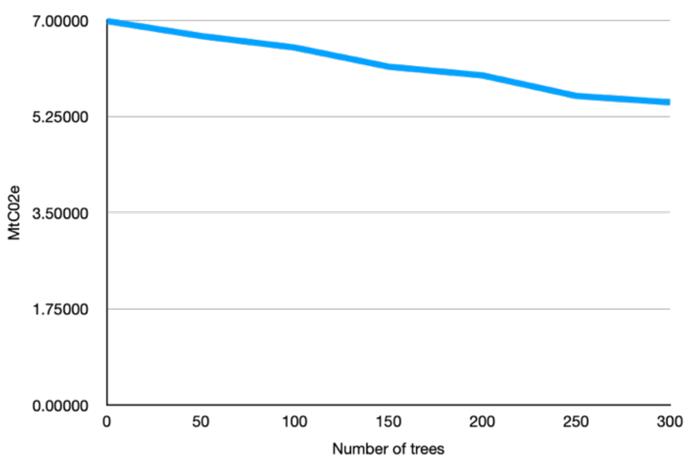

Figure 36. Ecological Model Experiment

Figure 37 is an example of an experiment designed to validate the network model. The experiment is created to run the simulation with the *network-influence?* switch turned off and then run again with the switch turned on. This evaluates the impact of social networks on the agent's decision-making. Social networks were designed to influence the farmer agents' policy decisions and should increase the total hectares of agroforestry and bioenergy crops planted. *Figure 37* supports this, showing simulations with network influence have a significantly larger impact on the total hectares planted. This experiment can therefore be considered successful in validating the implementation of social networks within the model.

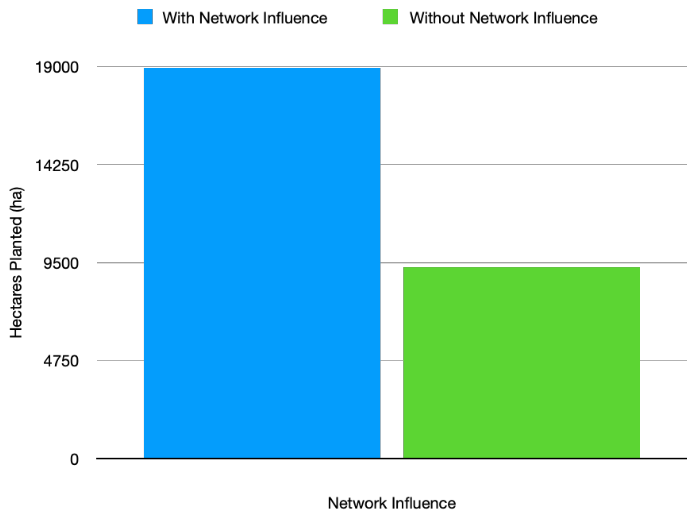

Figure 37. Network Model Experiment

Figure 38 demonstrates an experiment performed using the BehaviorSpace to validate one of the processes within the social model. The parameter *enviro-education* is given a range of values to be swept which help to determine the behaviour of this model process to ensure it functions as expected. In general, increasing environmental awareness in farmers should increase the number of hectares in agroforestry and bioenergy schemes. The results of the simulation are plotted in *Figure 38* and confirm that the initial hypothesis is correct. The environmental education method is now validated as it functions as expected.

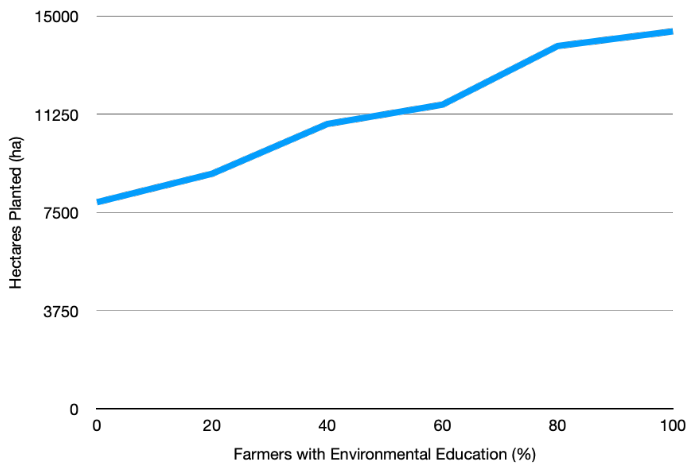

Figure 38. Social Model Experiment

Figure 39 displays the results of an experiment run within the economic model used to validate an aspect of its overall function. The payment rate per hectare for the agroforestry scheme is compared with the total hectares planted. Increasing the payment rate should increase the number of hectares converted to agroforestry. *Figure 39* proves this overall trend but also shows as the payment rate increases further the increase in hectares planted starts to slow down. The process is still validated however as these results aren't necessarily wrong and instead demonstrate emergent behaviour within the system.

