Evaluating the potential for natural capital investment to reverse soil degradation:

A dynamic simulation approach exploring connections between soil health and money in England

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One does not discover new lands without consenting to lose sight of the shore for a very long time.

André Gide

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Abstract

Soils are a form of natural capital that support economic activity and human well-being. However, in England, national soil resources have been degrading over the last two centuries. The total annual economic cost of soil degradation is significant, making the issue a national policy priority. A government advisory committee has recommended that investment in natural capital is needed to restore natural capital stocks such as soils. However, the dynamic interactions between soil health and systems of financial incentives are not clear, meaning that natural capital investments could produce unintended effects. In this thesis, secondary data were used to build a quantitative system dynamics model capable of reproducing historically declining trends in the soil health and natural capital indicator soil organic carbon (SOC). The model built on a pre-existing SOC model to operationalise the relationships between the indicator, the economic value of soil ecosystem services and land management decision processes. The model was used to clarify the structural mechanisms behind soil degradation and identify leverage points at which natural capital investments could be targeted to reverse the trend. The work confirmed that stocks of SOC are declining because the inflows of carbon from organic matter have historically been smaller than the outflows of organic matter decay. Analyses revealed the absence of a feedback mechanism by which land managers could account for the improvements or losses of soil ecosystem services in their business decisions, suggesting that there is no incentive to alter land management choices based on SOC levels. The model thus provided a quantified, operational representation of a hypothesis posed by earlier research that soil degradation is happening because its economic impact is an externality for the land user. On this basis the study identified land managers' accounting and decision-making processes as leverage points for natural capital investment. The model was used to design and test two types of investments that would introduce feedback mechanisms: a farm advisory service to enable land managers to account for the onsite ecosystem services value to their business of improving SOC stocks, and a payment for ecosystem services (PES) whereby offsite beneficiaries pay land managers for the economic benefits they experience when SOC loss is reversed. The study found that the policies' effectiveness differed depending on the initial SOC stock level of the land plot to which the investment was targeted. The reasons behind these findings were determined to be the slow and non-linear rate of SOC accumulation originating in biophysical stock and flow structures, and the high sensitivity of land management decisions to price and supply variables for organic materials. These findings can be generalised to inform the discussion on how natural capital investment could be used to improve other soil health indicators, as well as other types of natural assets. Further work is proposed for using the simulation model as a facilitation tool to explore the issue with policy stakeholders and as a natural capital investment appraisal tool for investors and suppliers.

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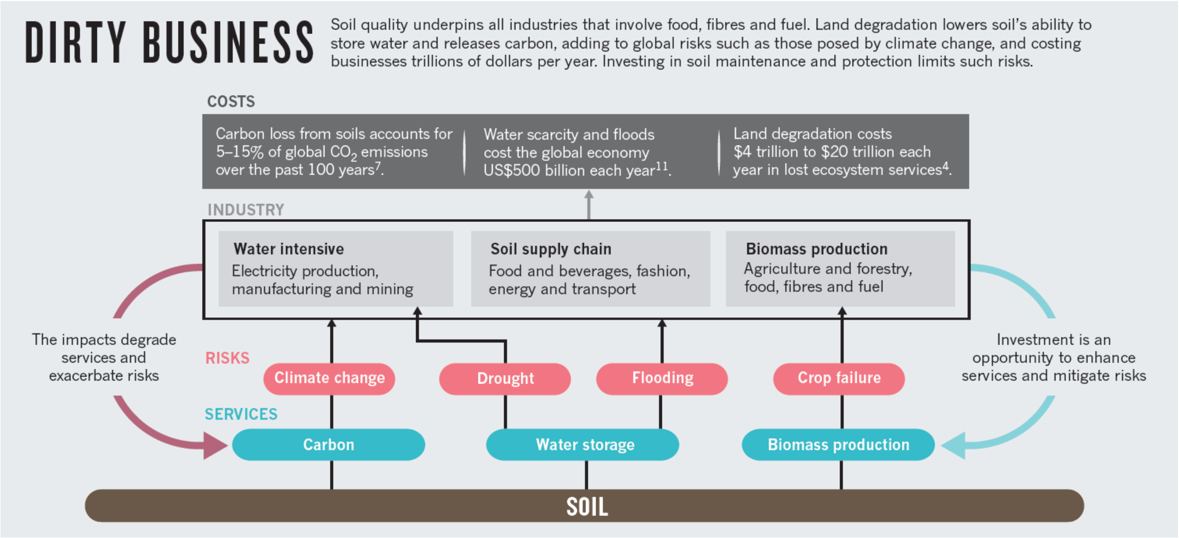
Chapter 1. Introduction

1.1 Background

Soils can be considered a form of natural capital because they are stocks of natural assets which provide ecosystem services that support economic activities and human well-being (Brady & Weil, 2016; Costanza & Daly, 1992; Dominati et al., 2010). Examples of ecosystem services that soils provide include supporting the provision of food and fibre and their role in storing greenhouse gases which regulate climate. However, the status of global soil resources is considered poor and their condition to be worsening (FAO, 2016). In England, national soil resources have degraded over the last two centuries due to the practices associated with their use and environmental pollution (Defra, 2009). In 2017 the UK's Environment Minister warned that some parts of the country were "30 to 40 years away from the fundamental eradication of soil fertility" (Van der Zee, 2017, p. 1). The total economic cost of soil degradation in England and Wales has been estimated at £1.2 billion per year (Graves et al., 2015). Addressing soil degradation can therefore be considered a national policy priority.

As part of a new 25-year strategic plan, the Department of Environment, Food and Rural Affairs ("Defra") has set the goal that "by 2030 we want all of England's soils to be managed sustainably, and we will use natural capital thinking to develop appropriate soil metrics and management approaches." (HM Government, 2018, p. 27). The Natural Capital Committee (2018), an independent advisory committee which provides advice to the UK government on the sustainable use of natural capital, has emphasised the importance of investment in natural capital for achieving Defra's 25-year vision. The business case for private investment in Britain's soil natural capital has also been made (Sustainable Soils Alliance, 2019) referring to soil's role in supporting supply chain resilience, mitigating financial risk and as an opportunity to capitalise on consumers' sustainability concerns (Davies, 2017; World Business Council for Sustainable Development, 2018). Figure 1 illustrates some of the benefits soils provide, how soils might be degraded by damaging practices, and shows how investing in soils can enhance ecosystems services and mitigate risks.

Figure 1: The business case for investing in soil natural capital. Sourced from Davies (2017).



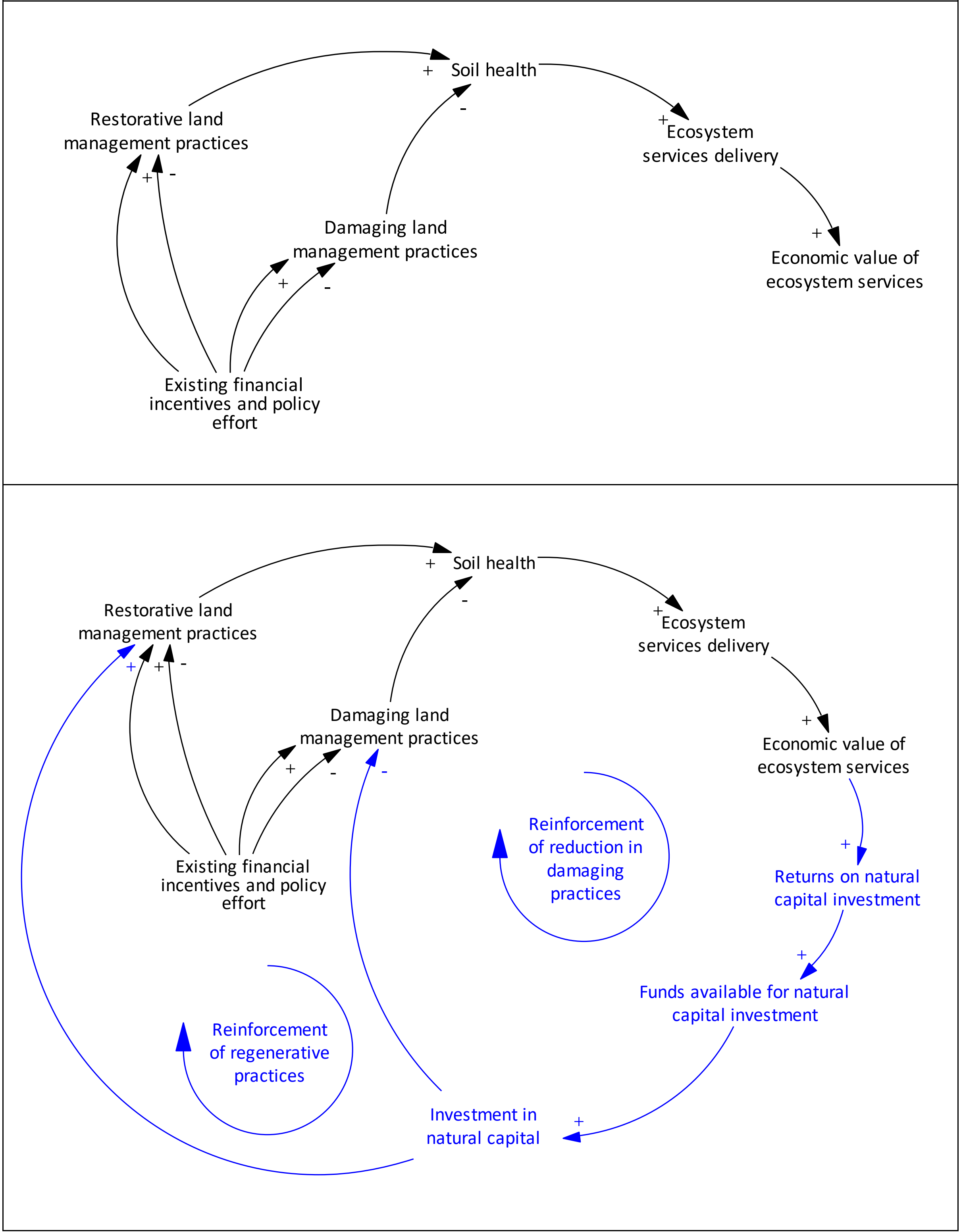
1.2 Research challenges

Since the soil environment can be considered a dynamic ecosystem (Brady & Weil, 2016), itself embedded in a complex socio-ecological system (Levin et al., 2012), proposals for investment in restoring soil natural capital and supporting policies must take account of the complex feedback relationships that characterise such systems and that could promote or hinder the success of these initiatives. Feedback processes interrelating the benefits humans receive from natural capital and how decisions are made about its management by people are part of the ecosystem services theoretical framework described in the relevant scientific literature (Braat & de Groot, 2012). Supposed feedback relationships interrelating investments, natural capital benefits, returns for the investor, and money available for future natural capital investments are also widely illustrated in the conceptual diagrams of publications aimed at business audiences, such as the Natural Capital Protocol (Natural Capital Coalition, 2016), a recent natural capital credit risk assessment in agricultural lending (Ascui & Cojoianu, 2019), and the seminal *Nature* article on the business case for investing in soils by Davies (2017) (see Figure 1). In their calculation of the total economic costs of soil degradation in England and Wales, Graves et al. (2015) refer to the current absence of such feedback mechanisms as an instance of market and institutional failure which has led to the most significant costs of soil degradation being borne by off-site actors (externalities), such as water companies, local councils and national governments. This absence of an incentive for soil users to employ more sustainable management practices was therefore proposed by these authors as an explanation for why soil degradation is occurring.

Academic publications in the soil science, natural capital and land use policy literature have focused on the not insignificant task of elucidating the logic pathways behind how stocks of soil natural capital deliver benefits for human society (for example, Dominati et al., 2010; Hewitt et al., 2015; Janes-Basset & Davies, 2018). Such work supports the policy and business case for tackling soil degradation, and for recognising the valuable role of soils for delivering public and private goods in decision-making processes. However, it is also apparent from the academic literature in this area that neither the existence (or absence) of dynamic feedback relationships between soil health, allocations of financial resources and land management decisions, nor their potential policy and business implications, have been studied explicitly. This represents a challenge for policy makers and business communities seeking to improve soil health using natural capital investments because the appropriate scientific evidence available to inform their proposals is scarce. Recognising this, the use of systems analysis techniques for understanding how soil and money interact has been proposed by the Sustainable Soils Alliance (2018), a campaign organisation which aims to improve the understanding and the health of UK soils. There is therefore a clear need to broaden the focus of the existing research agenda to investigate the potential for harnessing and/or creating dynamic feedback processes to reverse soil degradation using natural capital investments.

Figure 2a and 2b summarise the issue in causal loop diagrams (CLDs). Figure 2a (top) illustrates how both regenerative and damaging soil management practices are influenced by existing financial incentives and policies but are not based on changes in the value of ecosystem services provided by soils. Figure 2b (bottom) illustrates the theoretical mechanism by which natural capital investment is supposed to incentivise regenerating practices and reduce damaging practices. Natural capital investments are implicitly discussed as representing introducing reinforcing feedback mechanisms (e.g. Davies, 2017; Ascui & Cojoianu, 2019) because improving soil health should improve ecosystem services delivery, their economic value, and therefore the returns on natural capital investment which can provide more funds for further investment. These ideas are deserving of further exploration given the theoretical challenge highlighted above. This research project has been designed to help explore the issue.

Figure 2a (top) and Figure 2b (bottom): causal structure of the supposed "market failure" which has led to soil degradation and the supposed mechanism by which natural capital investment can introduce a reinforcing feedback to incentivise regenerative practices. Adapted from Graves et al. (2015), Natural Capital Coalition (2016), Davies (2017) and Ascui & Cojoianu (2019).



In addition to this theoretical challenge, the practical challenge of developing new decision support tools capable of informing natural capital investment appraisals has been recognised by the Natural Capital Committee (2018). A range of natural capital and ecosystem services assessment tools already exist with well-documented case studies on their use in both research and commercial applications (Howard et al., 2016), including highly sophisticated data-driven spatially-referenced models such as Viridian (Ecosystems Knowledge Network, 2017), as well as more conceptual visualisation aids such as ENCORE (Natural Capital Finance Alliance, 2019). None of these existing tools are currently able to operationalise the dynamic feedback relationships between soil natural capital stocks, the economic value of their ecosystem services benefits, systems of financial return for investors and land management decision processes. This represents a challenge for researchers as well as policy makers and business communities because the available appraisal tools are underdeveloped for informing their decisions or addressing the theoretical challenge outlined earlier. This research project recognises this practical challenge and was designed accordingly.

1.3 Research Objectives

The overall aim of this research is to clarify the dynamic interactions between soil health and money to explore why soil degradation might occur and evaluate the potential for natural capital investments to reverse it. In the context of the background and theoretical challenge outlined above, this research aim was elaborated into two specific Research Objectives:

1. Identify dynamic structures underlying soil natural capital degradation in England, highlighting dynamics linking soil health to systems of financial investments and incentives;
2. Use these dynamic structures to identify opportunities and limitations for the effectiveness of natural capital investments in regenerating soils in England.

To fulfil these objectives and address the theoretical challenge, this research required the development of a prototype soil natural capital investment appraisal tool which took the form of a dynamic simulation model. The development of such a tool was necessary in the context posed by the practical challenge mentioned above. Although developing this tool was not a formal research objective this was considered a valuable research output and potential for further applications and development are included in the text to support future work.

1.4 Research Questions

The following Research Questions were developed for this study based on the Research Objectives. The type of knowledge sought is indicated in brackets.

Objective 1:

1.1. Which dynamic structures could be responsible for promoting the decline of soil natural capital in England? (explanatory)
1.2. Which dynamic structures could be responsible for mitigating or slowing the decline in soil natural capital in England? (explanatory)
1.3. Which of these dynamic structures relate soil health to systems of financial incentives and investments? (descriptive)

Objective 2:

2.1. What are the leverage points in the dynamic structures of the system for reversing the decline in soil natural capital in England using natural capital investments? (predictive)
2.2. What are the strengths and opportunities for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital? (evaluative)
2.3. What are the limitations and risks for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital? (evaluative)

Chapter 2. Methods

2.1 Research Strategy

System Dynamics (SD) was chosen as the overall research methodology for this study. SD has been defined as “the use of informal maps and formal models with computer simulation to uncover and understand endogenous sources of system behaviour” (Richardson, 2011, p. 241). SD could be described as a mixed methods research approach since it combines qualitative and quantitative elements (Denscombe, 2012; Sterman, 2000). Turner et al. (2016) have argued that SD is “uniquely suited to investigate AGNR [agricultural and natural resource problems] given their inherently complex behaviours” (p. 1) and demonstrates how SD models have produced novel insights in this context. In cases related to soil erosion and sedimentation of watercourses, studies reported that using SD models offered advantages in exploring alternative scenarios, highlighting previously unrecognised feedback processes and identifying leverage points for policy design (Yeh et al., 2006; Cakula et al., 2012). Gerber (2016) has demonstrated the advantage of SD in exploring the dynamic relationships between financial incentives for farmers, food production and soil parameters. Given the focus of this study on the dynamic relationships between soil and money in a complex system and the potential role of simulation identifying leverage points for natural capital interventions, the rationale for adopting SD as the overall research method was supported by the foregoing precedents.

SD is itself a broad methodology and includes a range of approaches as classified and described by De Gooyert (2018). Considering the Research Objectives and Research Questions posed above, the SD research strategy adopted for this study resembles the so-called Phenomenon Replicating Explanation Strategy. This approach focuses on using existing knowledge and empirical data to build a quantitative model capable of reproducing a reference mode of behaviour which is used to compare scenarios for developing new policy insights. This is similar to the strategy employed by Gerber (2016) for building a simulation model to study the dynamics between food production and fertiliser subsidies in Zambia, where existing knowledge was synthesised to produce a high-level, aggregated model to clarify the structural mechanisms behind a system’s complex dynamics and identify strategic leverage points of policy interest. Given that a large archive of documented information is already available on the issue of soil degradation and land management decision-making in England, and that the focus of this work is on developing policy insights regarding the opportunities and limitations of natural capital investment, this SD research strategy was considered appropriate for fulfilling the Research Objectives of this study.

Following accepted SD guidance, iterative cycles of data collection, model building, simulation, analysis, validation and documentation were undertaken throughout the project (Sterman, 2000) adhering to the “Agile SD” principles (Warren, 2015). This allowed preliminary answers to Research Questions 1.1 to 2.3 to be revised with increasing confidence as the iterative cycles progressed and enabled different research activities to be conducted in parallel to improve efficiency. Given that soil degradation and natural capital investment are high-profile topics where the public discourse and state of existing knowledge is rapidly changing, the iterative method also enabled the most up-to-date information to be incorporated. The SD model was built and used in the Stella Architect software (isee Systems, 2019).

2.2 Data Collection

Two types of information were sought in order to build, test, validate and use the SD model for addressing the Research Questions:

- Nature of the structural components in the complex system that has produced the problem of soil degradation in England, particularly those relating to connections between soils and financial variables, including stock, flow and exogenous variables, causal relationships, and equations which describe the relationships between variables;
- Time series data for known modes of behaviour, such as data plotting behaviour of soil health indicators over time, and parameter data for exogenous variables.

Data sources often used in SD studies include documented numerical data, documented written data and mental data present in the minds of people operating within the system being studied (Forrester, 1992). Because of the large quantity of documented information, only the first two types of data sources were consulted, and no primary data collection was conducted. The secondary data was sought in peer-reviewed scientific literature using the Web of Science database and from “grey literature” including governmental and commercial reports. Relevant existing simulation models were also reviewed such that any pertinent structures, input parameter values, and output data could be used to build an integrated model (Voinov & Shugart, 2013). Such an approach was taken to improve model-building efficiency and to improve model confidence by incorporating pre-validated simulation model components. The International Soil Modelling Consortium (ISMC) model database (ISMC, 2019) was consulted to identify relevant existing simulation models. Only public and academically-licensed secondary information was consulted and only sufficiently validated, fully documented simulation model components (adhering to the minimum requirements of Rahmandad & Sterman, 2012) were used.

Given the multidisciplinary focus of the research, relevant secondary data and existing simulation models can be found across a multiplicity of sources and research domains. Since an iterative, agile modelling approach was adopted for the reasons outlined above, a traditional systematic literature review was not undertaken to collect the necessary data. Instead, as part of each iterative learning cycle, a model gap analysis was performed to identify model exclusions, weaknesses, sensitivities and uncertainties. These gaps were then used in the next modelling iteration to devise search terms by which to identify relevant documents for review, and the desired information was extracted if present. The development of the simulation model to supply answers to the Research Questions with increasing confidence and validity led the secondary data collection process in this way. The model description (Chapter 3) and results of analysis (Chapter 4) reported in this thesis thus represent the synthesis of the existing literature and critical discussion at the end of this iterative process.

Table 1 summarises the data collection methods used in this study, including examples of data sources, how the data was collected and processed, the contribution of the data to the study and access considerations.

Table 1: Summary of data sources, collection, processing and access

Source Type	**Example sources**	**Collection Method**	**Processing**	**Contribution**	**Access**
Documented numerical and written data	Published academic literature e.g. Gerber (2016), Official reports e.g. Defra (2009), Textbooks e.g. Brady & Weil (2016)	Literature review focusing on existing systems knowledge, soil quality trends, financial investment and incentive structures	Text analysis (Luna-Reyes & Andersen, 2003; Turner et al., 2013), Conversions of data to time series or other units when necessary	Key stock and flow variables, Causal relationships between variables, Equations, Time series data, Existing policy structures	Academic knowledge and government reports publicly available or via academic license, Commercial case study reports.
Existing validated simulation models	Published models e.g. Gerber (2016)	Model replication (Axelrod, 2003)	Structural aggregation, Unit conversions, Comparison of model outputs (Axelrod, 2003)	Ready-made stock, flow causal structures and equations, Input parameter values, Output parameter and time-series values.	Scientifically validated (referenced in published work) models with complete model documentation.