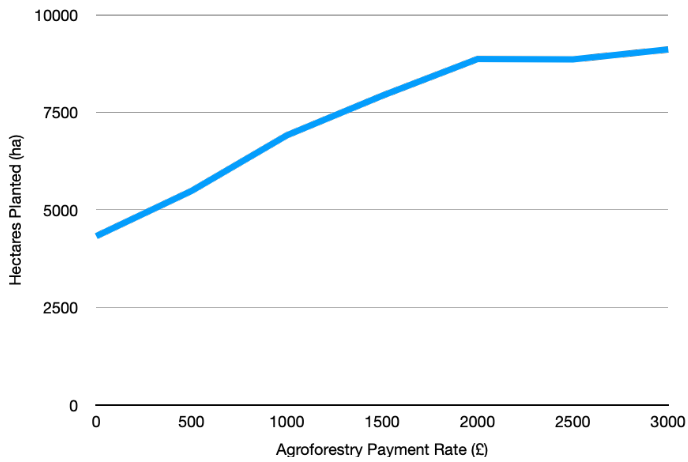

Figure 39. Economic Model Experiment

5.2 Example Experiment

Following the completion of the initial experiments used to validate the model, a larger experiment was run to demonstrate the potential of the model and how it is intended to be used. The validation experiments captured any unintended simulation behaviours and adjustments were made to correct any errors. Although a more rigorous validation process is always a possibility the results of the initial experiments were successful enough to consider the model as functioning as intended. This section details the experiment setup, which parameters were fixed and why they were fixed at a specific value. *Section 5.3* will report the results of the experiment including the process of importing the results into R for data visualisation.

The purpose of the experiment was to find the optimal policy payment rates that have the largest impact on land use while keeping overall costs to a minimum. The parameters under study are *bio-payment-rate-ha* and *agro-payment-rate-ha*.

Tables for the network, social and economic models describe the parameters and the fixed initial values the experiment is run with. A brief explanation of why specific values for parameters were chosen is provided. Parameters for the spatial and ecological models are not detailed as inputs within these models have no direct impact on the outcome of the experiment.

The parameters for the network model are initially fixed at the following values:

Parameter	Value
network-influence?	On
supp-neighbours	2
trad-neighbours	4
comm-neighbours	6
neighbour-influence	0.15

Table 10. The parameters fixed within the Network Model and their values

For the experiment network influence is switched on because the effects of social networks and how agents are influenced by other agents is an important aspect of the model. The number of neighbours in each farmer groups social network is representative of the characteristics in *Table 5.* Supplementary farmers are the least connected and have the least number of neighbours in their social group; commercial agents are most connected and have the highest number of neighbours in their social group; traditional farmers are moderately connected and therefore have a neighbour value between the other groups. The *network-influence* value in *Table 10* was chosen relative to the other values that increase the likelihood of policy adoption.

The parameters in the social model are initially fixed at the following values:

Parameter	Value
number-farmers-initial	500
tradition	35
commerc	35
supplem	30
trad-bio	0.25
trad-agro	0.28
comm-bio	0.20
comm-agro	0.20
supp-bio	0.33
supp-agro	0.35
farmers-with-successor	0.75
avg-death-age	85
farmer-retirement	0.20
retirement-age	65
farms-with-rented-land	0.49
enviro-education	30

Table 11. The parameters fixed within the Social Model and their values

The value of 500 for the initial number of farmer agents was chosen mainly because of computation time. 500 was considered an acceptable number to test the functions of the model while keeping the experiment runtime at a minimum. The remaining parameter values in *Table 11* were adapted from research conducted by Rehman and Garforth (2008) [62]. Their research into modelling farmer behaviour in England produced the most relevant data to the input parameters of the model.