2.3 Data Analysis

Following guidelines and techniques described by Barlas (1996) and Sterman (2000), formal model analysis and validation procedures were used to support model testing throughout the iterative research process. Partial model testing (Homer, 2012) was used to test and validate smaller model building blocks by identifying areas for improvement and/or additional data collection as early as possible. The purpose of the model analysis and validation was to:

1. Support an overall evaluation of the extent to which the model can be used with confidence to address the Research Questions;
2. Inform a deeper interpretation of model behaviour; and,
3. Highlight leverage points and challenges for natural capital investments to promote desired system behaviour.

Direct structure tests, indirect structure-oriented tests and behaviour tests were used, with tests for building confidence in model structure prioritised in advance of model behaviour tests (Barlas, 1996; Sterman, 2000). For example, Structure Confirmation is a Direct Structure Test in which the variables and causal relationships which control an important soil health stock variable were validated by comparing model flow equations with those documented in soil science literature, whereas qualitative Behaviour Reproduction Tests were used to compare outputs of partial model tests with patterns (direction, shape, magnitude) of empirical reference modes (Barlas, 1996). The results of all validation tests were used for interpreting internally generated model outputs to address the Research Questions. Analysis and testing were applied both to the model and any policy structures that were subsequently added.

Chapter 3. Model Description

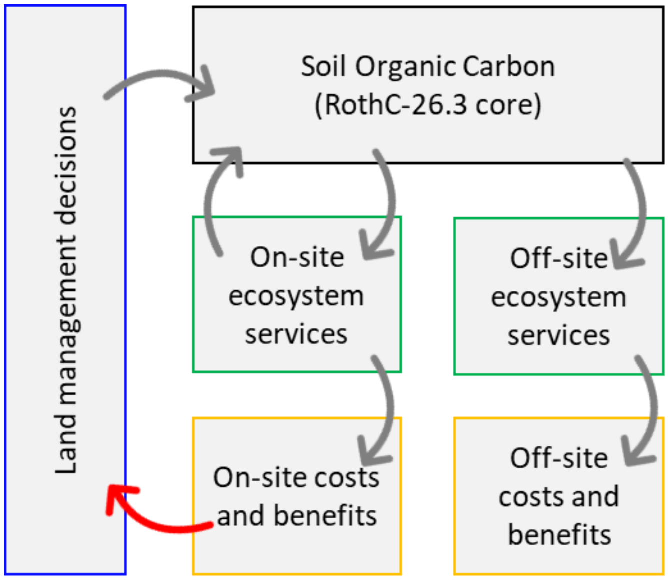
This Chapter presents a detailed description of the model which was developed to answer the Research Questions of this study. The model was built in iterative learning cycles and the model described here is the final product of the process. This model therefore represents both a quantified, operational and testable synthesis of existing literature as well as a prototype natural capital investment appraisal tool. A critical evaluation is provided in the text and further developed in Chapter 4 in the model analysis and validation testing.

As an initial overview, the model consists of the following sectors:

- A structure representing the biophysical processes controlling the soil health and natural capital indicator soil organic carbon (SOC) – this model core is based on the pre-existing RothC-26.3;
- A structure which operationalises the delivery of ecosystem services to onsite actors (land managers, farmers) from changes in SOC and a structure which quantifies the economic value of these onsite ecosystem services;
- A structure which operationalises the delivery of ecosystem services to offsite actors (water companies, local councils, national governments) from changes in SOC and a structure which quantifies the economic value of these offsite ecosystem services;
- A structure representing the decision process that land managers use to determine how much organic materials to add to their soil.

These sectors and their relationships are illustrated in the model overview presented in Figure 3. As shown, no feedbacks are present between the offsite costs and benefits of changes in ecosystem services delivery, and the potential feedback from the onsite costs and benefits of changes in ecosystem services delivery is portrayed as inactive (red). The remainder of this Chapter will describe the model in further detail and demonstrate its grounding in academic literature and documentary evidence. An overview of the feedback mechanisms in the model are illustrated in Figure 12 at the end of this Chapter.

Figure 3: Model overview



3.1 Soil natural capital

3.1.1 Soil health indicators as natural capital stocks

Despite the existence of a range of soil health indicators (e.g. Lima et al., 2013), integrated soil quality indices (e.g. Obade & Lal, 2016) and soil ecosystem services metrics (e.g. Greiner et al., 2017), there is still no standardised set of soil health indicators (FAO, 2015; Defra, 2018a). In order that soil natural capital could be modelled quantitatively to answer the Research Questions of this study, criteria were developed by which soil health indicators listed in the relevant scientific and policy literature could be reviewed. These criteria determined whether a soil health indicator was:

- Representative of a soil's qualitative state at a point in time and which may change over time i.e. a stock variable (Sterman, 2000);
- Manageable i.e. responsive to active management (Dominati et al., 2010);
- Widely considered critical to a soil's supply of ecosystem services (Greiner et al., 2017);
- Operational with standardised units of measure.

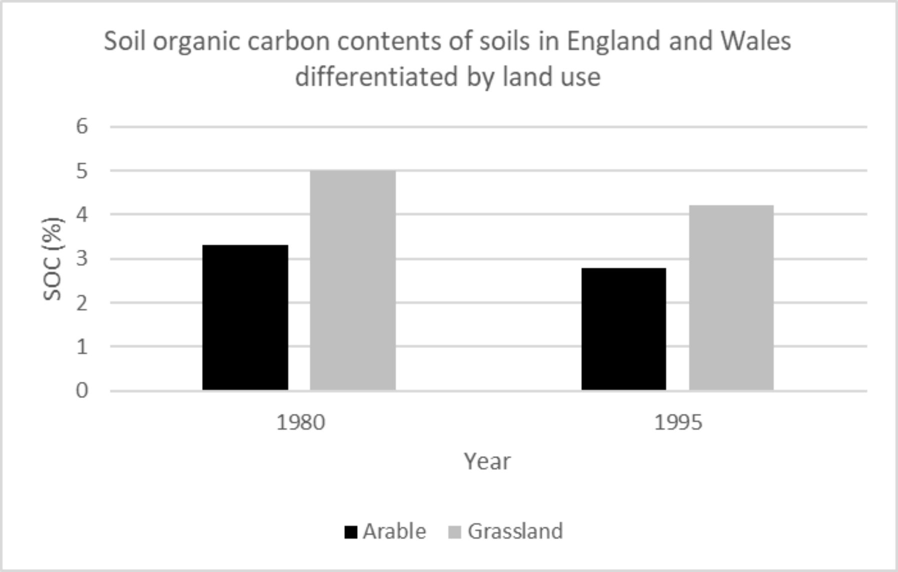
Soil organic carbon (SOC), which is a measure of a soil's organic matter (SOM) content, meets these criteria because SOC is:

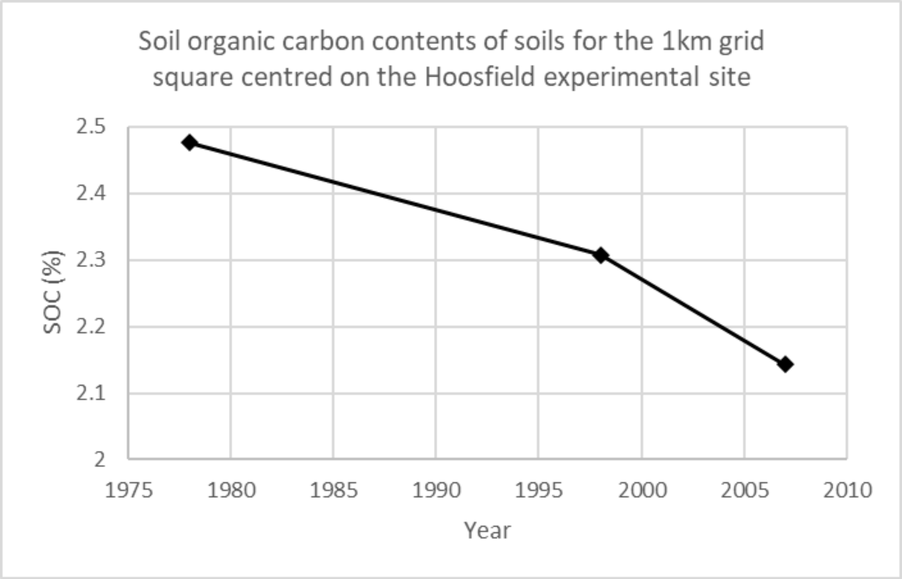
- A stock variable which can accumulate or deplete over time (Coleman & Jenkinson, 1996);
- Responsive to active management, such as through applications of organic amendments like manures (Minasny et al, 2017);
- Widely referenced as a soil health indicator or used in integrated indices (Huber et al., 2008; FAO, 2015; Obade & Lal, 2016; Sustainable Soils Alliance, 2019) and is considered critical to soil's delivery of ecosystem services such as food provision and climate regulation (Graves et al., 2015);
- Measured and reported in standardised operational units of tons of carbon per hectare (Mg C ha^{-1}) or carbon as a percentage of the total soil weight (% w/w) specified to a certain soil depth (Huber et al., 2008).

Although other soil health indicators such as available water capacity and earthworm biomass could also meet these criteria, SOC is widely considered to be the highest priority indicator for policy makers (Graves et al., 2015; FAO, 2016; Sustainable Soils Alliance, 2019). The model was therefore limited to focusing on SOC as the main soil natural capital stock with other soil health indicators included only in so far as they are dynamically related to SOC. This was a boundary decision relating to the model and prototype natural capital investment appraisal tool developed here, but other indicators of interest could be included in future work building on this thesis.

Available SOC data shows a declining historic trend at the national level (Rusco et al., 2001; Belamy et al., 2005) and for specific field sites (Bradley et al., 2005) providing an indicative reference mode of behaviour for a quantified measure of soil degradation in England. Figure 4a shows the national trends in SOC for grassland and arable land, and Figure 4b illustrates the trend for a particular 1km grid square centred on the Hoosfield experimental site at Rothamsted, near Harpenden, England. This data was used an indicative reference mode of behaviour for the issue of soil degradation.

Figure 4a (top) and Figure 4b (bottom): Time series data for SOC at the national and local scale.





3.1.2 Core model of biophysical processes

At a simplified level, SOC can be considered a single soil stock governed by organic matter inflows and decomposition outflows (Gerber, 2016) whereby carbon is either further recycled within the soil or lost from the soil as carbon dioxide emissions (Coleman & Jenkinson 1996). At a more detailed level, SOC can be considered to exist in a number of different carbon "pools", sub-stocks of the total SOC stock, each with separate inflows and outflows governed by different parameters and changing on different timescales (Jenkinson et al., 1990). Various qualitative conceptual models exist which distinguish these and illustrate their relationships, complimented by a range of validated quantitative simulation models. The models are used to help explore the dynamic consequences of these structures to support of land management decisions, scientific enquiry and public policy design. In order to improve model building efficiency and model validity, existing SOC models listed on the ISMC (2019) database were reviewed to determine which components could be replicated to support this thesis. The criteria used to determine whether all or part of a model structure could be used were that the model should be:

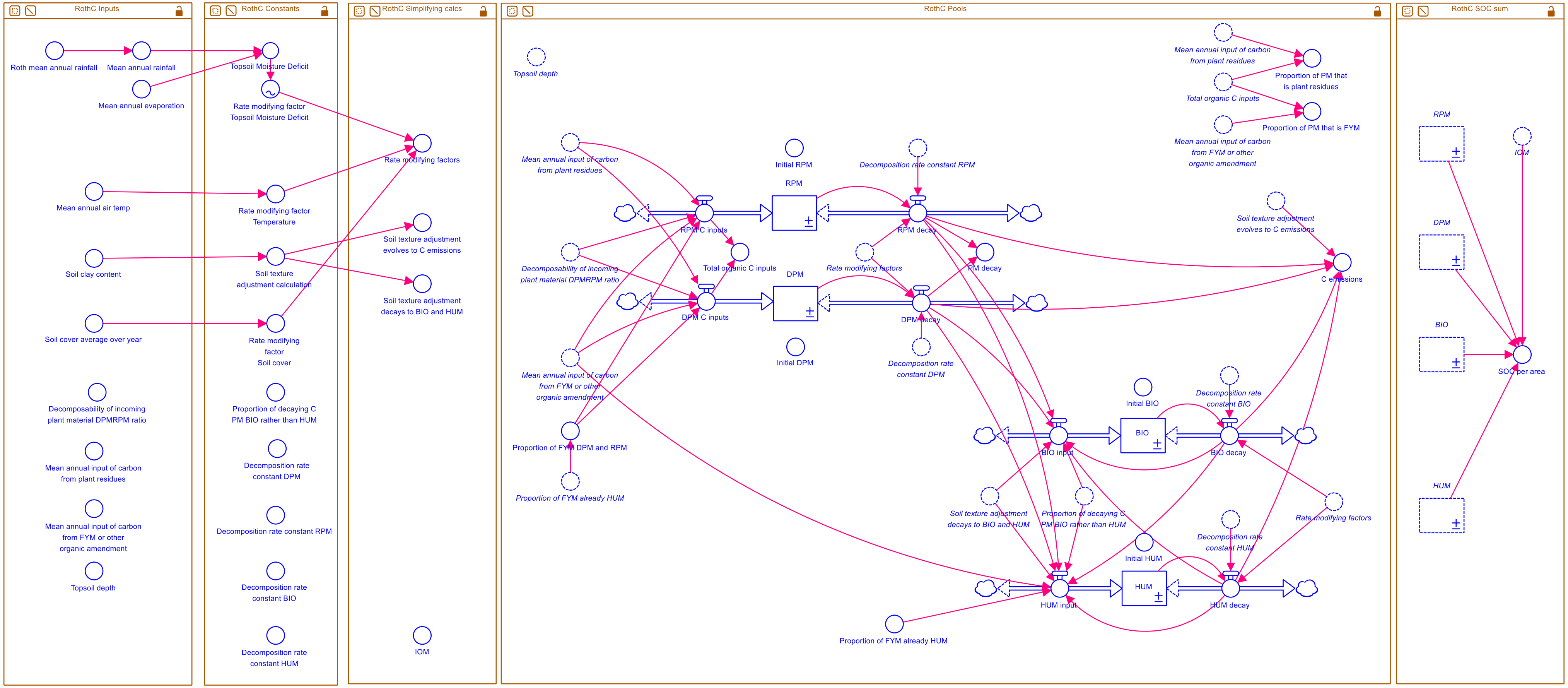
- Able to simulate SOC dynamics;
- Formally validated and referenced in published scientific articles;
- Freely available through open access or academic license;
- Fully documented such that model can be reproduced according to minimum documentation standards of Rahmandad & Sterman (2012);
- Adaptable to English environmental conditions;
- Adaptable at different geographical and temporal scales.

RothC-26.3 is a simulation model of SOC turnover which calculates total SOC and sub-stocks plant matter carbon, microbial biomass carbon, and humus carbon in Mg C ha^{-1} at timescales defined by the user, requiring a small number of easily obtainable inputs (Coleman & Jenkinson, 1996). RothC-26.3 has been validated using historic data for the Hoosfield barley experiment sites at Rothamsted Research Centre (Coleman & Jenkinson, 2014), conforms to empirical measurements in recent scientific studies (e.g. Herbst et al., 2018), has been applied in government commissioned research (e.g. Bhogal et al., 2010) and has been used as the basis of other soil simulation models developed for different purposes (e.g. the ECOSS model (Smith et al., 2010)). RothC-26.3 meets all of the above criteria including geographical scale adaptability, and here as in other applications is used in this research at individual plot or field scale. The entire RothC-26.3 structure (variables, causal relationships and equations) was therefore selected for use by this study.

To enable the RothC-26.3 structure to include new elements as a prototype natural capital investment appraisal tool for the purposes of this thesis, RothC-26.3 was replicated from the model documentation by Coleman & Jenkinson (2014) to build a stock and flow structure in the Stella Architect software (isee Systems, 2019). As part of this translation process, RothC-26.3's discrete system of sums of exponentials was converted to a first-order differential equation system with reference to Parshotam (1996). This structure was used as the core model adapted and added to for the purposes of this thesis. Other available simulation models could have been used, but many of these did not satisfy the documentation criteria that would enable their replication. Structures from other models could be used in future work building on this thesis should their replication be permitted.

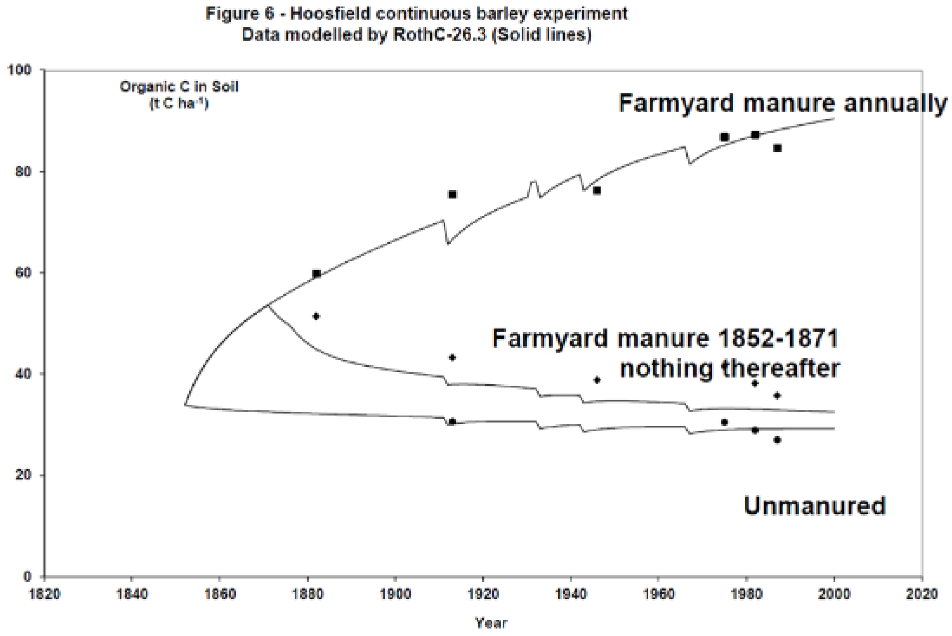
The structure for the RothC-26.3 core model is illustrated in Figure 5. This shows that SOC is present in four stocks: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). The carbon present in organic material within each stock decays to produce either more BIO and HUM, or is lost from the soil through carbon emissions. The proportion that decays depends on the "Rate modifying factors" ("Topsoil moisture deficit", "Temperature" and "Soil cover") within the decay time period converted from the decomposition rate constants for that stock. In this way, carbon enters the soil system, is recycled through the different stocks, and is eventually lost to the atmosphere. The variable "SOC per area" sums all of the stocks to give an overall value of SOC in MgC ha^{-1}. Carbon enters the soil through decomposing plant residues ("Mean annual input of carbon from plant residues") and organic amendments such as farmyard manure (FYM) ("Mean annual input of carbon from FYM or other organic amendment").

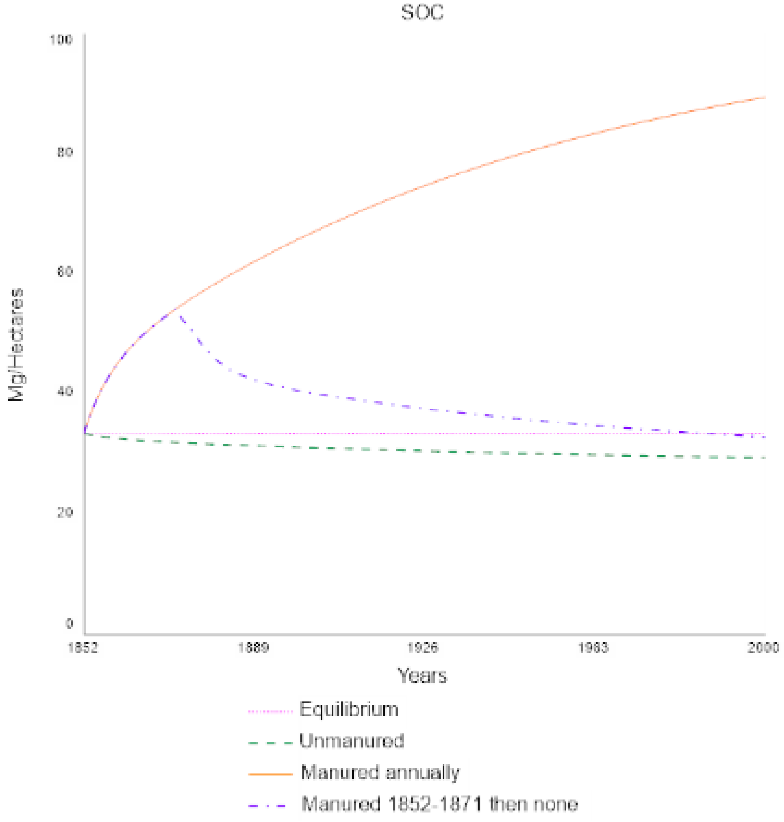
Figure 5: Stock and flow structure of RothC-26.3 replicated in Stella Architect as a system dynamics model (attached file name “RothC_Stella rebuild_04”). Adapted based on Coleman & Jenkinson (2014) using Parshotam (1996).



In the RothC-26.3 model documentation (Coleman & Jenkinson, 2014), the model developers provide a simulation model run comparison against historical SOC data collected from three experimental treatment plots at the Hoosfield barley experimental site near Harpenden, England. To confirm the RothC-26.3 structure had been accurately translated into a stock and flow structure in Stella Architect, the replicated model was simulated and the outputs compared with the original RothC-26.3 results presented in the model documentation. Partial model tests (Homer, 2012) were then performed according to the behaviour pattern validation sequence outlined by Barlas (1996). Figure 6a shows the RothC-26.3 documentation run comparison against the historical SOC data for the Hoosfield sites subjected to different organic matter treatment regimes. Figure 6b shows the results of the translated SD version which is the biophysical core of the model developed in this thesis. The replicated version of the model can be seen to reproduce a smoothed version of the RothC-26.3 output of Figure 6a for all three experimental treatments. This is because the replicated version used annual average input data for precipitation, evapotranspiration, plant residue additions and FYM applications rather than the monthly data used in the original model. This level of detail was considered sufficient for checking that the structure of RothC-26.3 had been replicated accurately.

Figure 6a (top) and 6b (bottom):





3.2 Ecosystem services

Ecosystem services are the benefits society receives from natural capital (MEA, 2005). Dominati et al. (2010) present a framework illustrating how the ecosystem services provided by soils are linked to soil properties. Janes-Basset & Davies (2018) propose “natural capital pathways” to illustrate how changes in drivers and supporting processes can affect specific soil properties and in turn lead to changes in specific ecosystem services, such as food production and climate regulation. Graves et al. (2015) distinguish between the costs of declines in ecosystem services due to soil degradation in England and Wales for “on-site” and “off-site” beneficiaries of those services. In the case of SOC loss, on-site costs due to decline in crop production (provisioning ecosystem service) borne by land managers was calculated at £3.5 billion per year, compared to the much larger off-site costs of climate change consequences of greenhouse gas release (climate regulation service) borne by society of £566.1 billion per year. Given the importance of different ecosystem services between on-site and off-site actors and the magnitude of the cost differences involved, it was decided that this distinction between on-site and off-site ecosystem services benefits and financial consequences would be reflected in further model development. This was also thought important given the potential for different feedback mechanisms by which on-site (farmers) and off-site beneficiaries might respond to financial incentives through changes in ecosystem services mediated by SOC (Graves et al., 2015).

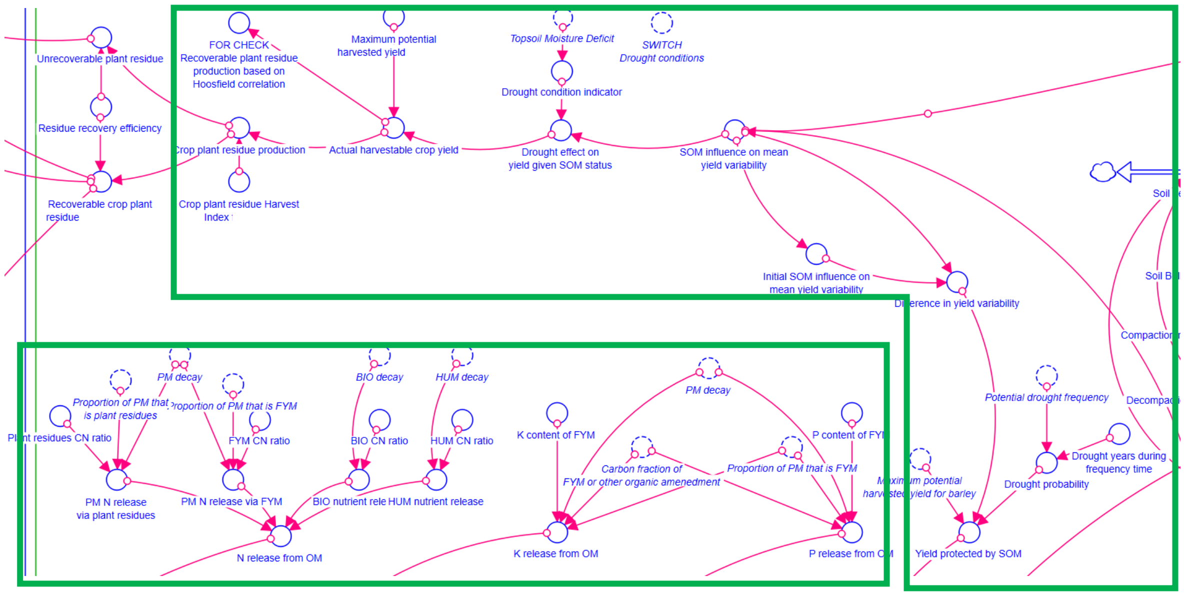
3.2.1 On-site ecosystem services

On plots of land containing soil, changes in soil organic matter influence crop yields (ecosystem service of food and fibre provision) (Pan et al., 2009), as well as soil compaction (Yang et al., 2014) and release of plant nutrients (Bhogal et al., 2010). Investments by farmers targeted at increasing their soil organic matter stocks (of which SOC is a measure) reported in a series of case studies by KeySoil (2010) confirm that raising soil organic matter levels improved yields, reduced soil compaction and meant that less inorganic fertiliser needed to be applied. KeySoil (2010) is a key reference used by Graves et al. (2015) in their economic analysis of soil degradation. Because the influence of SOC on these variables was not included in the original RothC-26.3 model and nor could they be identified from the model documentation of other models reviewed from the ISMC (2019) database, an attempt was made to operationalise these relationships by expanding on the replicated core model structure based on available scientific literature and secondary data.

SOC is correlated with both total crop production output and with crop yield variability (Pan et al., 2009). This is how SOC relates to food and fibre production as a provisioning ecosystem service. It has been proposed that SOC influences crop yield in these ways through the role of soil organic matter (of which SOC is a measure) in determining a soil's water holding capacity (Williams et al., 2016). This is corroborated by organic matter investment case reports where farmers observed improved water retention in previously droughty soils and reduced crop yield variability following improvements of soil organic matter levels (KeySoil, 2010). However, a meta-analysis of 60 published studies by Minasny & McBratney (2018) concluded that the effect of increasing SOC on soil water capacity was negligible and of little practical significance, raising questions for earlier model formulations of the influence of SOC on crop yield via soil water (e.g. Gerber, 2016), and posing challenges for how the food production ecosystem service should be understood and modelled for the purposes of this research. The issue is complicated further since soil organic matter also influences crop yield through release of plant nutrients (Brady & Weil, 2016). To resolve these points, a proposed structure was developed for the model which distinguishes the influence of SOC on regulating crop yield variability and the release of plant nutrients from decaying soil organic matter.

The influence of SOC on crop yield variability was modelled as a multiplier effect on the "Maximum potential harvested yield". The variable was parameterised for barley which is the crop grown on the Hoosfield experimental sites near Rothamsted, England, that the RothC-26.3 model was validated against above. This was set at 7 Mg ha^{-1} which is the highest per hectare yield value in a five-year averaging period for the whole UK 2013-2017 (Defra, 2018b). The variable "Actual harvestable crop yield" multiplies the "Maximum potential harvested yield" by the "Drought effect on yield given SOM status", which is the proportion of the maximum yield which is lost in a drought year. This is governed by the variable "SOM influence on mean yield variability" which calculates the yield variability (proportion of total yield at risk of loss during drought) based on the SOC stock calculated by the RothC-26.3 part of the core model. This "SOM influence on mean yield variability" uses a linear equation function reported in Pan et al. (2009) for intensive cereal production systems in China with a temperate climate. This is the available data representing this relationship which is most similar to a barley field in England. Through comparison with the "Initial SOM influence on mean yield variability", the "Yield protected by SOM" is calculated based on the "Drought probability" and "Maximum potential harvested yield". The "Yield protected by SOM" represents the loss of yield due to drought which is avoided through the resilience provided by the SOC natural capital stock, indicating the contribution of this variable to the food and fibre production ecosystem service. A "SWITCH" variable is included so the model can be set to include droughts occurring at a frequency defined by the user with base setting at 5-year intervals as reported in KeySoil (2010). "Crop plant residue production” is calculated from the “Actual harvestable crop yield” using the “Crop plant residue Harvest Index” parameterised for barley (McCartney et al., 2006). This then determines the quantity of crop plant residues which are available, thus introducing a capacity constraint on the amount of plant residues that can be used as an input to the RothC-26.3 core model component. This introduces a feedback loop, assuming that plant residues can only be sourced on-site and not imported. The structure is illustrated in the upper part of Figure 7. The influence of SOC on total yield was not modelled since changes in yield reported in case studies KeySoil (2010) were much more significant for yield variability and this was assumed to be resulting from improved soil moisture status.

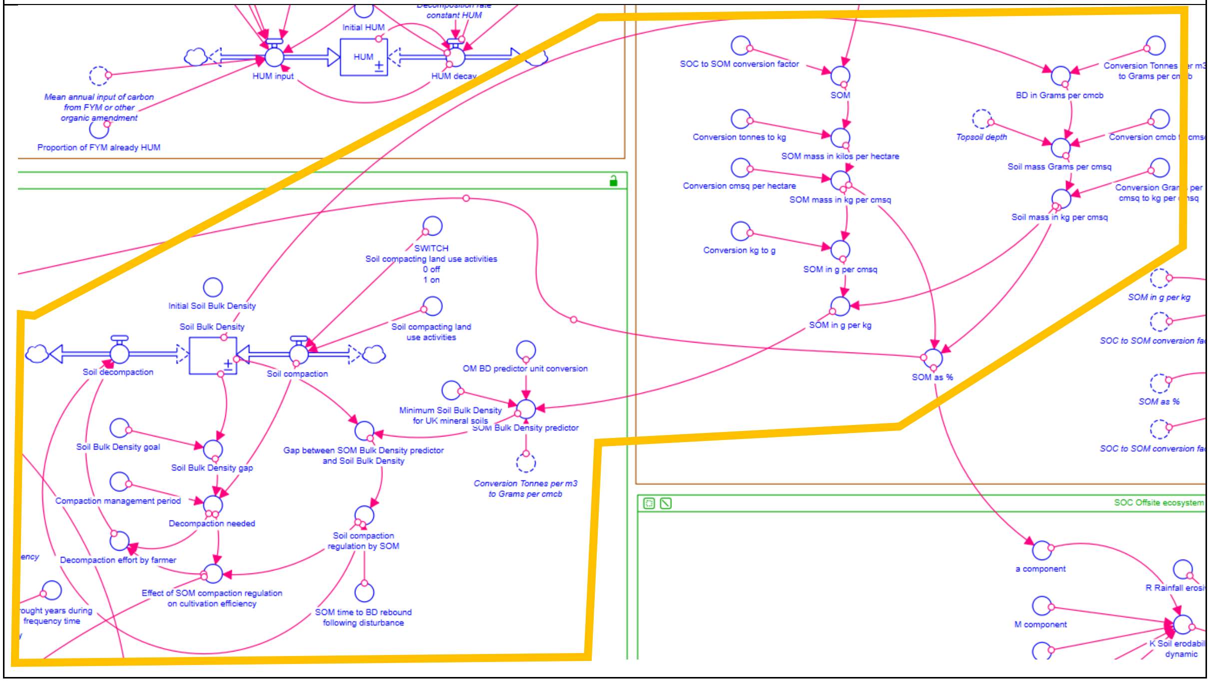
Figure 7: Model structures representing onsite ecosystem services of food and fibre provision and nutrient cycling.



Plant nutrients are released from decaying organic matter (Brady & Weil, 2016). In organic farming systems, organic amendments and crop residues are the only source of additional nutrients whereas in conventional farming systems, farmers can choose to use both organic and inorganic fertilisers (Watson et al., 2006). In this way, nutrients can originate from natural capital (organic matter) and manufactured capital (inorganic fertiliser). In case studies where farmers began investing in increasing their soil natural capital stocks of organic matter, farmers reported they were able to reduce their applications of inorganic fertiliser for the macronutrients nitrogen (N), phosphorus (P) and potassium (K) (KeySoil, 2010). The release of NPK from decaying organic matter according to this process was represented in the model using the decay outflows from the various RothC-26.3 stocks in the core model. In the case of P and K, these nutrients were released from PM originating from FYM based on reported P and K contents of FYM (Bhogal et al., 2010). N was modelled as being released from all SOC stocks depending on the C:N ratio (carbon to nitrogen ratio) of the organic matter in those pools. In this way a proposed structure was developed for operationalising the role of organic matter in nutrient release as a natural capital alternative to the manufactured capital of inorganic fertilisers. The structure is illustrated in the lower part of Figure 7.

Soil bulk density (BD) is the ratio of soil mass to its total volume and is used as an indicator of soil compaction (Al-Shammary et al., 2018). This measure is also commonly referred to as a soil health indicator because compaction has significant implications for crop productivity and erosion risk (Huber et al., 2008; Obade et al., 2016). Cases documenting the results of farmer investment in soil organic matter reported reduced soil compaction and greater tillage efficiency (KeySoil, 2010). A proposed structure for representing the contribution of SOC to compaction reduction was therefore added to the model. “Soil Bulk Density” was added as a stock controlled by the inflow of “Soil compaction” and the outflow of “Soil decompaction”. Soil compaction was driven by an exogenous variable of “Soil compacting land use activities” which assumes a constant rate of soil compaction caused by agricultural activities. Soil decompaction was represented as governed by two processes: decompaction by the farmer through tillage (“Decompaction effort by farmer”) and the soil’s natural resistance to compaction determined by the SOC stock (“Soil compaction regulation by SOM”). This enabled the farmer’s decompaction effort to be dynamic: the greater the contribution of organic matter to decompaction the lower their decompaction effort (tillage intensity) would need to be, and vice versa. The “Soil compaction regulation by SOM” was calculated based on the difference between the Soil Bulk Density stock value and a “SOM bulk density predictor”. This predictor variable uses a regression equation from Yang et al. (2014) where BD can be predicted on the basis of soil organic matter concentrations in an unmanaged Alpine landscape. This variable therefore represents what a soil’s BD “could be” under less intensively managed conditions. To make this calculation, the SOC output from the RothC-26.3 core model was converted to units of SOM g kg^{-1}. To make this conversion a BD is required, therefore the mathematical influence of BD on SOC was included so that changes in BD were reflected in the SOC conversion variable used in the “SOM bulk density predictor”. This adjustment accords with other scientific work (e.g. Bhogal et al. , 2010). The structure is illustrated in the lower part of Figure 8.

Figure 8: Model structures representing the role of SOC in regulating soil compaction.



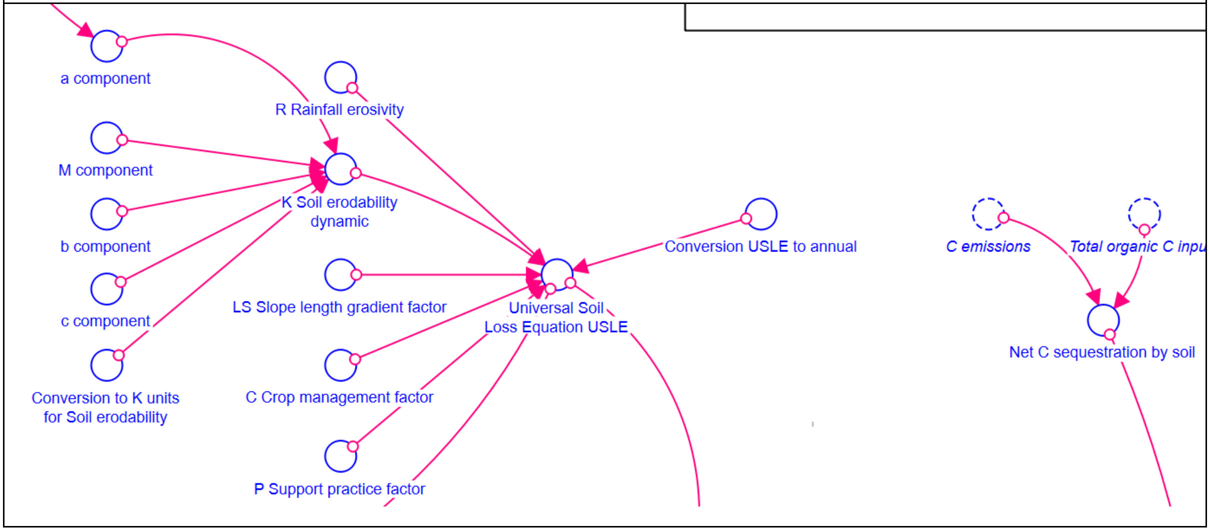
3.2.2 Off-site ecosystem services

Of the off-site costs of soil degradation in England and Wales, Graves et al. (2015) identified the most significant of these was the net release of carbon dioxide due to the net loss of SOC from degrading soil organic matter. Because carbon dioxide is a greenhouse gas, this loss represents a decline in the delivery of climate regulation as a regulating ecosystem service by soils. The release of carbon from SOC during decay is calculated on a per hectare basis by the replicated RothC-26.3 core model. The "Net C sequestration by soil" variable was added as an indicator of the soil natural capital stock's climate regulation ecosystem service. This was calculated from the variables of the RothC-26.3 core model by subtracting "C emissions" from the "Total organic C inputs".

Another important off-site cost of soil degradation calculated by Graves et al. (2015) was the removal of sediment (eroded soil) from rivers and canals, drainage systems and drinking water. This corresponds to the regulating ecosystem services of drinking water quality and flood protection an otherwise healthy soil would provide. The Universal Soil Loss Equation (USLE) is widely used to calculate soil loss (Renard et al., 1997) such including spatial ecosystem services models (Natural Capital Project, 2019). The factors used to calculate the USLE are Rainfall Erosivity (R), Slope Length (LS), a Crop Management Factor (C), a Support Practice Factor (P), and a Soil Erodibility Factor (K) which indicates the susceptibility of soil particles to detachment and transport by rainfall and runoff (Renard et al., 1997). K can be calculated based on soil texture (M), soil structure (b), soil profile permeability (c) and SOM content (a). Loss of SOM (as indicated by SOC) is therefore result in erosion and soil degradation (Lal, 2001). A structure was added to the model enabling the USLE to be calculated with a dynamic K factor while keeping the other USLE factors constant. The dynamic K factor was formulated in the additional structure to be calculated based on the dynamic "a" component determined by the SOC stock value generated by the RothC26.3 core model.

The structure used to calculate the "USLE" and "Net C sequestration by soil" is illustrated in Figure 9. A low and/or declining USLE indicates a poor and/or reduction in a soil's flood and water quality regulatory ecosystem services. A negative and/or declining "Net C sequestration" indicates the soil is a net emitter of carbon or that its ability to sequester more carbon is reducing, representing a loss or reduction in the soil's climate regulation ecosystem service.

Figure 9: Model structures representing soil's climate regulating and water quality and flood protection (via sediment retention) regulating ecosystem services.



Although soils provide a huge range of other ecosystem services (Dominati et al., 2010) not represented by the model, ecosystem services reported as being most significant in the relevant documentary evidence were prioritised for inclusion. Other ecosystem services and the dynamic relationships between them could be added in future adaptations for other uses of the model.

3.3 Economic benefits and costs

3.3.1 On-site benefits and costs

The model proposes a structure for operationalising the contribution of SOC as a natural capital stock to the provisioning ecosystem service of food production through its influence on yield variability, contribution to plant nutrient cycling and regulation of soil compaction. These contributions generate benefits for on-site actors, namely farmers and other land managers, who receive income for their produce and who spend money purchasing fertiliser and conducting cultivation activities (tillage) towards this. A structure for calculating an indicative monetary value for these benefits and the costs to the farmer for investing in them was added to the model. Structures to determine the marginal net benefit of investing in SOM on a per hectare basis was also including thus providing the means to conduct a cost-benefit analysis (CBA) for the lad manager. The factors added correspond to those used in the CBA's of KeySoil (2010) for calculating the economic benefit to farmers of investing in SOM.

To calculate the "Drought resilience value of SOM for yield income protection", "Yield protected by SOM" is multiplied by "Price per crop ton". Here the price for barley is used, corresponding to the crop grown on the experimental plots at Hoosfield, Rothamsted, and the other model parameter settings. To calculate the value of nutrients released from SOM during decay, the quantity of NPK released is compared to the national mean application rate of each nutrient in inorganic fertiliser for cereals (Defra, 2018c), representing a potential cost saving for that nutrient. The value of "Cost saving on compaction relief cultivation due to [the] influence of SOM" is calculated based on the potential avoided fuel costs that could be made based on the "Effect of SOM compaction regulation on cultivation efficiency". These benefit values are summed in the variable "Annual onsite benefits of SOM per area". All of these variables and their relationships in the model are shown in the structure illustrated in Figure 10.

Costs to farmers associated with investment in SOM included in the economic assessments of KeySoil (2010) include the costs of purchasing FYM or other organic amendments if they are unavailable on the farm, costs of handling and spreading FYM to land, costs of additional slug and weed management, and costs related to ploughing in of crop plant residues. A particularly important variable highlighted in these cases was the income foregone from selling plant residues, namely cereals straw. This "Potential income foregone from plant residue sales" was calculated by subtracting the "Actual income from plant residue sales by area" from the "Potential income from plan residue sales by area" based on the "Price per Mg of plant residue". This was reported an important variable for the sensitivity of the economic assessments by KeySoil (2010). The “Potential income foregone from plant residue sales” was summed with the other costs to calculate the “Additional annual onsite cost for investing in SOM per area”, as shown in Figure 11.