The parameters in the economic model are initially fixed at the following values:

Parameter	Value
agroforestry-policy?	on
bioenergy-policy?	on
avg-dairy-income	55000
avg-cattle/sheep-income	20000
avg-poultry-income	60000
avg-pigs-income	85000
avg-arable-income	70000
avg-other-income	30000
avg-savings	40000
avg-investment	50000

Table 12. The parameters fixed within the Economic Model and their values

The policy option switches are turned on as the experiment seeks to find the optimal payment rates for both the agroforestry and bioenergy scenarios. The remaining input values for the parameters in *Table 12* are taken from data provided by the Department of Agriculture, Environment and Rural Affairs Policy, Economics and Statistics Division. Their latest report on Farm Incomes in Northern Ireland for 2018/19 [63] provided the necessary input values for the model parameters.

5.3 Results

With the appropriate input parameter values selected the experiment can be created and run. *Table 13* shows the values set for the bioenergy and agroforestry rate parameters. The experiment was repeated 5 times to ensure the results are reliable and the integrity of the data is maintained. The variable *total-hectares* was measured during the run which represents the total hectares converted to agroforestry and bioenergy schemes.

The data plotted in *Figure 40* and *Figure 41* are the results of two separate experiments; one that measures runs at every step and one that only measures runs after they are complete. The experiments were both saved in table output format and imported into the R software for statistical analysis. *Table 13* details the summary statistics of the model experiment, *Figure 40* plots a summary graph of the model results and *Figure 41* plots a time-series graph of the data.

Figure 40 shows that increasing the payment rates doesn't always increase the total hectares planted as an increase from £2500 to £3000 reduces the total hectares planted. An Interesting result from *Figure 41* suggests that an increase from a payment rate of £1500 to £2000 produces the largest increase in hectares planted. A reasonable deduction from the graphs is that a rate of £2000 for both policies is the most optimal payment rate. Increasing the rate above £2000 seems to produce diminishing returns.

Agroforestry-rate	Bioenergy-rate	Mean	Std Dev
500	**500**	11870	1456.2795
1000	**1000**	13580	1279.4530
1500	**1500**	15940	2432.6940
2000	**2000**	18230	1389.5143
2500	**2500**	18900	1311.9642
3000	**3000**	16630	825.8329