Figure 10: Structure for calculating the on-site benefits of soil ecosystem services.

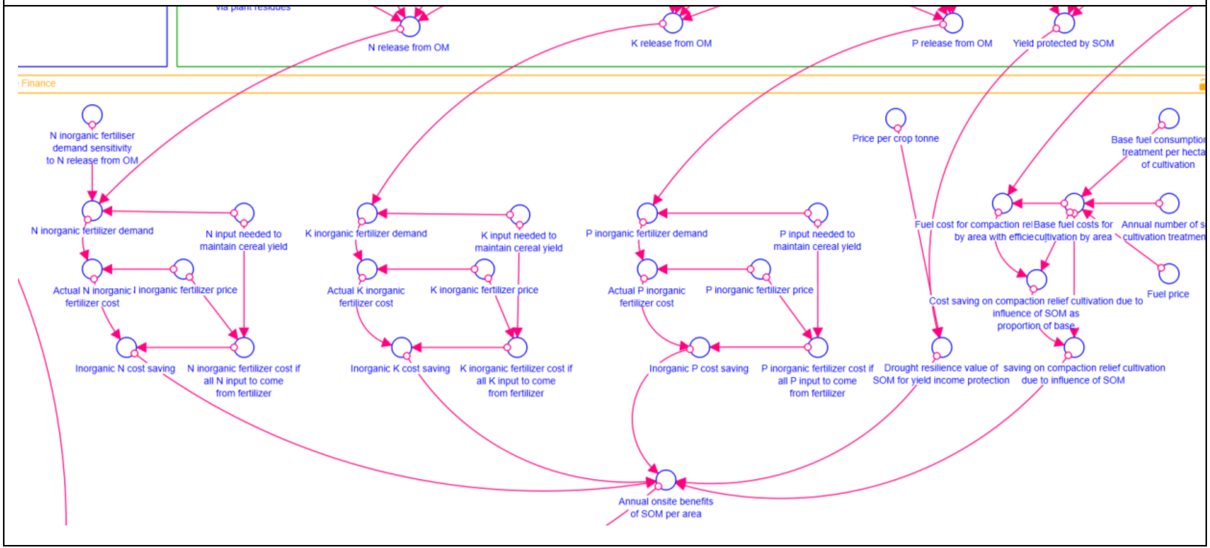
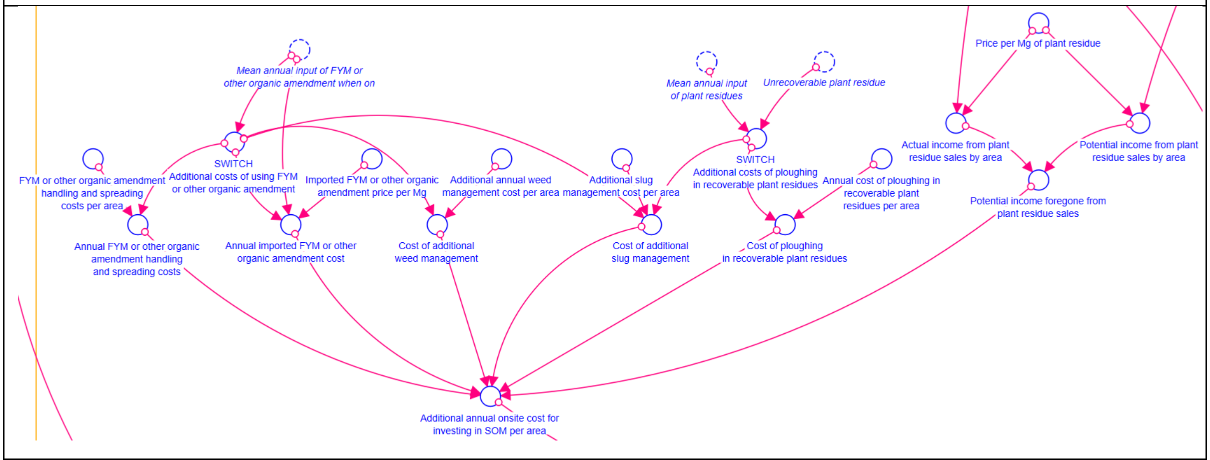


Figure 11: Structure for calculating the costs to the land manager of increasing SOC stocks.



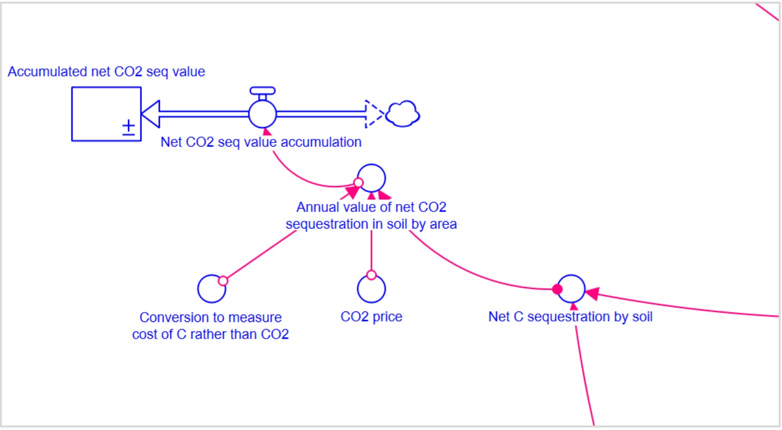
The “Additional annual onsite cost for investing in SOM per area” was subtracted from the “Annual onsite benefits of SOM per area” to calculate the “Farmer net benefit of OM per hectare”. This was represented as a net flow controlling the stock “Farmer CB balance for investing in OM” to track the accumulated balance of on-site OM benefits and costs over time. The “Farmer net benefit of OM per hectare” was controlled by the switch “Farmer Decision to make CBA”, reflecting whether or not the economic value of OM was being recognised in the decision-making processes of agricultural businesses. Since this stock was used to inform decision making elsewhere in the model, this control enabled the model to reflect the assumption that if the benefits and costs of investing are not being accounted for by a land manager, they cannot affect decisions about land management practices.

3.3.2 Off-site benefits and costs

Further structures were added in the model for calculating the value of "external" costs and benefits of ecosystem services generated for off-site actors.

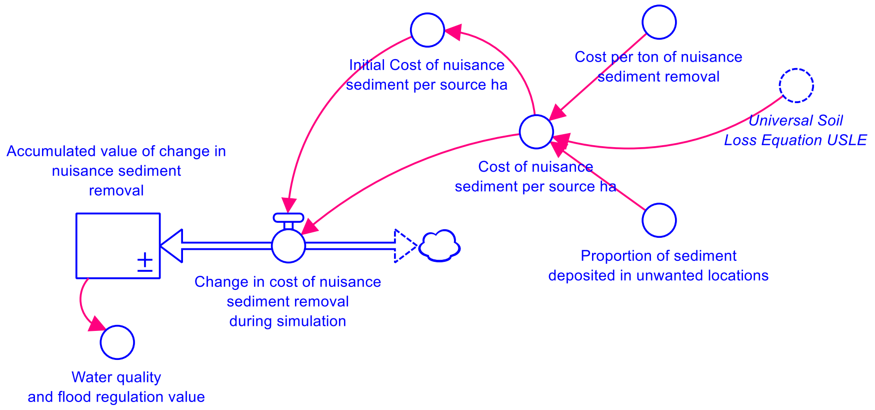
The economic value of the "Net C sequestration by soil" can be considered as the soil's net contribution to the climate change burden borne by society, or soil's potential for providing the climate regulation ecosystem service. Following Graves et al. (2015), this is calculated based on the marginal abatement cost (MAC) of reducing emissions, which the UK Government considers to reflect its long-term policy commitments greenhouse gas emissions reduction (DECC, 2009). In the model, this is used as the "CO2 price" which is multiplied by the variable "Net C sequestration by soil" and a "Conversion to measure cost of C rather than CO2" to calculate the "Annual value of net CO2 sequestration in soil by area". This drives a net flow controlling the "Accumulated net CO2 seq value" to determine the accumulated value of climate regulation over the course of the model simulation. Negative values imply soil is failing to provide a climate regulation service because it is losing SOC and leading to net emissions. Positive values imply soils are providing this ecosystem service. Whether this is increasing or decreasing indicates whether this ecosystem service is improving or declining. The structure is shown in Figure 11.

Figure 11: Structure for calculating the value of soil's climate regulation ecosystem service.



The economic value of soil's contribution to flood regulation and drinking water quality regulation was determined based on the cost of removing sediment used by Graves et al. (2015) based on Anthony et al. (2009). This cost can be considered as an indication of the expenses borne by drinking water companies for removing sediment from drinking water sources and by local authorities for the clearance of public drainage systems. These are off-site costs because they are borne by these actors away from the site of soil degradation and ultimately are borne by drinking water customers and taxpayers. The "Cost of nuisance sediment per source ha" is calculated by multiplying the USLE by the "Cost per ton of nuisance removal" and by the "Proportion of sediment deposited in unwanted locations". This latter variable determines how much of the eroded soil from a source hectare is eventually deposited in a location requiring removal by the example actors mentioned above (base setting at 1 i.e. 100%). The "Accumulated value of change in nuisance sediment removal per ha" for the duration of the simulation is based on the "Change in cost of nuisance sediment removal during simulation" which is the difference between in the "Initial Cost of nuisance sediment per source ha" and the "Cost of nuisance sediment per source ha" to provide a marginal indication of gain or loss in erosion prevention value relative to the starting conditions at the beginning of a simulation run. The "Water quality and flood regulation value" is an indicator equal to the stock (Figure 11).

Figure 11: Structure calculating the value of the water quality and flood regulation services.



3.4 Soil management decisions influence over biophysical processes

Soil organic matter (as represented by SOC) is a manageable soil factor identified by Dominati et al. (2010). Land managers can increase SOC in a number of ways, such as by adding an organic amendment like FYM or compost, through the use of crop rotations with incorporation of plant residues, and through reductions in the number and intensity of tillage practices (Johnston et al., 2009). The original RothC-26.3 model enables the exploration of the quantities and timings of organic materials applications as well as the incorporation of plant residues on a per hectare basis, with each model run representing a particular plot or field as a homogenous land management unit (Coleman & Jenkinson, 1996). This functionality was included as part of the replicated RothC-26.3 core model where the RothC input variables “Mean annual input of carbon from plant residues” and “Mean annual input of carbon from FYM or other organic amendment” are determined by the “Mean annual input of plant residues” and the “Mean annual input of FYM or other organic amendment” respectively, as well as their respective carbon fractions (proportion of their biomass which is carbon). The use of crop rotations can be included in the model using different parameter configurations: for example, the variables “Maximum potential harvested yield” and “Crop plant residue Harvest Index” could be set to rotate annually using different values for the relevant crops, and the linear equation controlling the variable “SOM influence on mean yield variability” (currently set for cereals) changed accordingly. These variables were parameterised for barley corresponding with the rest of the model.

The RothC26.3 model does not include functionality to explore alternative cultivation (tillage) practices. Tillage is said to influence SOC by increasing the rate of organic matter decomposition and promoting SOC mineralisation (Powlson et al., 2011). Reduced tillage is often recommended as a technique for improving soil quality and storing more carbon in the soil as SOC (Minasny et al. 2017). Such activities could be explored in the model with tillage included as a “Rate modifying factor” controlling the decay rates (outflows) of the four SOC stocks. However, despite case studies supporting the idea that reduced tillage can lead to soil improvement and beneficial economic outcomes for farmers (KeySoil, 2010), Chenu et al. (2019) explains that the scientific evidence remains inconclusive and highlights future research needs to help resolve the controversy. Others have also criticised advocating reduced tillage for the purpose of increasing SOC in the UK because “There is a very limited number of publications giving results on the impact of reduced or zero tillage on soil C under the temperate humid climatic conditions of the UK or nearby regions of northwest Europe, as opposed to a large body of data from regions of continental climate in North America or tropical and sub-tropical regions in South America and elsewhere." (Powlson et al., 2011, p. 25). Although structures were added to the model to explore the reported benefit of increasing SOC for improving cultivation efficiency (see sections on-site ecosystem services and on-site costs and benefits), structures relating to cultivation effects on SOC mineralisation were not added to the model in recognition of the scientific uncertainty and relevance to the regional context being studied.

Structures were added to the model to representing land managers' decision-making process of whether to incorporate their crop residues or to sell them ("DECISION To return plant residue to field or to sell"), and whether or not to add an organic amendment such as FYM ("DECISION Add FYM or other organic amendment"). The former controls the variables "Mean annual input of plant residues" and "Harvested plant residue", while the latter controls the variable "Mean annual input of FYM or other organic amendment". Both "DECISION" variables are determined by "DECISION To invest in OM". The "DECISION To invest in OM" is (in the absence of a policy intervention) influenced by "Standard practice to invest in OM" which is determined by "DECISION To keep investing in OM". This is determined by the stock "Farmer CB [cost benefit] balance for investing in OM" which is controlled by the flow "Farmer Net benefit of OM per hectare". This subtracts the "Additional annual onsite cost for investing in SOM per area" from the "Annual onsite benefits of SOM per area" already mentioned in the section about on-site benefits. This flow calculation is only active (switched on and making the calculation) if "Decision to make CBA switch" is 1, based on the stock "Farmer making a CBA".

The whole structure reflects an assumption underlying farmer education policies: the premise that if the farmer makes a cost benefit analysis of the economic costs and benefits of SOM investment, and those investments can be expected to yield a net benefit within a reasonable time frame (here 5 years) (equation for "DECISION To keep investing in OM" is "(IF(FORCST(CB_balance_for_investing_in_OM, 1, 5)> 0) THEN 1 ELSE 0"), it will be "Standard practice [for the farmer] to invest in OM", leading to their "DECISION To invest in OM". However, if the farmer is not making the cost benefit analysis, or the farmer's forecast for "Farmer CB balance for investing in OM" is negative based on existing information available to them, they will take not choose the "DECISION To keep investing in OM" and therefore won't return plant residues or add an organic amendment. Such an assumption has support based on the KeySoil (2010) cases where farmers were inspired to continue investing in organic matter once they were aware of the economic benefits they received as a result. This structure nevertheless only represents a part of the farmer decision-making process for on the land management practices they use. These can be based on but are not limited to a range of socioeconomic factors (Boardman et al., 2017). The decision process represented in this model is based on detailed case studies specifically focused on organic matter management corresponding to the purpose of this model.

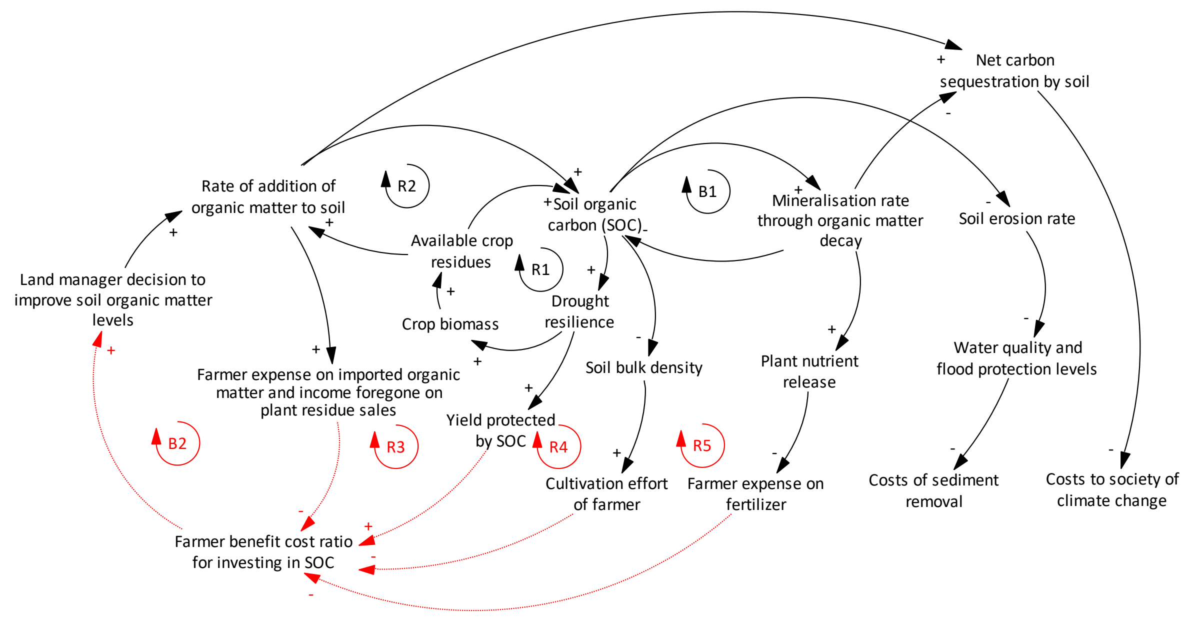
3.5 Model overview: feedback loops

Figure 3 presents a schematic of the model sectors. As shown, SOC is driven by a combination of land management decisions (whether to add an organic amendment or crop residues to the soil) and onsite ecosystem services (the quantity of crop residues available is driven by food and fibre production). The onsite ecosystem services are themselves determined by SOC, thus indicating a feedback mechanism. The land management decisions taken to manage SOC can be informed by the onsite ecosystem services benefits and costs of investing in SOC if the land manager is making a cost benefit analysis and recognising the importance of SOC in their financial assessments. Historically this feedback is assumed to have been inactive, hence the need for the economic assessments recorded by KeySoil (2010). If farmers are unaware of these benefits their land management decisions will not be informed by them. The red arrow represents this conditional relationship. If present, this would indicate a second feedback mechanism. The offsite ecosystem services delivered by SOC and the associated costs and benefits are not connected to the land management decision structures and are thus represented in the model as “externalities” reflecting Graves et al. (2015).

The CLD in Figure 12 distinguishes the feedback mechanisms in the model as individual reinforcing (R) or balancing (B) feedback loops. The variables depicted are simplified aggregations used to distil the essence of the operational SFD structure of the simulation model. As shown, there are three “biophysical” feedback loops (black) and four inactive “decision” feedback loops (red). R1 represents how increases in SOC can improve drought resilience leading to higher crop biomass production and more available crop residues, a proportion of which are unavoidably added to the soil because they are irrecoverable by the farmer, increasing the SOC stock further. R2 reflects the same process for crop residues which are recoverable by the farmer who decides whether to sell them (e.g. as straw) or to add more organic matter to the soil. B1 represents the balancing feedback loop whereby higher SOC stocks increase the rate of mineralisation (with more organic matter there is more organic matter decaying per unit of time) which depletes the SOC stock. The inactive decision loop R3 shows how increases in SOC reduce the soil bulk density which, because of the positive relationship, would reduce the cultivation effort the farmer needs to relieve soil compaction. The cultivation effort is then accounted for in farmers’ business finances (e.g. based on fuel costs, as in the model). The inactive decision loop R4 shows how higher SOC stocks and improve drought resilience provides yield protection which has a financial value. The inactive decision loop R5 shows how higher SOC stocks lead to higher mineralisation of organic matter and release plant nutrients which reduce farmers’ need for expenditure on inorganic fertilizers. The inactive decision loop B2 shows how if the farmer increases the amount of organic matter added to the soil, it will increase their expenses, such as on handling or importing FYM, and reduce the income they receive from plant residue sales. All of these loops are inactive because they are not accounted for in a cost benefit ratio of investing in organic matter and used to support land manager decisions on whether to improve soil organic matter levels.

The influence of SOC on the external costs of eroded sediment removal (water quality and flood regulation) and costs to society of climate change (climate regulation) are not part of a feedback loop.

Figure 12: CLD showing the feedback loops in the model.



3.6 Basic settings

The global settings of the simulation model defined in the modelling software may be changed for the purposes of validation testing, policy design or use of the model for other purposes beyond this thesis. The basic settings used in this thesis were:

- Start time: 1852 (first year with RothC-26.3 data for the Hoosfield plots (Coleman & Jenkinson, 2014) for comparison with historical data, or 2020 (roughly the “present day”) for policy tests;
- Stop time: 2020 (roughly the “present day”) for comparison with historical data, or 2030 (Defra target year for sustainable soil management (HM Government, 2018));
- Time units: years;
- Delta Time (DT): 1/365 (i.e. provides a daily timestep);
- Integration method: Euler.

The model is fully documented according to the guidelines of Rahmandad & Sterman (2012) in the Appendix and the Stella “.stmx” model file is attached to this thesis.

Chapter 4. Model Analysis

4.1 Model behaviour

The model parameters were adjusted to reproduce the RothC-26.3 simulation results for SOC on the “Unmanured” Hoosfield treatment plot at Rothamsted and were extended to the year 2020 (roughly the “present day”). This was considered to represent a “Base Case” of declining SOC stocks which mirrored the historical trend of SOC decline in England and Wales on arable sites at a national level. The model parameters were also adjusted to reproduce the RothC-26.3 simulation results for SOC on the “Manured annually” Hoosfield treatment plot for the same time period. This was considered to represent a “Best Case” in which SOC stocks had been increasing historically on the plot contrary to the national trend. Additionally, model parameters were adjusted to produce a “Worst Case” with a more rapidly declining SOC trend than at the Hoosfield unmanured plot. These simulation results and the model settings required to produce them were compared with each other and those of an “Equilibrium” (no change) simulation run to investigate which model structures were responsible for the resulting behaviour. Simulation results for SOC in Mg ha^{-1} and % carbon (w/w of soil) are shown in Figures 13a and 13b respectively.

Figure 13a: Base, Best and Worst Case model runs for SOC (units Mg ha^{-1}).

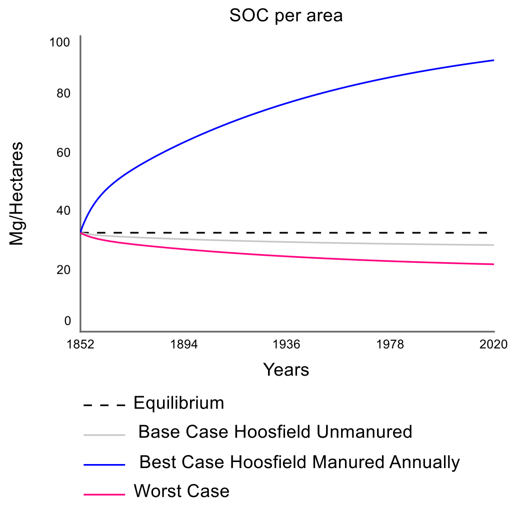


Figure 13b: Base, Best and Worst Case model runs for SOC (units % carbon w/w).

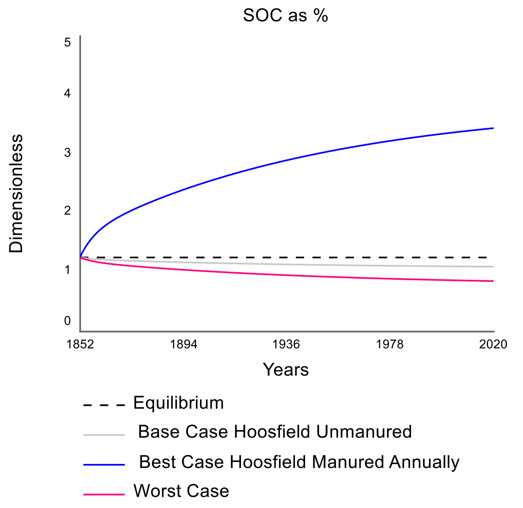


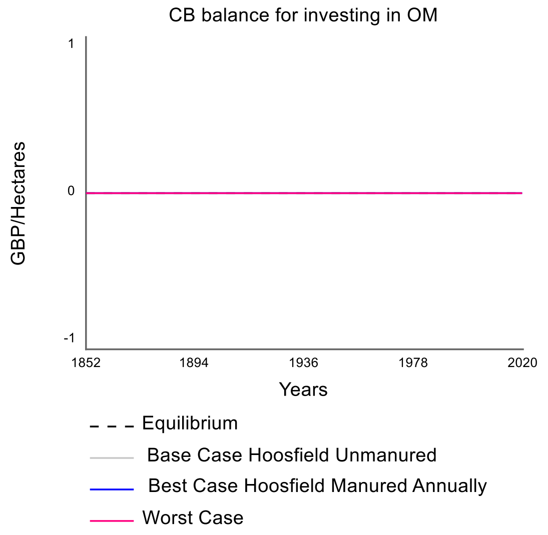
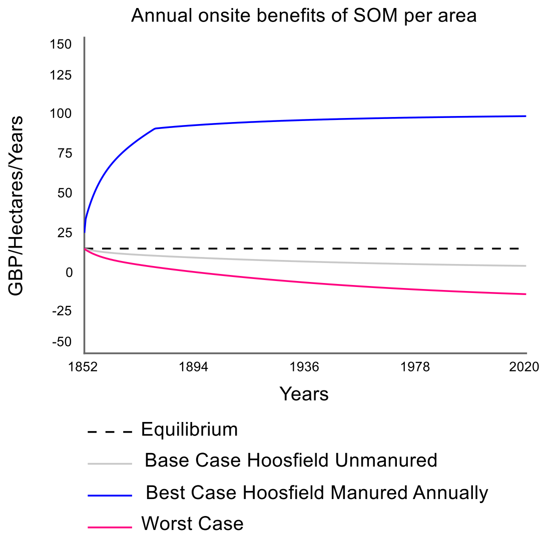
Table 2 shows which model settings were altered to produce the behaviour for each Case. As shown, the Base Case results could only be generated assuming a maximum and constant barley yield of 7 Mg ha^{-1} (which is the national maximum for the years 2013-2017) and assuming that even when the land manager decides not to invest intentionally in SOC, 28.5% of recoverable crop residues are still returned to the field. This differs from the historical barley yields at Hoosfield which vary over time and on average were much lower, while the proportion of crop residues generated on the plot which were incorporated into the soil is not reported (Rothamsted Research, 2012). The Equilibrium results were generated using the same settings, but using an unrealistically high maximum yield of 8.34 Mg ha^{-1} to enable 1.6 Mg of carbon to be added per hectare per year from plant residues as in the Base Case. Using the same settings as the Base Case, the Best Case could only be generated by introducing an exogenous reason to invest in SOM i.e. a decision to increase SOC levels not determined endogenously by the model structure. At the Hoosfield site, this was because of the motivation to conduct a scientific experiment. Beyond Hoosfield, other motivations could be farmers adopting organic production methods dependent on manures for nutrient inputs, or through existing policy instruments which are not based on actual or desired SOC levels. By comparison, the Worst Case results were generated with the same settings as the Base Case, except that the "Minimum proportion of recoverable plant residue being returned" was set equal to 0%.

Table 2: Parameter settings used in the Equilibrium, Base, Best and Worst Case simulation runs.

Variable	**Equilibrium**	**Base Case**	**Best Case**	**Worst Case**	**Units**
Maximum potential harvested yield for barley	8.34	7	7	7	Mg ha^{-1} year^{-1}
SWITCH 1 Exogenous reason to invest in SOM 2 Dynamic reason to invest in SOM	2	2	1	2	Dimensionless (switch)
Minimum proportion of recoverable plant residue being returned	0.285	0.285	0.285	0	Dimensionless (fraction)

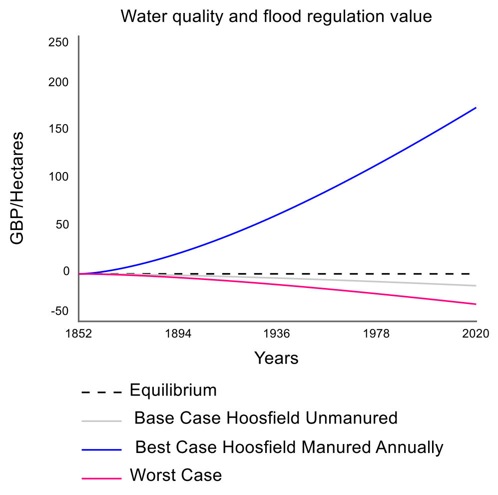
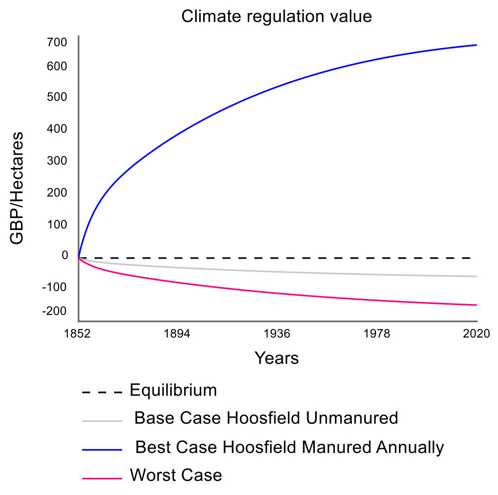
In the Base, Worse and Best Cases the SOC indicator variables exhibit goal-seeking behaviour (Figures 13a and 13b), converging towards a new equilibrium beyond the year 2020 at a different level for each Case. The structural reason for this dynamic behaviour is that SOC is a sum of the four carbon stock levels as represented in the RothC-26.3 core model: RPM, DPM, BIO and HUM. The outflow of each of these stocks is determined by the quantity of carbon in the stock (a first-order control as represented by balancing feedback loop B1 in Figure 12), the rate modifying factors (proportion of carbon in the stock being decayed) and the decomposition rate constant (residency time). These outflows add further carbon to the BIO and HUM stocks or are lost as carbon dioxide emissions. The long residency time of the HUM stock in particular (50 years) means that if the inflow of carbon, such as from plant residues and manures, is higher than the outflow of decay and set at a constant rate, carbon will accumulate in the stocks. However, it will accumulate at a decreasing rate over time, because a higher stock level increases the rate of decay when the rate modifying factors are fixed at a constant fraction as is the case here. Likewise, if the inflow of carbon is lower than the outflow of decay, the stock will begin to deplete. However, it will deplete at a decreasing rate over time, because a lower stock level decreases the rate of decay when the rate modifying factors are fixed at a constant fraction due to the balancing feedback loop B1. The Equilibrium run maintains SOC levels throughout the simulation time because the maximum yield has been set sufficiently high such that the inflow of carbon from crop residues matches the outflow of decaying organic matter. In dynamic terms, balancing loop B1 dominates reinforcing loops R1 and R2.

Looking beyond the RothC-26.3 core model sector, the origins of the simulated behaviour can be identified in the wider model structure. First, a comparison of the simulation results for each Case for the variable “Farmer CB balance for investing in OM” (Figure 14a) illustrates why an “exogenous reason” is required to increase SOC levels and that efforts to improve SOC may not arise endogenously through land managers’ decision structure represented in the model: the benefits and costs of investing in SOC are not being calculated or considered in land management decisions, and actions to increase SOC such as incorporation of plant residues or addition of FYM or another organic amendments are not being made with reference to the role of SOC in delivering on-site ecosystem services. This means that land managers don’t receive an information feedback from their financial decision making that result from changes in SOC following how they use plant residues and organic amendments. The unknown consequences of this are declining on-site ecosystem services and corresponding loss of unaccounted economic benefits for the land manager (Figure 14b), such as declining drought resilience value and reduction in cultivation efficiency, attributable to the loss of SOC in the Base and Worst Cases. By comparison, the economic benefits of the Best Case are also unaccounted for by the land manager. This is why even under these circumstances an exogenous (non-dynamic) reason still is needed for the farmer to invest in OM throughout the simulation period. To the land manager who is unaware of the role of SOC in influencing the performance of their business, the Base, Best and Worst Cases appear to be financially the same as an “Equilibrium” simulation. Feedback loops R3, R4, R5 and B2 in Figure 12 do not operate.

Figure 14a: Farmer CB balance for investing in OM for the Base, Best and Worst Cases.	Figure 14b: Value of ecosystem services benefits provided by SOC which are unrecognised by the land manager in the Base, Best and Worst Cases.
	

The structural reason behind these results is that, in the modelled Cases, the land manager is initially unaware of the potential ecosystem services benefits of SOC and is not making a cost-benefit analysis based on this knowledge when the parameter "Initial making CBA" is set to zero. This means that their "Farmer CB balance for investing in OM" remains constant at zero and does not affect the farmers' "DECISION To keep investing in OM" and thus it is not a "Standard practice to invest in OM". The information feedback loop which influences the "DECISION To invest in OM" therefore does not operate throughout the simulation, and a farmer would only invest in OM with its unrealised costs and benefits attributable to changes in SOC if encouraged by a factor exogenous to the model. This corresponds to the assumption behind farmer advisory initiatives such as KeySoil (2010) which aim to assist farmers in making a CBA of investing in SOC, assuming that they are not already making a CBA and are therefore unaware of SOC's role in onsite ecosystem services provision.

A similar structural explanation can be proposed with reference to the simulation results for the variables "Water quality and flood regulation value" and "Climate regulation value" presented in Figures 15a and 15b respectively. These variables indicate the net value of SOC to water companies and local authorities who need to remove eroded soil sediment, and to civil society who expect to bear the costs of climate change impacts. Neither of these variables are connected to the decision-making process of the land manager about whether to add more organic matter and are therefore externalities to the farmers' business. This means that in the Base and Worst Cases, the decline in water quality, flood and climate regulation services do not influence the land manager's decision to alter their practices. Likewise, the increase in the value of SOC providing a climate regulation service and in avoiding sediment removal costs in the Best Case are not used to reward the land manager who instead requires an exogenous reason for investing in SOC in this simulation run. The absence of this feedback loop from changes in offsite ecosystem services to land managers is proposed by Graves et al. (2015) as representing an example of market and institutional failure and is proposed as a structural explanation for why soil degradation may have been occurring historically despite high offsite costs. Referring to Figure 12, it can be seen that no causal relationships connect these impacts with land managers' decision processes

Figure 15a: Change in economic value of the water quality and flood regulation ecosystem services for the Base, Best and Worst Cases.	Figure 15b: Change in economic value of the climate regulation ecosystem services for the Base, Best and Worst Cases.
	

4.2 Validation testing

Following guidelines and techniques described by Barlas (1996) and Sterman (2000), formal model analysis and validation procedures were performed throughout the iterative modelling process to continually build confidence in the model. Where relevant, partial model testing (Homer, 2012) was used to test and validate smaller model building blocks as documented in Chapter 3. The results of model validation procedures pertinent to the whole model are presented in this Chapter with three purposes:

1. Support an overall evaluation of the extent to which the model can be used with confidence to address the Research Questions;
2. Inform a deeper interpretation of the model behaviour provided in 4.1 above;
3. Highlight leverage points and challenges for natural capital investments in promoting desired system behaviour.

Following Barlas (1996), three types of validation tests are reported: direct structure tests, structure-oriented behaviour tests and behaviour pattern tests. Tests focused on assessing model structure were prioritised over tests focused on model behaviour to ensure “the right outputs are being generated for the right [structural] reasons” (Barlas, 1996, p.189).

4.2.1 Direct structure tests

Direct structure tests help assess the validity of a model’s structure by comparing it with existing knowledge about the “real” system (Barlas, 1996). The direct structure tests reported here include the structure verification test, parameter verification test, direct extreme-conditions test, boundary adequacy test, and the dimensional consistency test.

The purpose of the structure verification test is to determine the extent to which a model’s structure conforms to existing knowledge about the structure of the “real” system (Barlas, 1996). This test can be conducted on an empirical basis through a comparison of the model equations with relationships that are known to exist in the real system (Forrester & Senge, 1980), and on a theoretical basis by comparing the model against generalised knowledge reported in relevant literature (Barlas, 1996) or through engagement with system operatives (Andersen et al., 2012; Forrester, 1992). As reported in Chapter 3, the model component representing the biophysical processes controlling SOC as a soil health and natural capital indicator was replicated and translated into a stock-and-flow structure from the well-established, widely-used and empirically validated RothC-26.3 model based on the model documentation (Coleman & Jenkinson, 1996). The forms of the equations were altered to translate RothC-26.3 into a system dynamics stock with reference to Parshotam (1996). This part of the model can therefore be considered to pass the structure verification test on an empirical basis. As reported in Chapter 3, the remainder of the model structure was constructed from a vast quantity of documentary evidence (secondary data) including peer-reviewed sources, Defra commissioned scientific reports and individual farm case studies. To do so, variables and relationships identified in the literature search were translated into a stock and flow structure according to the guidance of

Sterman (2000). Where uncertainties about system structure were reported in the literature, linear functions were used based on regression equations from peer-reviewed sources: for example, the controversy surrounding the extent to which SOC can influence crop yield variability through its effect on soil water holding capacity, and the decision to use the function reported in Pan et al. (2009). In some instances it was necessary to infer variables and relationships from secondary sources where these were not sufficiently explicit in the text: for example, the structure controlling the "Effect of SOM compaction regulation on cultivation efficiency" and resulting "Cost saving on compaction relief cultivation due to influence of SOM". On a theoretical basis, the model can therefore be considered sufficiently valid given its strong grounding in published sources, while proposing some explicit formulations of implicit or hypothesised causal relationships. The latter presents the opportunity to further improve the model with research stakeholders beyond the completion of this thesis.

The purpose of the parameter verification test is to determine whether each parameter (constant exogenous variable) corroborates with the known components of a "real" system (conceptual) and whether their values lie within plausible ranges (numerical) (Barlas, 1996). Based on Chapter 3 and the above discussion of structural validity, the corroboration between the model parameters and existing knowledge of the system can be considered sufficient to provide confidence of conceptual parameter validity. Regarding the numerical validity of parameter values, actual data was used where possible: for example, the MAC price of CO_2 used in Graves et al. (2015). If such parameter data was unavailable, assumptions needed to be made using available information: for example, the "Maximum potential harvested yield" for barley was based on the 2017 figure reported in Defra (2018b). Other simplifying assumptions needed to be made about certain parameters to suit the model to a specific setting to ensure internal consistency. For this reason, the model was set up for a plot of land producing barley on a continuous cropping basis according to environmental conditions (e.g. soil type, climate) at the Hoosfield site near Harpenden. Where information was insufficient for well-grounded assumptions to be made, these were estimated experimentally by running simulations to explore which parameter values produced the most reasonable behaviours: for example, the value of the parameter "SOM time to BD rebound following disturbance" was set in this way by comparing the results of "Cost saving on compaction relief cultivation due to influence of SOM" with case studies reported by KeySoil (2010). Based on this discussion, confidence in numerical parameter validity can be concluded to be strongest where these were based on actual data, less strong where based on reasonably supported assumptions, and sufficiently strong when estimated through model experimentation.

The purpose of the direct extreme-conditions test is to evaluate the response of the model to extreme settings of each model parameter against how the "real" system is known or can be expected to respond (Forrester & Senge, 1980). Each parameter was altered in the model to have extremely low or extremely high values and the model software was consulted to see if computational errors would be generated. No errors were detected using these tests and the structure of the model can be considered sufficiently robust to extreme conditions.

The purpose of the boundary adequacy test is to determine whether all structures necessary for fulfilling the purpose of the model are present (Sterman, 2000). In this study, the purpose of this model is to provide answers to the Research Questions listed in Chapter 1. This means that the functionality of the model must be sufficient for identification of the structural causes of soil degradation in England that relate to financial incentives (Objective 1) and explore opportunities and challenges for natural capital investment as an intervention to address them (Objective 2). Given the strong grounding of the model in documentary evidence spanning soil science, environmental economics, system dynamics and farmer decision making as discussed above and presented in Chapter 3, the model boundary can be considered sufficiency adequate for its purpose. One potential objection to this argument is the exclusion of explicit structures representing existing agricultural and environmental policy which is known to influence farmers' decisions about the adoption of soil and water conserving practices via a variety of socioeconomic influences (Boardman et al., 2017). Such an argument is supported by the view that existing policy should be considered a part of a system's structure (Sterman, 2000). Nevertheless, the purpose of the model was to seek endogenous causes of soil degradation and was the reason the system dynamics method was chosen (see Chapter 2 for methods choice). One of the criticisms of existing UK environmental and agricultural policy such as the Single Farm Payment is that financial incentives for achieving environmental goals are based on inputs and practices ("action oriented") rather than outcomes ("results based") (Burton & Schwartz, 2013). Existing UK policy that influences farmers' management of SOM cannot be said to be based on achieving certain SOC levels or change trajectories, so considering this policy as an exogenous factor outside of the model boundary (such as through the "SWITCH 1 Exogenous reason to invest in SOM 2 Dynamic reason to invest in SOM") is supported and adheres to the purpose of the model. The potential also remains for the model to be adapted to serve the purpose of a policy evaluation tool for assessing the effectiveness of historic or existing policies. A second potential objection is that the model is focused on specific ecosystem services as influenced by SOC only and do not account for the broader potential impacts of management practices that aim to manage SOC, such as nitrogen leaching issues relating to FYM applications. Potential important exclusions are considered in the interpretation of model results and highlight areas for further refinement in potential future work.

The purpose of the dimensional consistency test is to confirm the mathematically consistent use of units on both the left- and right-hand sides of model equations (Barlas, 1996). This was performed using the modelling software with the “check units” function. In the case of this model, no unit errors were reported and thus confirm the overall dimensional consistency. The other component of this test is to check that units have “real world” equivalents such that no variables had been introduced with the purpose of “forcing” the model to function. As already discussed, sufficient structural validity was confirmed. A feature of this is that all variables have units with real world equivalents or are permissible as part of operational calculation steps.

4.2.2 Structure Oriented Behaviour tests

Structure-oriented behaviour tests help determine the validity of a model’s structure indirectly by assessing model-generated behaviour patterns using simulation to uncover potential structural flaws (Barlas, 1996). The structure-oriented behaviour tests reported here include the integration error test, qualitative features test, family member test and multiple mode test.

The purpose of the integration error test is to determine whether model simulation results are sensitive to the choice of time step or numerical integration method used in the model settings (Sterman, 2000). To do this, results from the Base Case which were produced using the settings mentioned in section 3.6 were compared with simulations using half of the original timestep, and then with using the RK4 integration method instead of the original Euler method. No difference in model outputs were observed, confirming that the simulation results were not sensitive to alternative timesteps or integration methods within these ranges.