Table 13. Summary statistics of the experiment

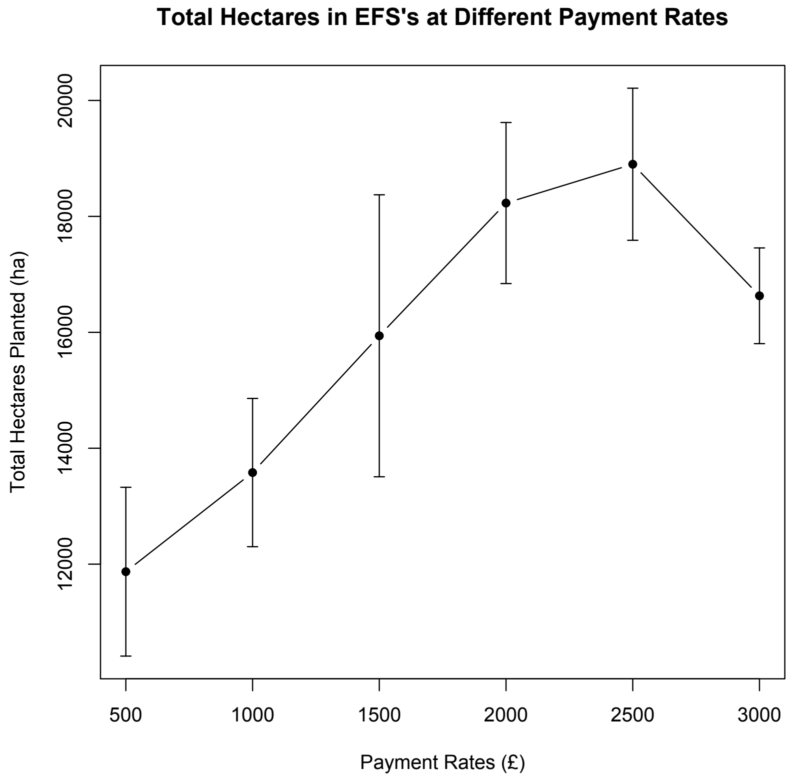

Figure 40. Total Hectares in EFS's at Different Payment Rates

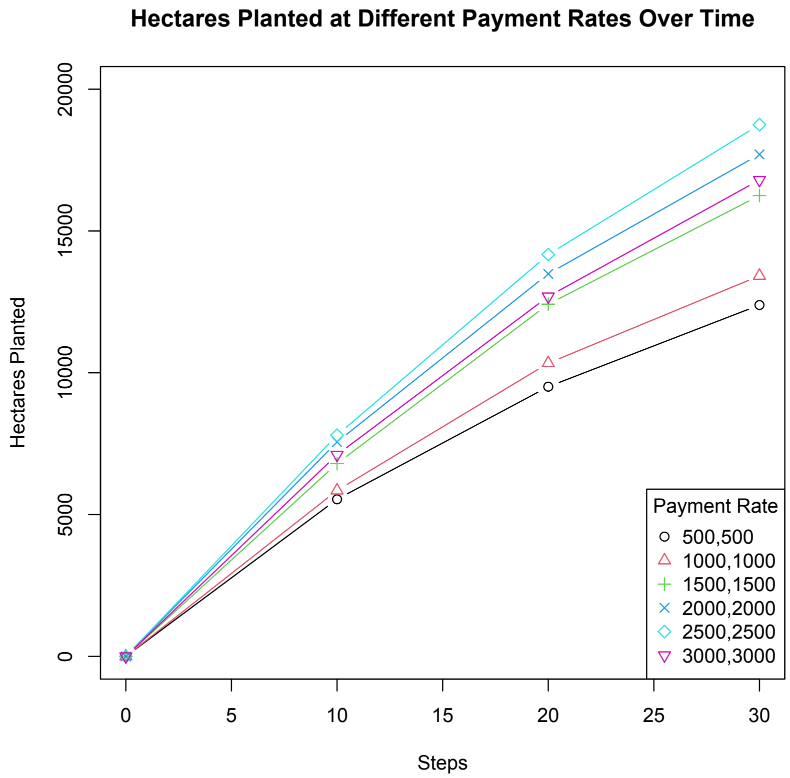

Figure 41. Total Hectares Planted at Different Payment Rates Over Time

6 User Evaluation

The user testing process was completed remotely by 5 different testers. Using the questionnaire in *Appendix 1*, each tester was instructed to complete several tasks with the model. After completing each task, they were to report how easy or difficult the task was. As feedback from policymakers was unable to be captured, the testing of the model was completed by fellow students.

The testers were split into three separate groups. The first group represented computing students with prior experience in NetLogo with the second group consisting of computing students with no experience with NetLogo. The third group was comprised of one student with no significant computing or NetLogo experience but was the only tester familiar with the study region being modelled. The groups were designed mainly to ascertain the usability of the model; also, to distinguish any differences depending on the level of experience or knowledge of the study area.

The general feedback obtained from testing was positive; the majority of problems highlighted were non-technical and focused on issues with the model interface.

The user guide was identified as being useful in assisting with setting up and running the model. Some testers, however, reported that the guide was underdeveloped or didn't make sense in places leading to confusion on some aspects of the model parameters. After testing was complete the guide was updated to correct these issues. The latest version of the user guide is provided in *Appendix 2*.

The headings used to separate parameters into the individual models was reported as being beneficial to the overall interface layout. Despite this, the majority of issues gathered from testing describe the interface as feeling cluttered. Initially, users felt overwhelmed with the many different options, input parameters and outputs, especially those in groups with no prior NetLogo experience. The proximity of interface components is said to have exacerbated the problem. This culminated in the users having to scroll side to side to access all the inputs and outputs of the model. While I recognise the validity of these concerns and ideally the problems could be solved, in practice this isn't achievable. The interface components are part of the NetLogo framework and will inevitably take up a set amount of space. Therefore, these issues represent the limitations of NetLogo and are not something I could change in any future model implementation.

Some users also experienced issues with the R extension when exporting outputs to an external file. This error is something I could not replicate when running the model and testing the export feature. After investigating I believe the error stems from how the user installed or configured the R extension on their machine. For future users, a link should be provided to NetLogo's documentation that describes how to properly install and configure the R extension.