The purpose of the qualitative features test is to assess whether the major qualitative behaviour patterns of simulated model variables correspond to actual data (reference modes) for those variables in the “real” system under specific conditions: in other words, to determine whether “the right output behaviour is being generated for the right reasons” (Barlas, 1996, p. 186). To perform this test the results of the Base Case, Worst Case, Base Case and Equilibrium simulation runs were compared with reference mode data for the central soil health indicator SOC (both Mg carbon ha^{-1} and % carbon w/w soil). As mentioned in section 4.1, SOC (Mg carbon ha^{-1}) results for the Base and Best Cases matched to a sufficient degree of accuracy the RothC-26.3 output data from Coleman & Jenkinson (1996) for the unmanured and manured annually plots. In the original source these had been validated by empirical field data. In the expanded model described in Chapter 3, to produce these results (Figures 13a and 13b) required the assumption that the “Minimum proportion of recoverable plant residue being returned” is 28.5% of “Recoverable crop plant residue based” and that the “Maximum potential harvested yield" is 7 Mg ha^{-1}. The behaviour pattern of SOC for the Worst Case also exhibits a goal-seeking transient, but appears to stabilise at a lower equilibrium level to that of the Base Case. The direction of declining SOC (% carbon w/w) levels for the Base and Worst Cases correspond to declining SOC patterns recorded for aggregated arable sites in England and Wales between 1980 and 1995 (Figure 4a), and to declining SOC levels from 1978 through 1998 to 2007 for the 1km grid square in which Hoosfield is located (Figure 4b). The shape of declining SOC levels for the Base and Worst Cases correspond to actual plot-scale data reported at Hoosfield (Figure 6a). The shape of SOC patterns over time for the national data is discrete, so it is only possible to compare their trajectory. The SOC values of the Base and Worst Case differ in absolute terms from the national and the 1km grid square estimates to a considerable extent (see Table 3). However, this is to be expected given the difference in spatial granularity of the datasets, since the model is being run at the individual plot-level representing highly specific conditions, whereas the national and $1km^2$ grid data present aggregate measures at much broader scales. For these reasons, the results of this test suggests that if the Base and Worst Cases are considered to represent English soils with particularly poor SOC status (i.e. indeed the "worst case"), the model structure could be considered sufficiently valid to the extent that it has the potential to provide SOC data corresponding to the "real system" in a certain configurations. This is because, according to the model settings for the Hoosfield unmanured plot, a continuous monoculture of barley is being grown without regular crop rotations contrary to modern agricultural practice in England (Powlson et al., 2011). Because of this, the results of this test suggest that "the right output behaviour is being generated for the right reasons" (Barlas, 1996, p. 186): even though the absolute numbers appear sensitive to parameter settings, these actually define local conditions, while the structure produces reasonable behaviour for such conditions. This test thus provides confidence in the validity of the model structure while also recommending parameter sensitivity tests be used to support the interpretation of results. Results of parameter sensitivity tests are reported in this Chapter.

Table 3: Comparison of reference and modelled data.

Year	**Reference data**		**Model**		
	Eng arable (Rusco et al., 2001)	**Topsoil C conc. g/kg for Hoosfield 1km grid sq (Bradley et al., 2005)**	**Base**	**Worst**	**Best**
1978	N.D.	2.476	1.11	0.89	3.23
1980	3.3	N.D.	1.11	0.89	3.24
1995	2.8	N.D.	1.11	0.88	3.33
1998	N.D.	2.307	1.11	0.87	3.34
2007	N.D.	2.143	1.10	0.86	3.39

The purpose of the family member test is to determine whether the model structure is capable of generating behaviours observed in other instances of the same system (Sterman, 2000). As mentioned above, the model parameters were set to correspond to environmental (climate, soil type) and crop conditions (barley) at the Hoosfield site at Rothamsted to produce the Base, Best and Worst Case results. To perform the family member test, the model was run with a different set of parameter values designed to reflect a plot with a permanent grass (pasture) crop while under the same environmental conditions as the Hoosfield site. Table 4 reports which variables were reset for the run "Family member test (grass)" and the simulation results can be compared against the other runs as shown in Figure 16a and 16b.

Table 4: Comparison of parameter settings for the family member validation test.

Variable	**Units**	**Worst Case (barley crop)**	**Family member test (grass as a crop)**
“Maximum potential harvested yield”	Mg ha^{-1} year^{-1}	7	13 (Cotswold Grass Seeds Direct, 2019)
“Crop plant residue Harvest Index”	Dimensionless (fraction)	0.5	0.5 to return the same value as “Actual harvestable crop yield” because all the “Maximum potential harvested yield” accounts for all biomass as the plant residues are the crop itself
“Residue recovery efficiency”	Dimensionless (fraction)	0.6	0.6 (assumed the same as barley)
“Carbon fraction of plant residues”	Dimensionless (fraction)	0.4	0.4 (FAO, 2019)
Initial stock levels (1852) RPM, DPM, BIO and HUM	Mg ha^{-1}	Reported in RothC-26.3 model documentation (Coleman & Jenkinson, 1996)	Same as Base Case (Coleman & Jenkinson, 1996).
“C Crop management factor” (for USLE calculation)	Dimensionless (multiplier)	0.1	0.004 (Morgan, 2005)
“Plant residues CN ratio”	Dimensionless (ratio to 1)	80	20 (Planet Natural, 2019)
“Price per Mg of plant residue”	GBP Mg^{-1}	6	38 (The Farming Forum, 2019a)
“Price per crop ton”	GBP Mg^{-1}	190	38 because the plant residue is the crop (same as above)
“Minimum proportion of recoverable plant residue being returned”	Dimensionless (fraction)	0	0 (same as Worst Case)

Figure 16a: Family member test results for SOC indicator (% carbon w/w soil).

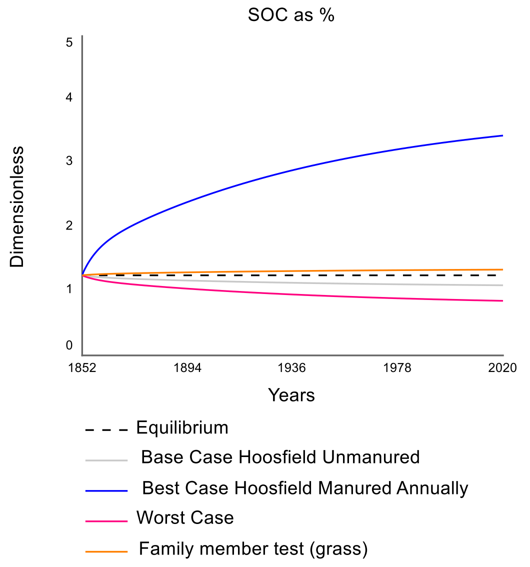
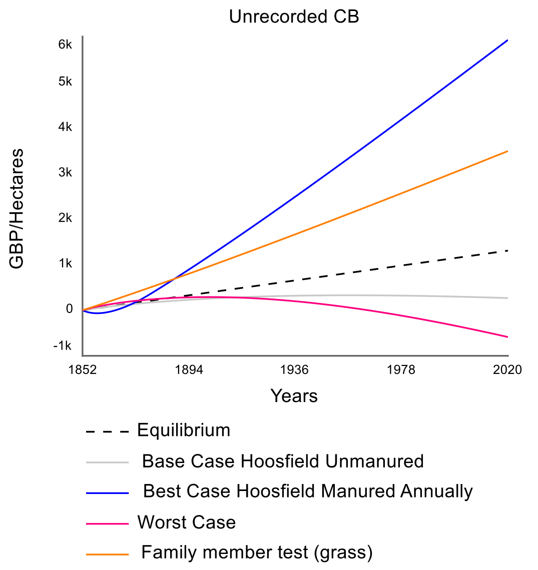


Figure 16b: Family test results for the potential (unaccounted for) cost benefit balance of investing in OM the farmer could receive if aware



The results of the family member test using settings for permanent grass crops indicate that SOC levels increase to converge at an equilibrium slightly higher than the Equilibrium run. This is because of the higher "Maximum potential harvested yield crop yield" which returns a higher quantity of "Unrecoverable plant residue" than barley in the Base and Worst Cases. Grass cover is reported to stabilise SOC at higher levels than arable crops (Chenu et al., 2019). These results therefore suggest that the model structure is capable of producing reasonable SOC behaviour for alternative cropping configurations at the same site. Looking at the potential cost benefit balance from changes in onsite ecosystem services, as reported in the variable "Unrecorded CB" of which the farmer is unaware and does not influence their management practices so far, it appears that this cropping choice could offer greater overall returns to the farmer than the Base or Worst Case because they can also sell all grass crop residues (silage) to receive an income. This is because of the higher "Price per Mg of plant residue" while maintaining and unknowingly benefiting from stable SOC levels. This highlights the sensitivity of the financial model outputs to the variable "Price per Mg of plant residue" for further analysis. This test also highlights the potential importance of crop choice, since this determines the ecosystem services value of SOC on a particular site. The structure of land managers' decision process for crop choice (including rotations and different costs of managing specific types of crop) is not yet included in the modelled structure but could be a valuable addition in future work beyond this thesis.

The purpose of the multiple mode test is to determine how many modes of behaviour are produced with a view to highlighting those that could be targeted by policies. In the case of SOC as the central variable, it is evident that this indicator always converges towards stabilising at an equilibrium for the structural reasons discussed above. As highlighted by the family member test, financial indicator variables are driven by SOC but are sensitive to the values of exogenous parameters such as “Price per Mg of plant residue” which can determine the behaviour mode for a cost-benefit analysis outcome over time. That SOC exhibits a specific mode of behaviour regardless of crop type (goal-seeking), whereas the behaviour of financial indicators may present different modes of behaviour, presents parameters for further behaviour sensitivity analysis (section 4.2.3) and considerations for later policy design (Chapter 5).

4.2.3 Behaviour reproduction tests

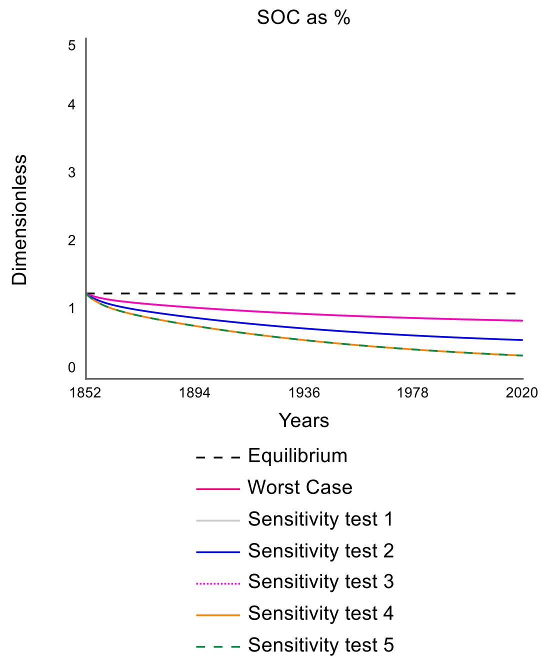
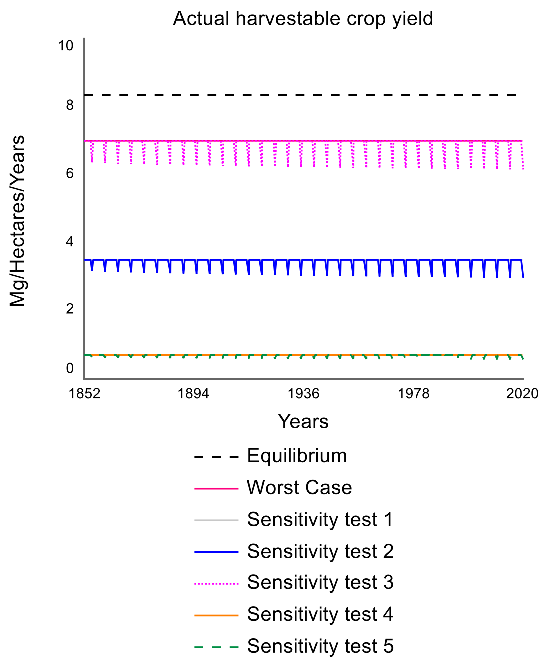
Behaviour reproduction tests help determine whether the model outputs are sufficiently similar to the behaviour of interest in the system being studied (Barlas, 1996; Sterman, 2000). Correspondence between the behaviour of model outputs and actual timeseries data have already been discussed from the perspective of structure-oriented behaviour tests (section 4.2.2), showing that SOC behaviour direction and shape patterns were sufficiently similar to confirm model structure, while discrepancies in the absolute quantities for SOC indicator variables suggested that the model was sensitive to certain parameter settings given the model’s detailed (though adaptable) spatial resolution. Multiple modes of behaviour for financial variables were also determined to be sensitive to exogenous parameter values, although these did not affect land manager decision variables given that endogenous information feedbacks were not operating according to the conditions of the modelled Cases: in short, in the existing model structure, sensitivities in economic variables do not affect SOC because they are not endogenized as shown in Figure 12.

That SOC behaviour is sensitive to environmental conditions and crop choice is not a new insight and can be explored in the original RothC-26.3 model regardless of the contribution of this thesis, such as through changing soil type and climatic conditions (Coleman & Jenkinson, 1996). That modelled behaviour of financial indicators added in this thesis are sensitive to exogenous parameter conditions but are not driven endogenously also has few implications for the accuracy of modelled behaviour when land managers do not receive information feedbacks that influence their land management decisions, as in the Base, Best and Worst modelled Cases. This is important, however, if policies are to be tested which aim to affect information feedbacks between onsite and offsite financial variables to motivate changes in land management practices, such as by using natural capital investments. From the perspective of the model's ability to reproduce behaviour reference modes, the sensitivity insights delivered through the structure-oriented behaviour tests suggest that the model is sufficiently robust. From a policy design and analysis perspective, the structure-oriented behaviour tests point out the potential for counterintuitive and non-linear behaviour to be generated if natural capital investment products aim to internalise economic externalities by introducing information feedback mechanisms between economic indicators of SOC's contribution to ecosystem services and land management decisions.

In addition to these behaviour sensitivity insights from other tests, focused sensitivity tests were also used. In the preceding discussion, settings for the value of the variable "Maximum potential harvested yield" was identified as being overoptimistic compared to historical data for barley yields at the Hoosfield site. In this model, the "Actual harvestable crop yield" is dynamically determined through "SOM influence on mean yield variability" and "Drought effect on yield given SOM status" which is driven by SOC, and this acts as a multiplier on the "Maximum potential harvested yield" to calculate the "Actual harvestable crop yield". Runs exploring lower yields, and with or without drought conditions, were compared against the Worst Case. The parameter changes are shown in Table 5 and the results presented in Figures 17a and 17b. The results indicate that modelled SOC is not sensitive to drought conditions, but more so to changes in the "Maximum potential harvested yield". This meaning that the reinforcing feedback loop of SOC influencing the "Actual harvestable crop yield" (R1 in Figure 12) is less important in driving behaviour than the "Maximum potential harvested yield" as an exogenous input. That the SOC results for runs with drought conditions were indistinguishable from those without drought conditions illustrates that where drought events every 5 years may reduce the amount of plant material available to be added to soil ("Crop plant residue production") in the short term, this is inconsequential for SOC compared to the absolute maximum yield potential.

Table 5: Comparison of values used in sensitivity analysis for the variable “Maximum potential harvested yield”.

Run	**“Maximum potential harvested yield” (Mg ha^{-1})**	**“SWITCH Drought conditions” (Dimensionless)**
Equilibrium	8.35	0
Worst Case	7	0
Sensitivity test 1	3.5	0
Sensitivity test 2	3.5	1
Sensitivity test 3	7	1
Sensitivity test 4	0.7	0
Sensitivity test 5	0.7	1

Figure 17a: SOC sensitivity analysis results for variable “Maximum potential harvested yield”.	Figure 17b: Actual harvestable crop yield results for sensitivity analysis for variable ““Maximum potential harvested yield”.
	

4.2.4 Validation summary

Table 6 summarises the results of the model validation tests, including comments on their implications for model confidence, understanding of model behaviour and policy design.

Table 6: Summary of validity test results and implications.

Test	**Results**	**Implications**
Structure verification	Sufficiently to strongly valid	Structure strongly grounded in published sources; opportunity to improve upon some proposed formulations in future work; structure is appropriate for model purpose.
Parameter verification	Sufficiently to strongly valid	Grounded in published sources; assumptions strongly supported; suitably tested experimental variables; structure is appropriate for model purpose.
Direct extreme-conditions	Strongly valid	Robust to direct extreme conditions.
Boundary adequacy test	Strongly valid	Structural exclusions recognised and noted opportunities for inclusion during future work; structure is appropriate for model purpose
Dimensional consistency test	Strongly valid	Dimensionally consistent and variables with real-world equivalents; structure is appropriate for model purpose.
Integration error	Strongly valid	Not sensitive; model setting choices appropriate.
Qualitative features	Strongly valid	Direction and pattern sufficiently similar to reference mode behaviour; absolute values vary but reflect differences in data spatial scale and the local conditions to which the model parameters are set; structure is appropriate for model purpose; recommends parameter sensitivity tests to support results interpretation.
Family member	Strongly valid for this model structure, while	Capable of producing reasonable patterns of behaviour for different local conditions (e.g. crop types); confirms adaptability of model structure to other locations beyond parameter ranges set for the analyses in section 4.1;

	recommends points of consideration for policies that introduce new feedback structures.	differences in behaviour patterns between SOC indicators and financial indicators not significant for this model structure because no operating feedbacks between ecosystem services values and land manager decisions (Figure 12); however, test results suggest potential for surprising non-linear effects to result should policies be used to introduce such feedbacks – recommends consideration in policy analysis; structure is appropriate for model purpose and provides behaviour insights.
Multiple mode	Strongly valid for this model structure, while recommends points of consideration for policies that introduce new feedback structures.	Consistent modes of behaviour for SOC and other key biophysical variables (goal-seeking); multiple behaviour modes for financial indicator variables which in this structure are not endogenized (Figure 12) so do not lead to non-linear results; however, test results suggest potential for surprising non-linear effects should policies be used to introduce feedbacks between biophysical, financial and decision variables – recommends consideration in policy analysis; structure is appropriate for model purpose and provides behaviour insights.
Behaviour reproduction	Sufficiently valid	Direction and shape sufficiently similar to reference mode; discrepancies in absolute values traced to difference spatial scales of reference and model data and local conditions on modelled field plots; parameter sensitivities highlighted in earlier tests also highlighted here.
Behaviour sensitivity	Sufficiently valid, while recommends parameters for further sensitivity testing for model analysis.	Behaviour modes are consistent for biophysical variable confirmed; additional insight that initial stock conditions influence rate of change in stock indicator; multiple modes of behaviour for financial variables confirmed; sensitivities in biophysical variables traced to parameter values which recommends parameter sensitivity testing for model analysis; multiple modes of financial variable behaviour recommends for consideration in policy analysis.

Parameter sensitivity	Sufficiently valid recognising which parameters most sensitive	SOC more sensitive to “Maximum potential harvested yield” (exogenous parameter) than “Drought effect on yield given SOM status” (endogenous parameter) suggests feedback loop R1 (Figure 12) less important than exogenous input in driving “Actual harvestable crop yield” which determines plant residue production; important for interpretation of behaviour in addressing Research Questions.

4.3 Main insights from behaviour analysis and validity testing

The insights generated from the model behaviour analysis and validity testing are discussed here in relation to the Research Questions posed in Chapter 1. Research Questions 1.1, 1.2 and 1.3 are addressed here in contribution towards Objective 1. Some provisional insights are provided for Research Questions 2.1, 2.2 and 2.3 towards Objective 2 and further assessment of Natural Capital Investments as presented in Chapter 5.

4.3.1 Understanding of soil degradation

Research Question 1.1 asks “Which dynamic structures could be responsible for promoting the decline of soil natural capital in England?” The results of the model analysis revealed that the stock and flow structure of accumulating cause and effect relationships were central to the decline in SOC as a soil health and natural capital indicator. This is because SOC can be considered as a stock and therefore depletes if the inflows of adding organic matter from crop residues or organic amendments are smaller than the outflows due to organic matter decay. This means that in order for SOC stocks to remain in equilibrium, the inflows of organic matter must equal the outflows of decay, and if SOC stock levels are to be increased, the inflows must exceed the outflows. This corroborates with the findings of Gerber (2016). The additional insight provided by this thesis is that the influence of SOC on yield variability according to the operationalised structure developed in this model does not represent a strong reinforcing mechanism to increase the input of crop residues under normal nor droughty condition settings. Instead the absolute long-term crop yield is more important, which is represented in this model as an exogenous variable. Controversy surrounding how SOC influences absolute crop yield was discussed in Chapter 3, and operationalising this effect in a model based on the latest scientific knowledge can be considered an important contribution for future research. For the purposes of addressing Research Question 1.1, the insight about absolute crop yield suggests that the supply of organic materials, whether crop residues or FYM and other organic amendments, could be important, whether imported to or grown in the field: if the market supply of organic materials constrained means organic inputs are lower than necessary to maintain SOC equilibrium, the inflow will be smaller than the outflow and SOC stocks will decline (Powlton et al., 2018). The second major insight is that the decline in SOC could be promoted by the absence of a feedback mechanism between the ecosystems benefits of SOC and land management decisions (Figure 12). The model analysis suggests that this could be considered an example of market failure as proposed by Graves et al. (2015) since the majority of the economic costs of soil degradation are borne as externalities to land managers. The finding also implies that this also represents a limitation of existing action-oriented agri-environment policies and subsidy payments (Burton & Schwartz, 2013) for addressing soil degradation because they are not referenced to soil health indicators such as SOC.

Research Question 1.2 asks “Which dynamic structures could be responsible for mitigating or slowing the decline in soil natural capital in England?” The model analysis and validity testing provide three points in response to this question focused on the soil health and natural capital metric SOC. The first is the first-order control mechanism (balancing loop B1 shown in Figure 12) whereby the outflow of SOC through organic matter decay is determined by the current SOC stock. This structure mitigates or slows the decline of SOC, producing behaviour corresponding to exponential decay, which will converge at an equilibrium point above zero so long as the inflow of organic matter is above zero. The second response to Research Question 1.2 is crop choice, since which crops are grown on a plot of land determine the total quantity of biomass production, and also what proportion of that crop will be reincorporated back into the soil. This insight was delivered by the family member validity testing and is an observation widely recognised in the relevant soil science literature. The third response to Research Question 1.2 is that reasons exogenous to the model feedback structures are responsible for mitigating or slowing the decline in SOC, because endogenous feedback mechanisms are absent in the current system: factors not related to SOC are currently affecting land managers’ decision processes about how to manage their SOM rather than the value of ecosystem services driven by SOC. This is an insight that strengthens the argument made by Graves et al. (2015) by representing the theory in an explicit model structure capable of quantitative simulation.