Overall, the user testing process was successful in that the majority of users found the tasks to be easy or very easy. The testing groups showed no significant difference in task completion apart from users familiar with NetLogo completed the tasks in a shorter time. I attribute this to a concise user guide and the accessibility of the NetLogo environment.

7 Conclusion

7.1 Summary

Throughout the development of this project, the objectives outlined in *Chapter 1* have been achieved. Existing modelling techniques and tools were analysed, user requirements captured and described, and from this, a model was created which provides a reasonable exploration of the impacts of policy schemes on land use in Northern Ireland.

The final implemented model:

- Considers and applies existing land-use and agent-based research in its overall design architecture
- Effectively formalises the initial designs for the spatial, social, economic, ecological and network models using diagrams
- Imports county boundary data and a land-use map for Northern Ireland using the GIS extension. This provides the spatial environment on which farmer agents can make land-use decisions.
- Implements a decision-making process that allows individual farmer agents to make choices on agri-environmental policies.
- Introduces two policy schemes that focus on reducing GHG emissions through carbon sequestration. The agroforestry and bioenergy schemes can be introduced at varying payments rates.
- Monitors the outputs of the simulation through four separate plots. The plots display the GHG emission reductions, the total hectares in agroforestry and bioenergy schemes, and the financial cost of each scheme.
- Uses NetLogo's BehaviorSpace to validate the model and demonstrate how the model could be utilised as a tool to support policy design.
- Exports the results of the experiment for data visualisation in R which provides an accurate visualisation of how different policy scenarios impact land use in Northern Ireland.

7.2 Evaluation

As I had no prior experience with modelling complex systems, I feel satisfied with the skills, knowledge and experiences I have acquired throughout each phase of the project. I believe the model is successful from an implementation view. The model achieves the objectives outlined and functions as intended. The majority of the design criteria specified diagrammatically for each sub-model process features in the final model implementation. Although the outputs and results generated by the model are as expected, they lack the accuracy to be considered useful to future policy design. However, the final model proves that with more time, a greater knowledge of the system under study and additional data a powerful policy tool could be developed.

Throughout the research phase of the project, I gained a comprehensive understanding of Northern Ireland's agriculture sector, the potential issues Brexit poses and how policymakers are attempting to overcome these obstacles and address the criticisms of the current agricultural policy all within a new policy framework.

In designing a model to analyse the impact of policy intervention within this new framework I was introduced to the concept of agent-based modelling. I was able to establish a firm understanding of this modelling technique and how it is deployed with existing land-use research in solutions similar to the problem in this project. I was then able to utilise these agent-based and land-use change modelling concepts during the implementation of the model.

Implementation of the model in the NetLogo environment allowed me to gain experience programming with a new language. Before this project, I had no knowledge of NetLogo and through programming with it recognise it is very different to conventional languages I am familiar with such as java and python. However, the extensive documentation and online resources enabled me to quickly advance my knowledge and skills of the language. Following the completion of the model, I am now familiar with the programming aspects of the language and have enjoyed the overall learning experience.

Programming with the NetLogo language was also beneficial in that I had access to a plethora of tools called extensions that are bundled within the software framework. In particular, the two that were of initial interest and are utilised in the final model implementation are the GIS and R extension. The GIS extension provided the ability to load raster GIS data in the form of a land-use map into NetLogo. The R extension provided the primitives to use R for statistical analysis of model results. Altogether these extensions offered additional functionality to the existing model. Using GIS data to generate the landscape is more accurate than manually producing the spatial landscape. Using R for analysis was preferred over other software tools such as Excel as it contains many advanced functions and capabilities.

Following the initiation of the spatial landscape the two processes fundamental to the model's functionality was the decision-making process of farmers and the agri-environmental schemes they make decisions on. After finalising the final model and considering the objectives outlined in *Section 1.2,* I believe these methods to be successful in their implementation and overall function. The decision-making process presents individual farmers with decisions on different policy scenarios while influencing these decisions through internal and external processes. The model successfully deploys two environmental schemes with payment rates specified by the user. However, these methods both represent key areas of improvement in any future work. The details of specific improvements are discussed in *Section 7.3.*

Experimentation with the model using the BehaviorSpace was successful in both validating the model and demonstrating the model's use as a tool. Without these processes, it wouldn't be possible to prove the model implementation matches that of the model design and that the model functions in a way that is expected.

7.3 Future Work

Although all the objectives defined in S*ection 1.2* were implemented and function correctly in the final model, there is significant scope for improvements in the various sub-model processes. Further development of the model could be implemented by myself and also has the potential for continuation by future students. In any case, this section lists key areas of improvement in any extension of the current model.

An obvious first step to improving the model would be to utilise more detailed land-use datasets. If such datasets were obtainable, the spatial model could be adapted to handle the new land-use map. The detailed land-use map would most likely be stored as vector data. As the current land-use map used to generate the spatial landscape is in raster format the model would require updating to apply the vector land-use map.

The current process of distributing the farmer agents throughout the landscape and allocating each agent land is random and can be considered to be rather simple. Any further model development should recognise this as an area to improve. If data pertaining to the location of farmers throughout Northern Ireland was available, it could be utilised to accurately distribute the farmer agents. A more complex method of land allocation could be proposed to better reflect the farmland boundaries that exist in the real world. These improvements would produce more realistic land-use changes throughout the landscape.

The core process that enables the agents to make policy choices is the decision-making methods of the model. Any continuation of the model should prioritise developing these methods further. The decision-making process should be improved by enhancing the internal and external influences that determine policy adoption. These processes could also implement additional influence factors to better realise real-world agriculture systems.

Greater knowledge of agri-environmental policy design would benefit any further progression of the model. With this additional understanding, policies, more realistic to those considered for real-world implementation, could be introduced into the model. This would significantly increase the effectiveness of the model as a tool to support policy design.

The model would also benefit from interviewing local farmers to improve the defined agent typology. From this, agent behaviour could be modelled to more accurately reflect farmers throughout the region. This would provide policymakers with greater awareness of the factors that determine the adoption of different policy scenarios.

Other general model improvements include developing the agents' social networks further to match more closely those that exist in real-world agriculture systems. A more accurate process of measuring and calculating emission reductions could also be formulated.

Overall, there are several areas from which the model could be improved by myself or future computing students. Any students wishing to continue the model could reuse the majority of the sub-model methods, improving and adapting them to the specific requirements of their project.

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Appendix 1 – User Testing Questionnaire

Download the latest version of NetLogo here:
https://ccl.northwestern.edu/netlogo/download.shtml

Before performing any of the tasks please first read the 'Info' tab to familiarise yourself with the model. It will provide you with a brief overview of the model, how it works and how to begin running a simulation

Now you can begin with the tasks, please complete them in the order they are set and if you have any issues, please contact me either on teams or using my e-mail:
johnpoole329@gmail.com

After completing each task, please select how easy or difficult it was to complete the task. If you are unable to complete one of the tasks, please explain why in the comments box at the end. Feel free to leave any other questions or queries you may in the comments.

Your tasks are as follow:

- Generate the land-use map for Northern Ireland using any input parameters
- Report the colour and shape that represents the commercial farmers
- Report the colour of the links that exist between supplementary farmers
- Report the number of farms in County Antrim
- Set the likelihood that commercial farmers will respond to the bioenergy policy to 0.44
- Set the average life expectancy of the farmers to 90 years old
- Set the Agroforestry payment rate to £1000
- Set the Planting density of trees to 155 per hectare
- Set the number of traditional neighbours to 7
- Run the simulation for 2 ticks and confirm the graphs update with outputs
- Re-start the simulation and let it run until it stops
- Reset the simulation and run it again changing only the percentage of supplementary owners to 40%
- Export the results and confirm if a graph was exported to the space you specified

1) How easy was it to generate the land-use map?

1 (very difficult)	2	3	4	5 (very easy)

2) Colour and Shape:

3) Colour:

4) Number of Farms:

5) How easy was it to change the slider to 0.44?

1 (very difficult)	2	3	4	5 (very easy)

6) How easy was it to set the life expectancy to 90 years old?

1 (very difficult)	2	3	4	5 (very easy)

7) How easy was it to set the payment rate to £1000?

1 (very difficult)	2	3	4	5 (very easy)

8) How easy was it to set the planting density to 155 trees?

1 (very difficult)	2	3	4	5 (very easy)

9) How easy was it to set the number of neighbours to 7?