Research Question 1.3 asks “Which of these dynamic structures relate soil health to systems of financial incentives and investments?” For SOC as an important soil health and natural capital indicator, the model analysis and validity tests confer with Graves et al. (2015) to show that that changes in SOC present unrecognised economic benefits and costs to land managers, with the costs of declining water quality, flood protection and climate regulation being borne by offsite actors as externalities. If dynamic structures could relate soil health to systems of financial incentives and investments, these might produce different behaviour in the system. This insight can be used to help inform the design of policy interventions such as natural capital investments.

4.3.2 Design of natural capital investment as systems interventions

Research Question 2.1 asks “What are the leverage points in the dynamic structures of the system for reversing the decline in soil natural capital in England using natural capital investments?” The model analysis and validation testing offer the preliminary answer that the land managers’ lack of awareness about the potential economic benefits of investing in SOC could represent a potential leverage point. Introducing an information feedback mechanism such that land managers could recognise the economic value of SOC to their business could influence their decisions about how they manage crop residues and use FYM and other organic amendments with a view to improve their SOC stock.

Research Question 2.2 asks “What are the strengths and opportunities for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?” The model analysis and validation testing offers the preliminary answer that natural capital investment has the potential to create a feedback mechanism to relate SOC as a soil health and natural capital indicator to its onsite and offsite economic benefits, and thereby influence land manager decision making by initiating awareness and providing financial incentives to change their practices. This corresponds with the portrayal of natural capital investments as feedback mechanisms for encouraging beneficial environmental outcomes (e.g. Natural Capital Coalition, 2016).

Research Question 2.3 asks “What are the limitations and risks for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?” The analyses presented in this structure provide three preliminary responses. First, the validation tests highlighted the potential for high sensitivity of financial indicators to price parameters such as “Price per Mg of plant residue” which may not themselves be constant. In combination with the current absence of operating feedback mechanisms and lack of results-based policy interventions, this presents the possibility for natural capital investments to produce counterintuitive and nonlinear effects. Second, the validation testing also highlighted that different site conditions and different granularity of spatial data present important contextual considerations, such that natural capital investments might produce desired results on some plots of land but produced undesired results on others. Third, the model analysis showed that in order for SOC to accumulate, inputs of organic matter must exceed the outflows of decay, while to achieve a constant rate of increase in SOC the inflow of organic materials must be increased to ever higher rates because of the balancing mechanism affecting organic matter decay. This is because of the balancing feedback loop B1 (Figure 12) which operates as a first order control mechanism. These structures also mean that it necessary to maintain organic matter inputs to avoid declines in SOC. This means that natural capital investments would need to incentivise long term conservation of SOC which may present both financial and practical challenges given that organic matter supply (such as FYM) might not be available.

In Chapter 5, these preliminary answers to Research Questions 2.1, 2.2 and 2.3 are given further consideration through policy design and analysis.

Chapter 5. Policy Analysis

5.1 Policy aims

Defra has set the goal for ensuring that by 2030 all of England's soils are being managed sustainably (HM Government, 2018). This thesis is focused on exploring the potential for natural capital investments to contribute towards this goal, using SOC as a soil health indicator and natural capital metric. In the design of natural capital investments as policy interventions, 2030 was considered as the target year for achieving desired outcomes in SOC. The policy horizon was considered as being from 2020 (approximately the present day) to the target year of 2030. Based on insights from the model analysis and validation testing (Chapter 4), the differentiation of two potential starting points was considered important: plots of land with poor and worsening SOC status, and those with better SOC status. The SOC stock values for the Worst and Base Cases at 2020 were considered to represent these respective situations. For the Worst Case, the policy aim was therefore considered to be to achieve or exceed the SOC level of the Best Case in 2020 with an increasing or stabilising trajectory, while for the Best Case, the policy aim was also considered to be to maintain or exceed the SOC levels of the Best Case in 2020 with an increasing or stabilising trajectory. These levels were used to initialise the DPM, RPM, BIO and HUM stocks for the policy analysis simulations shown in Table 7. Because the model testing identified the importance of site contextual factors in determining differences in absolute values between simulated and reference SOC behaviour, it was considered important to explore the implications of initial SOC status for policy success.

Table 7: Initial conditions for policy design and analysis for the Worst and Best Cases.

	Worst	**Best**
Initial RPM	2.66	15.1
Initial DPM	0.115	0.542
Initial BIO	0.393	1.96
Initial HUM	16.9	71.5
SOC (% w/w)	0.855	**3.44**
SOC (Mg ha^{-1})	22.8	**91.9**

To achieve the goals set above, policies were designed based on the findings of the model analysis, answers to Research Questions 1.1-1.3 and preliminary answers to 2.1-2.3. The policies were designed to create feedback structures connecting the onsite economic benefits of SOC and the offsite economic benefits of SOC to land managers' decision making about the use of crop residues and organic amendments. Introducing and activating such feedback mechanisms seems to be the purpose of natural capital investments (e.g. Natural Capital Protocol, 2016) for overcoming the issue of market failure as proposed by Graves et al. (2015) and demonstrated in the model analysis. These policy structures were introduced to the model, simulation results were analysed and validation was testing performed to develop further insights.

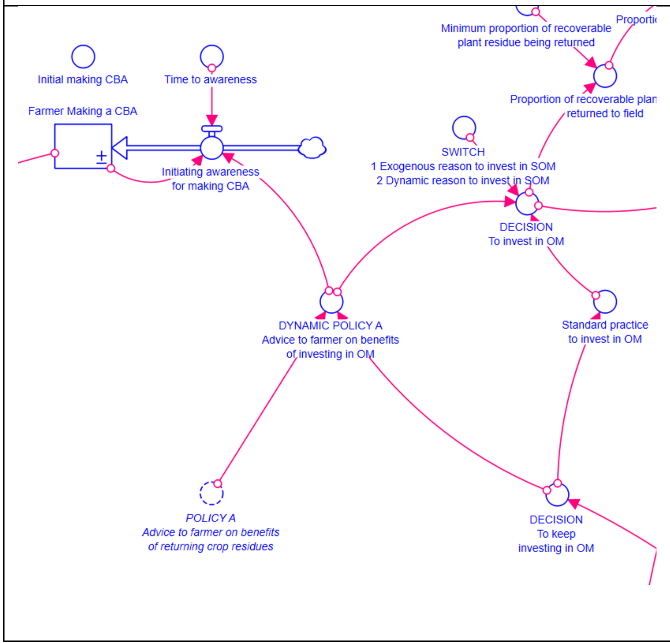
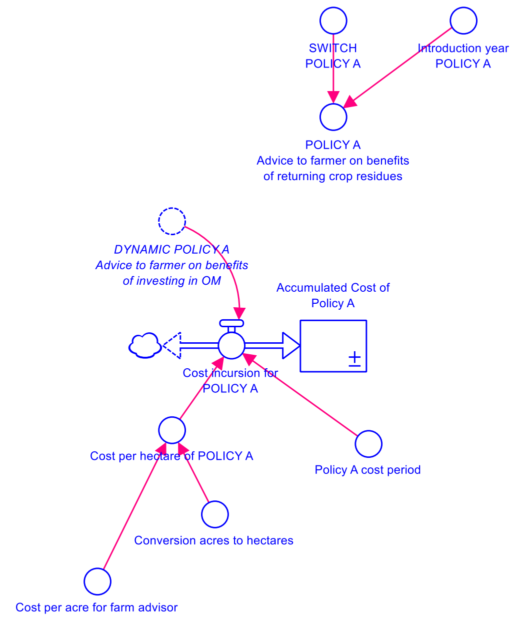
5.2 Policy A

5.2.1 Policy A Design

"Policy A" was constructed as a farm advisory structure designed to mirror the economic analyses performed in the KeySoil (2010) case studies. The purpose of this policy structure was to activate a feedback loop between land management practices and the potential economic benefits for farmers of using organic materials (crop residues and manures) to increase their SOC stocks (R3, R4, R5 and B2 in Figure 12). The purpose of the policy is therefore to initiate the farmer to invest in natural capital based on the ecosystem services benefits they are likely to receive. The idea is that because SOC delivers onsite ecosystem services, offsite actors (e.g. water companies, local councils, governments) receiving offsite benefits will invest in farm advice as a "kickstart" such that land managers will begin to invest in SOC directly themselves. The leverage point being targeted is farmers' awareness that including in their accounting practices a cost-benefit assessment for the potential economic return on boosting their SOC stocks could be important to their business interests.

Looking at the structure of Policy A, the variable "POLICY A Advice to farmer on benefits of returning crop residues" is a switch which activates "DYNAMIC POLICY A Advice to farmer on benefits of investing in OM". This switches on land managers' "DECISION To invest in OM" and leads the land manager to incorporate available crop residues and add organic matter at the same rate as in the original Best Case through 8.8 Mg ha^{-1} of FYM each year. The "DYNAMIC POLICY A Advice to farmer on benefits of investing in OM" also activates the "Initiating awareness for making CBA" which determines whether the land manager is making a cost-benefit assessment (CBA) of whether building

SOC levels offers a positive investment to them. Whether the farmer is making a CBA is represented by the stock “Farmer Making a CBA”. This stock activates or deactivates the switch “Farmer Decision to make CBA switch” which enables the calculation of the “Farmer Net benefit of OM per hectare” and “Farmer CB balance for investing in OM”. This structure operates on the assumed causal relationship described in Chapter 3 whereby the land manager will likely take the “DECISION To keep investing in OM” if the trend in “Farmer CB balance for investing in OM” looks like it will reach positive (>0) within 5 years. If so, the decision to incorporate crop residues and add FYM will become a “Standard practice to invest in OM”, and the variable “DYNAMIC POLICY A Advice to farmer on benefits of investing in OM” is switched off automatically once the land manager adopts a “Standard practice to invest in OM”. The expected investment by public or private bodies in deploying Policy A is calculated using the “Cost per acre for farm advisor” as a proxy based on reported agronomist fees (The Farming Forum, 2019b). The policy structures are depicted in Figures 18a and 18b according to their stock and flow structure of the model software. For a simplified version, Policy A introduces a structure which activates R3, R4, R5 and B2 in Figure 12.

Figure 18a: SFD structure showing which leverage point Policy A targets.	Figure 18b: stock and flow diagram of the policy structure for Policy A and how the costs of the policy are calculated.
	

5.2.2 Policy A analysis

As shown in Figures 19a-19f, the effect of Policy A on SOC and the onsite and offsite ecosystem services benefits differed depending on whether the Policy was deployed in relation to plots with initially poor (Worst Case) SOC status or initially better (Best Case) SOC status.

Without Policy A, SOC stocks decline away from the policy goal in both Cases, and with a more severe and rapid loss for Best Case plots. This is because in both Cases land managers are not calculating the cost-benefit balance of SOC and therefore are unable to recognise its importance for their business activities. Although in these situations there is no policy cost being incurred since Policy A is not activated, this results in a loss in the value of the offsite ecosystem services of water quality and flood regulation as well as climate regulation, thus confirming the need for intervention. The loss is more pronounced in the initially better (Best Case) plots because of the balancing feedback loop where the mineralisation rate is higher for larger SOC stocks (B1 in Figure 12).

In contrast, introducing Policy A was able to maintain SOC levels above the target on Best Case plots, leading to avoided cost savings over the 10 year simulation period of around £3 ha^{-1} for water quality and flood regulation to water companies and local authorities, and £220 ha^{-1} for climate regulation by society. Introducing Policy A also increased SOC levels on the Worst Case plots, but failed to reach the policy target for SOC stocks by 2030 despite improving the water quality and flood regulation value by around £2.50 ha^{-1} and climate regulation value by £200 ha^{-1} during the ten year simulation period. This is because the inflows of organic matter were not sufficiently large enough to accumulate SOC at the required base with “normal” rates of plant residue and FYM additions (based on available plant residues and FYM usage rates estimated from literature).

For the Best Case plots, funding for Policy A was only required in the first year because the “Farmer CB balance for investing in OM” was immediately positive, such that the farmer was assumed to want to continue investing in SOC once aware of its economic contribution to their business. This meant introducing Policy A in such circumstances only required the one-off cost of £17.30 ha^{-1} by water companies, local councils, or through a government instrument. On plots with poorer initial SOC status, continuing farm advice is required to keep encouraging land managers to increase SOC throughout the 10-year simulation period. This is because the SOC stock cannot build to sufficiently high levels within the 10-year time period to deliver sufficient benefits to make the adding more organic matter worthwhile to the farmer. This is reflected in some of the KeySoil (2010) case studies, where farmers’ return on investment in organic matter can take up to 15 years to “break even”. On Worst Case plots, the continuing need for deploying Policy A resulted in an accumulated investment cost of £173 ha^{-1} by the end of the 10-year simulation period. There’s little reason to suppose the additional benefits of £223 ha^{-1} for climate regulation and £2.54 ha^{-1} for water quality and flooding regulation would be achieved since the farmer is unlikely to keep adding organic matter voluntarily if they are not seeing a return just because they are advised to. The overall net present values (NPV) (excluding discounting factors) to the investor of Policy A for plots with different initial SOC levels are presented in Table 8. They illustrate the potential added value of introducing Policy A compared to not introducing it, bearing in mind for Worst Case plots the investor is unlikely to realise these benefits.

Figure 19a: Policy A simulation results SOC

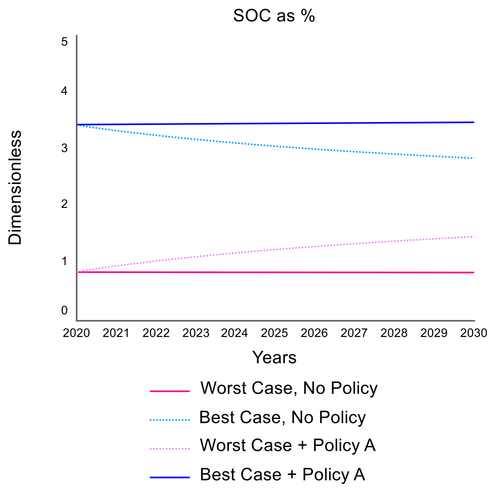


Figure 19b: Policy A simulation results farmer CB

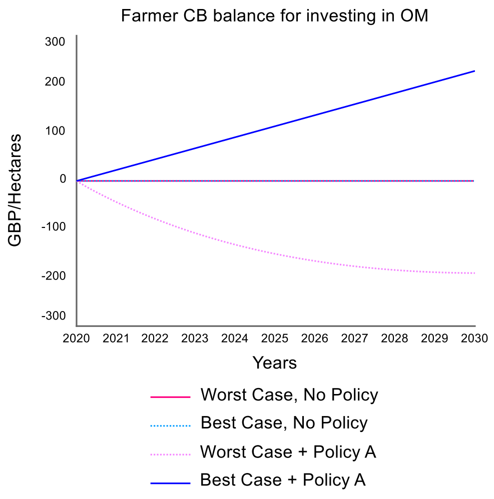


Figure 19c: Policy A water and flood regulation

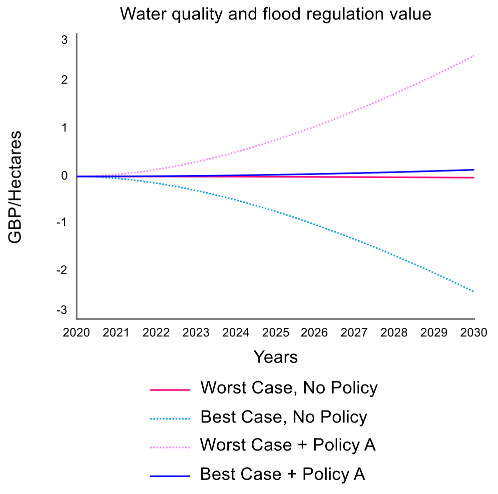


Figure 19d: Policy A climate regulation value

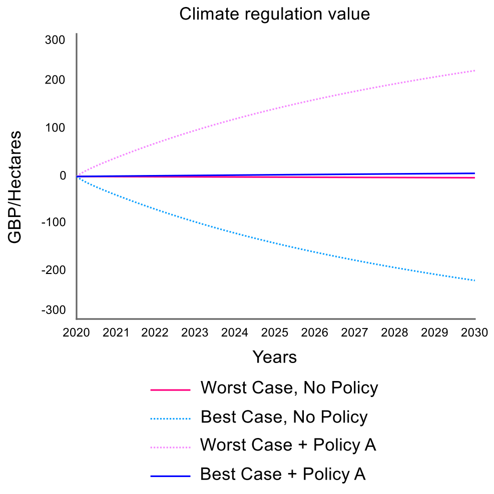


Figure 19e: Policy A costs over time

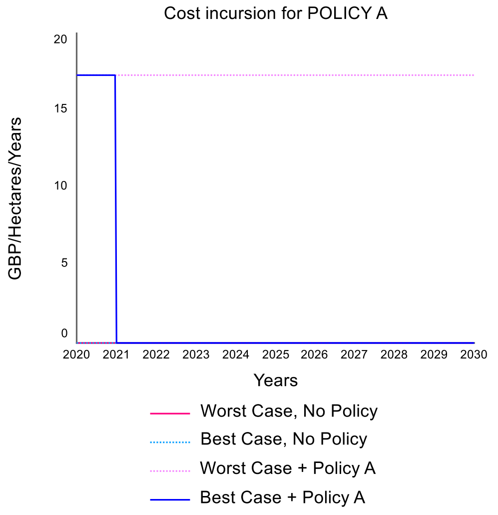


Figure 19f: Policy A accumulated costs

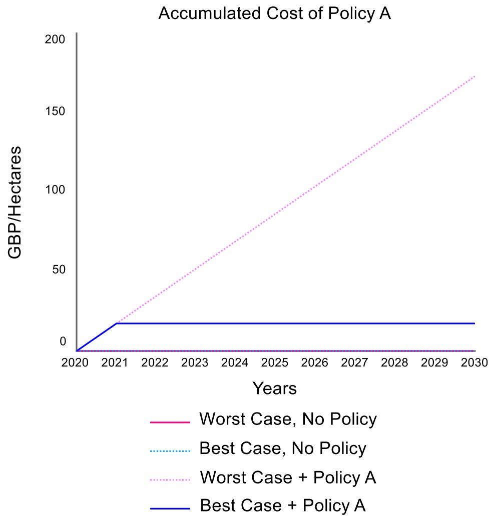


Table 8: Net present value (NPV) results (excludes discounting) for Policy A differentiating between plots will initially poor (Worst Case) and good (Best Case) SOC status. Values based on accumulated values over policy timeframe 2020-2030.

Initial SOC status	**Variables**	**No Policy A (GBP)**	**With Policy A (GBP)**	**Difference (GBP)**	**Policy A NPV (GBP)**
Worst Case	Benefit: water quality, flood and climate regulation value (sum)	-2.67	225.53	228.20	55.20
	Cost: investment in policy	0	173.00	173.00	
Best Case	Water quality, flood and climate regulation value (sum)	-221.43	6.72	228.15	210.85
	Investment in policy	0	17.30	17.30	

5.2.3 Policy A sensitivity

Sensitivity analysis was applied to the simulation runs including Policy A in order to further develop the preliminary answers to Research Questions 2.1-2.3 provided at the end of Chapter 4. As shown in Figures 19a-19f, the same type of natural capital investment mechanism can produce desired results on some plots of land and fail to do so not on others depending on their initial soil status (initial conditions).

Chapter 4 also reported that model simulation results were sensitive to changes in the parameter values, particularly the “Maximum potential harvested yield” and highlighted the potential constraint to policy effectiveness of a shortage in FYM supply. Figures 20a-20d show that, under Best Case SOC conditions, low yields or periodic yield drops, FYM supply shortages, and combinations of yield drops and FYM supply shortages do lead to slightly lower SOC levels and reduce water quality and climate regulation values. They do not however affect the land managers' "DECISION To keep investing in OM" because under these circumstances the "Farmer CB balance for investing in OM" is actually higher than the original Best Case POLICY A simulation runs. This is because they are able to sell less crop residues so will need to forego less income to incorporate them into the ground and spend less on FYM (here assuming a fixed price). Under Worst Case initial conditions, the same low yields or periodic yield drops, FYM supply shortages, and combinations of yield drops and FYM supply shortages also lead to lower SOC levels and reduce water quality and climate regulation values. The "Farmer CB balance for investing in OM" is still negative for these conditions. These results indicate that although SOC is sensitive to these instances, the effectiveness of Policy A is exploiting the leverage point is not since feedback loops R3, R4, R5 and B2 in Figure 12 are operating. With these parameter conditions, however, they are not powerful enough because the rates of organic matter application from are reduced, hence their failure to reach the policy goal by 2020.

Building on these sensitivity results, their assumption of a fixed price in FYM was explored further. As shown in Figures 20a-20d, changes in "Imported FYM or other organic amendment price per Mg" does not influence SOC levels, but does influence the "Farmer CB for investing in OM" and therefore the potential effectiveness of Policy A for exploiting the targeted leverage point. In Best Case initial soil conditions, if the FYM price increases (as it may during an FYM shortage or during high demand) by 2.5 times (2 Mg ha^{-1} to 7 Mg ha^{-1} as is plausible according to manure prices used by KeySoil (2010)), the "Farmer CB for investing in OM" and Policy A needs to be reintroduced at the cost of the investor (water company, local council, government etc.).