1 (very difficult)	2	3	4	5 (very easy)

10) How easy was it to run the simulation for 2 ticks?

1 (very difficult)	2	3	4	5 (very easy)

11) How easy was it to restart the simulation?

1 (very difficult)	2	3	4	5 (very easy)

12) How easy was it to change the number of supplementary owners?

1 (very difficult)	2	3	4	5 (very easy)

13) How easy was it to export the results to a graph?

1 (very difficult)	2	3	4	5 (very easy)

14) Comments

Appendix 2 – User Guide

WHAT IS IT?

The purpose of this model is to simulate the impact of agri-environmental schemes on land use. Land-use conversions are determined by the adoption decisions of farmers in response to different policy scenarios.

Policy scenarios are introduced with clearly defined target outcomes for the environment to meet UK-wide emission targets. Greenhouse gas emission reductions as a result of land-use changes will be monitored in the model to determine the success of policy intervention.

The model intends to serve as a tool to be used by policymakers to help support policy design by allowing predictive evaluation of sustainable schemes before implementation to avoid unintended consequences.

HOW TO USE IT

Setting up the spatial environment
To interact with the model, first, you have to create the environment. Ensure you download both the GIS land-use map and vector boundary data with the correct path to file set for all. You will be unable to run the model if these are not correct. Then, click on the 'setup environment' button and you should see the GIS land-use map for Northern Ireland.

Creating the farmer agents
The second step before running the simulation is to add the farm owners to the spatial landscape. Under the social sub-model, first, select the total number of farmers you want to simulate. Next, choose the percentages of different farm owner types. These must add up to 100% otherwise an error message is returned. Now, choose the likelihood that each of the farmer groups adopts either of the environmental schemes. This can be done by adjusting the next six sliders under the social sub-model (comm-bio, trad-agro, etc).

Adjusting the policy scenarios
The economic sub-model holds different options for policy schemes. You can choose to run the model with the agroforestry and bioenergy policy scenarios turned on or off. In the case that the model is run with either scenario turned off a base scenario is run which is based on current empirical data for land-use changes. You can change the various other sub-model parameters if you wish to run the model under different conditions and incentives.

Monitoring the greenhouse gas reductions
Model parameters under the ecological sub-model can be adjusted by you to impact the reductions in greenhouse gas emissions over the 30-year timeframe. Changing the planting density of trees per hectare and the sequestration rate of one tree will vary the amount of carbon removed from the atmosphere per hectare per year. Changing the percentages of bioenergy crops planted in either willow or miscanthus and their respective sequestration rates will vary the amount of carbon removed from the atmosphere per hectare per year. The percentages of willow and miscanthus planted must add up to 100% otherwise an error message is returned.

Changing the influence of farmer networks

Each of the three groups belongs to a social network with other members of that same group. You can vary the number of neighbours each member of each group has. You can also choose to run the model with or without the influence of networks so you can see easily the effects of being influenced by the policy decisions of neighbours. The extent that each farmer is influenced by their neighbours' decisions can also be adjusted by you.

Starting a single model run

Once you are happy with the input parameters you are ready to start the model. Press 'setup scenarios' and then either 'go' or 'single step'. 'go' is a forever button and when pressed will keep going at each time step (one year) until the simulation is complete. 'single step' will run the model for one tick stopping at the end of each time step. One run of the simulation last 30 ticks which represents 30 years as the period being modelled is 2020 to 2050.

THINGS TO NOTICE

- To reset the model for another simulation you must always press 'setup environment', then 'setup scenarios' before pressing either 'go' or 'single step'

- To run experiments with the model you will need to use NetLogo's built-in behaviour space tool

- When the model is running you can view each of the four plots that measure the number of hectares converted to agroforestry and bioenergy crops, the reductions in greenhouse gas emissions and the total costs involved in implementing these schemes.

- You can also view the number of farms that participated in either scheme and the total hectares of agricultural land belonging to each farmer group using the monitors

- Pressing the view farmers or view links buttons will reveal the locations of the farmers' agents and the links that exist between them. These buttons will only work if the 'setup scenarios' button has been pressed

- Pressing the 'get information' button will allow you to click your mouse anywhere on the land-use map and receive the county you selected and the number of farms with land in that county