Figure 20a: Policy A sensitivity SOC

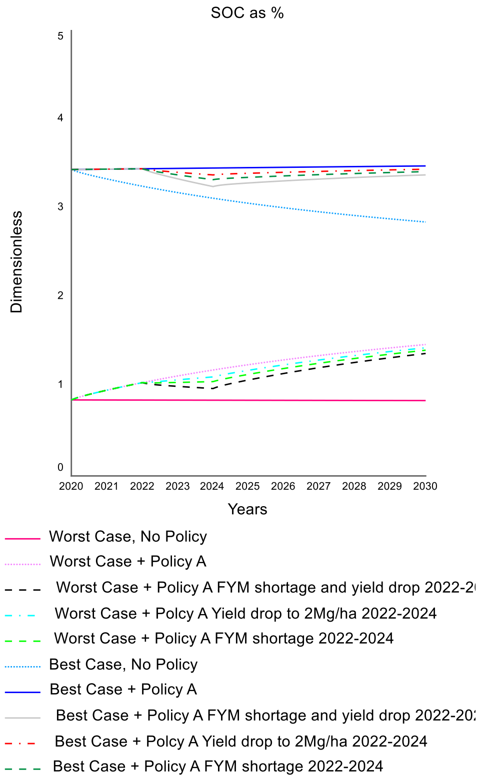


Figure 20b: Policy A sensitivity Farmer CB

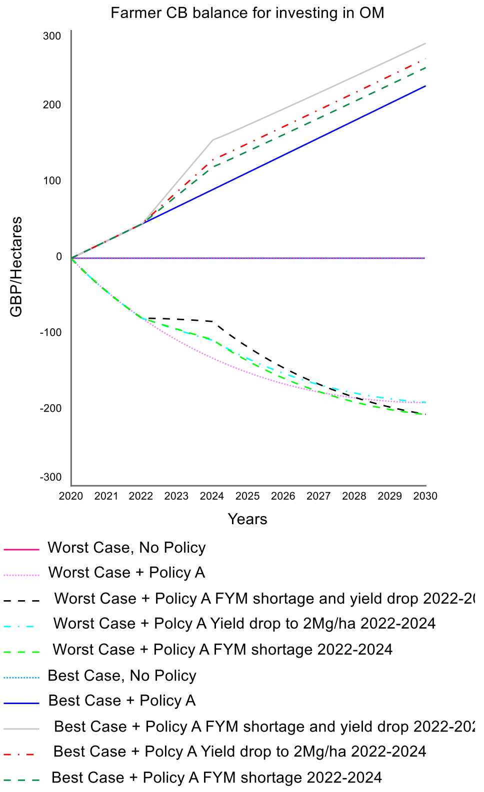


Figure 20c: Policy A sensitivity water and flood

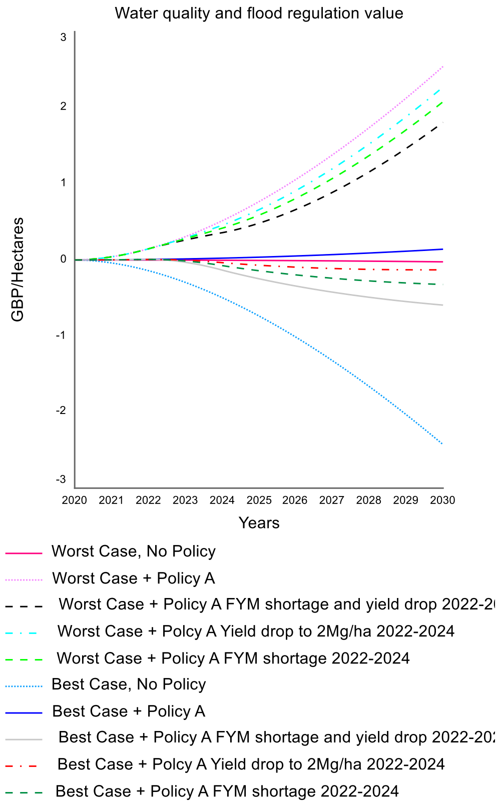


Figure 20d: Policy A sensitivity climate reg.

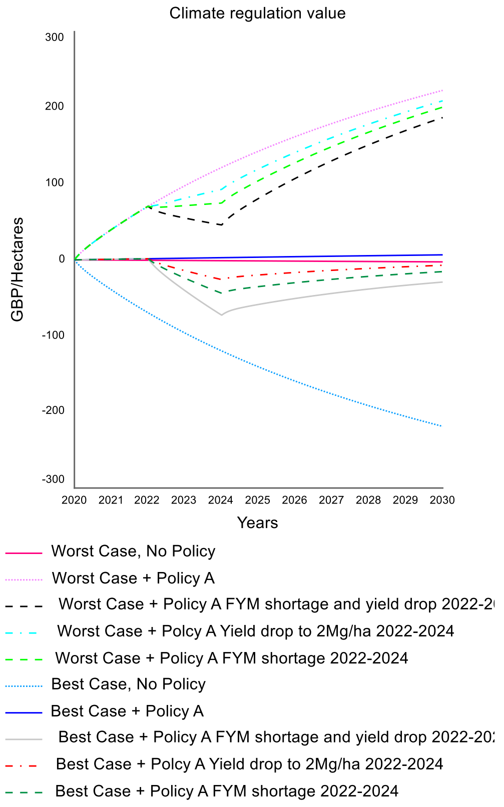


Figure 21a: Policy A SOC sensitivity FYM price

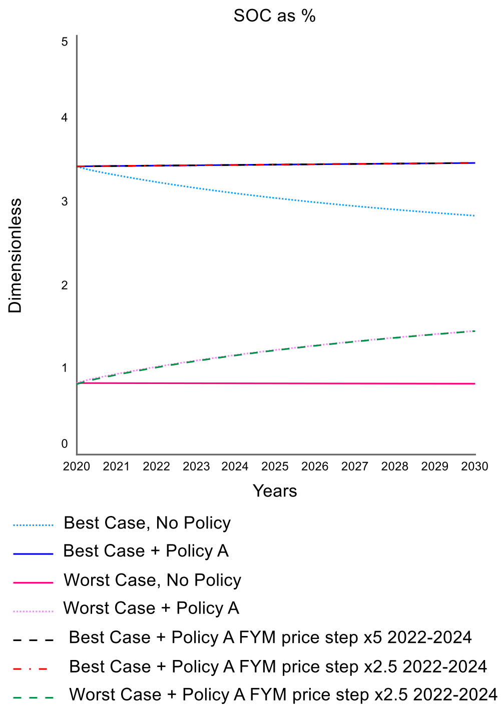


Figure 21b: Policy A CB sensitivity FYM price

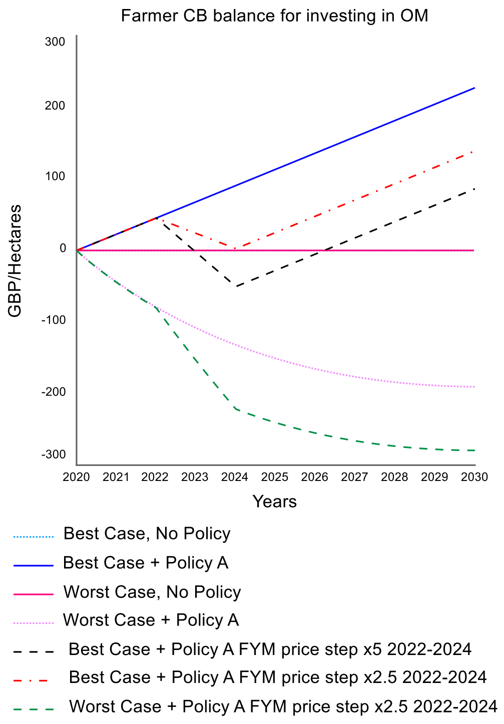


Figure 21c: Policy A water sensitivity FYM price

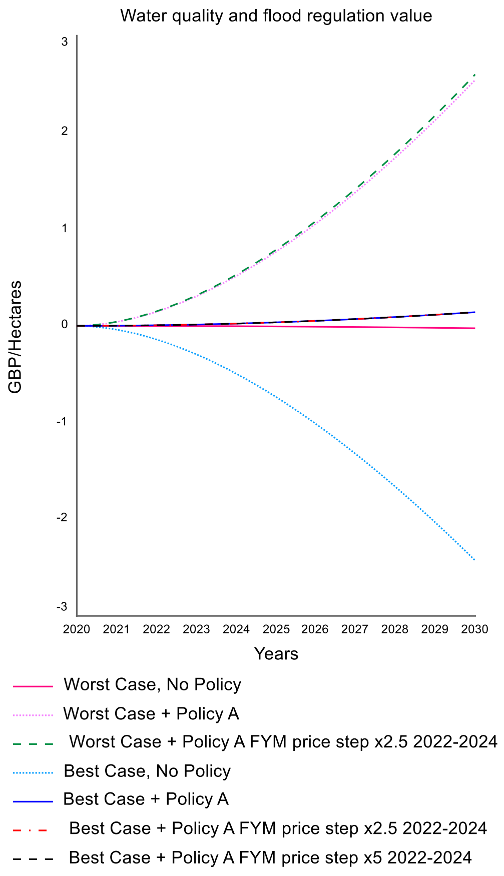
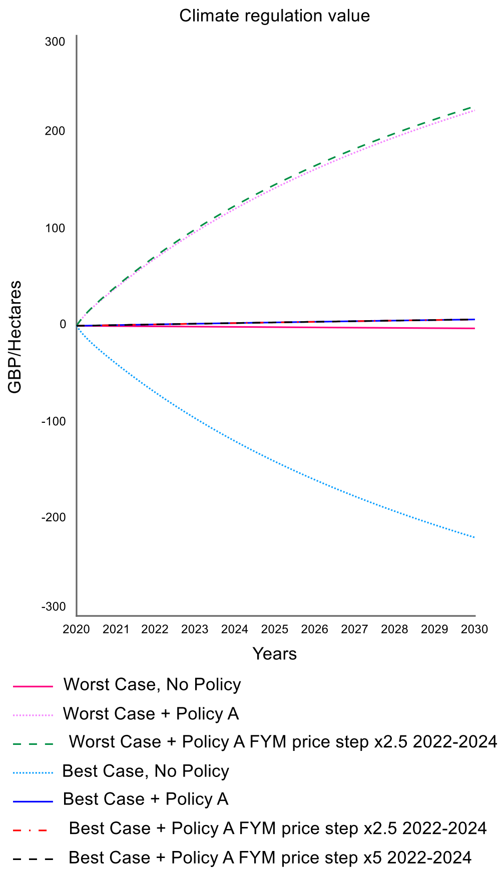


Figure 21d: Policy A climate sensitivity FYM price



The “Price per Mg of plant residue” was also highlighted by KeySoil (2010) as a particularly important factor in determining the economic return on land managers’ investments in SOM. Figures 22a and 22b show sensitivity analysis results for different plant residue prices for the Best Case initial SOC conditions and Worst Case. The results illustrate that for the Best Case conditions, Policy A is sufficiently robust to higher levels of “Price per Mg of plant residue”, even with a variable rate (Best Case + Policy A Plant Residue price step x2 2022-2024), except where plant residue prices are consistently high from the beginning at double the base level. In these latter circumstances the land manager experiences negative economic benefits of investing in SOC throughout the simulation and therefore Policy A requires continual funding even under Best Case initial conditions with no reason to believe it will succeed. The results of analysis for the Worst Case show that “Price per Mg of plant residue” must be as low as one third to one sixth or their normal price to offer the prospect of a positive return for the farmer and enable deactivation of Policy A by the end of the 10 year simulation period. Even with the lowest crop residue price of 1 £ Mg^{-1} Policy A still needs to be deployed again in 2029 to encourage land managers continue to invest in OM with the Worst Case initial soil status.

Figure 22a: Policy A CB sensitivity residue price

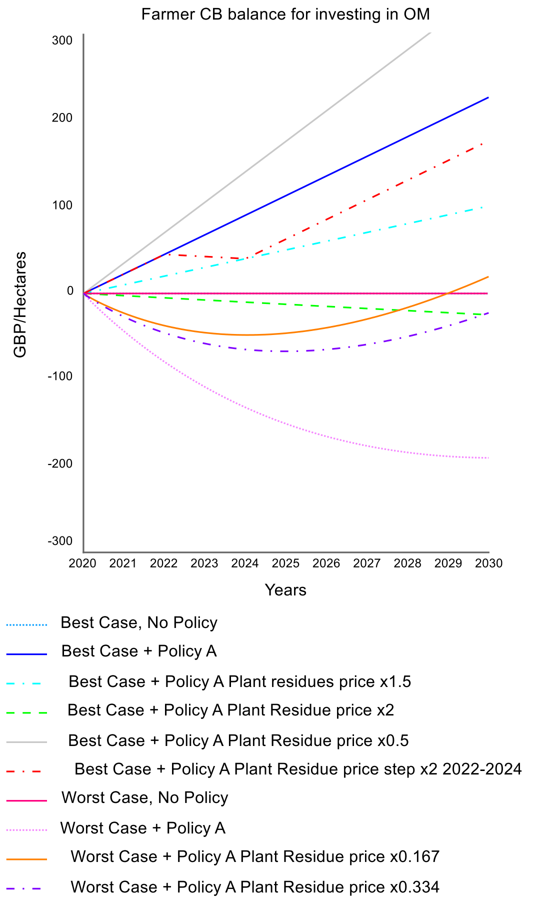
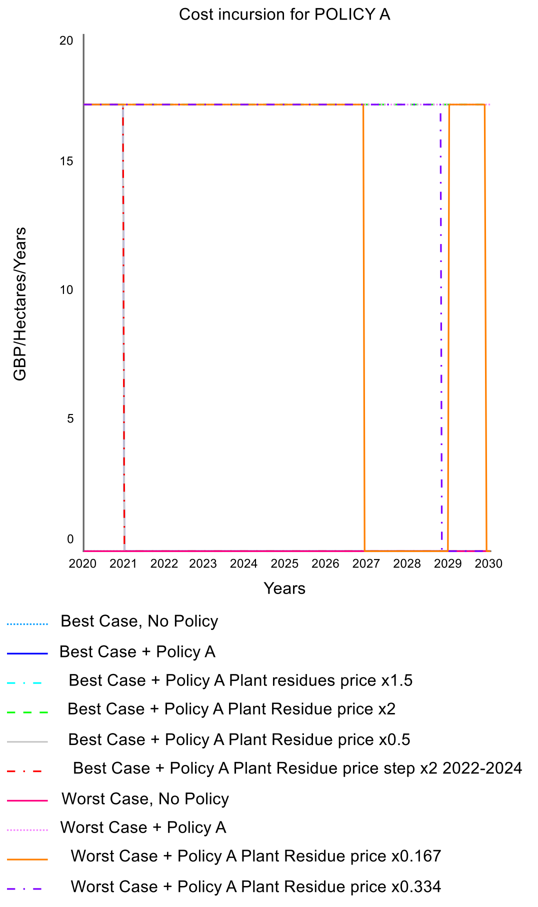


Figure 22b: Policy A cost sensitivity residue price



These results highlight the sensitivity of Policy A to "Imported FYM or other organic amendment price per Mg" and "Price per Mg of plant residue" even with initial Best Case status. Although the initial analysis (section 5.2.2) suggested Policy A could be effective under these circumstances, it is clear that relying on a one-shot farm advisory policy to enable land managers to include the economic value of SOC to their business operations in their decision making is risky: changes in "Imported FYM or other organic amendment price per Mg" and "Price per Mg of plant residue" could make adding these materials less economically viable. Both of these prices can vary at regional and local scales (KeySoil, 2010), further highlighting the susceptibility of Policy A to these variables. Instances of FYM supply shortages and the "Imported FYM or other organic amendment price per Mg" are also likely to coincide, introducing FYM supply and demand price dynamics which are not included in this model. On the basis of sensitivity analysis, Policy A alone does not therefore appear to offer a robust option for investing in SOC as natural capital.

Perhaps more crucial than sensitivity to these parameter settings, Policy A is structurally dependent on the assumption that if farm advice is being deployed, farmers will still act according to that advice and invest in SOC even when their return is negative in the long term (at least the 10 year period), even for farms with poor initial soil status. That this is an unlikely outcome provides further support to the argument that farm advice (Policy A) may not be enough on its own to ensure that land managers will be encouraged to invest in organic matter when their economic return appears to be negative. The potentially positive returns to natural capital investors for funding farm advice therefore appear to be present an unlikely prospect. These insights from the analysis of Policy A can be used to inform the design of further policies for testing, such as Policy B.

5.3 Policy B

5.3.1 Policy B Design

Building on the insights delivered by Policy A, "Policy B" was designed as an attempt to try to overcome some of its shortcomings, particularly the unrealistic prospect of relying on land managers acting on advice about the benefits of investing in SOM even when they were not apparent in a cost-benefit analysis by the farmer. Policy B was also designed to try to overcome Policy A's sensitivities to the "Imported FYM or other organic amendment price per Mg" and "Price per Mg of plant residue", and ensure "Farmer CB balance for investing in OM" is positive for plots starting with poor SOC status.

Policy B was constructed as a payment for ecosystem services (PES) for increasing SOC stocks to improve water quality, flood protection and climate regulation benefits. It was therefore designed as a natural capital investment to be made by investors experiencing these offsite ecosystem services benefits, such as water companies, local councils responsible for drain clearance, and national government with climate change commitments. The purpose of this policy structure was to create the supposedly absent feedback loop between the offsite costs and benefits of soil degradation to land managers, thereby enabling farmers to internalise the externality created by market failure. The purpose of the policy is therefore for offsite entities to pay the farmer for increasing the benefits they are likely to receive. The idea is to enable the farmer to be paid for the offsite ecosystem services benefits they generate, include the income from those benefits in their balance sheet, and decide on that basis whether to invest in SOC on their field plot or not. The leverage point being targeted by Policy B is the farmers' balance sheet.

Looking at the structure of Policy B in Figure 23, the variable "POLICY B PES" is a switch which activates "POLICY B PES to Farmer" which sums the "Change in cost of nuisance sediment removal during simulation" and the "Net CO2 seq value accumulation". The "POLICY B PES to Farmer" also includes a MAX function which chooses the highest value from the sum and the "POLICY B First five years investment" which acts as a minimum level of payment for the first five years of the policy (2020-2025), intended to provide an initial stimulus for farmers to invest in SOM. This contribution is then added to the "Annual onsite benefits of SOM per area" which the land manager uses to calculate their "Farmer Net benefit of OM per hectare" and "Farmer CB balance for investing in OM". The variable "POLICY PES proportion of value" sets what proportion of the total offsite ecosystems services value the external actor choses to pay – the default for this setting is 1, meaning that 100% of the ecosystem services value is paid to the land manager. POLICY B also instigates the same effects as POLICY A by "Initiating awareness for making CBA", but without incurring the added costs of farm advice. This is because the offer of funds is assumed to initiate the farmer making a cost benefit analysis about the expected returns on adding more OM . Building on Figure 12, Figure 24 depicts the feedback structures introduced by Policy B in a CLD using simplified variables.

Figure 23: Stock and flow structure of Policy B.

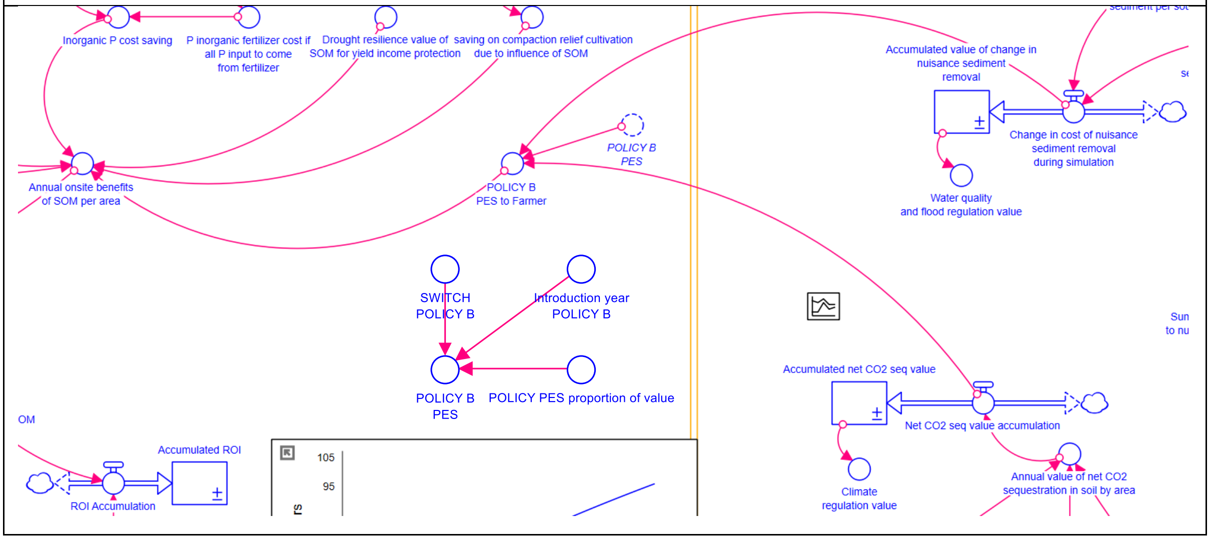
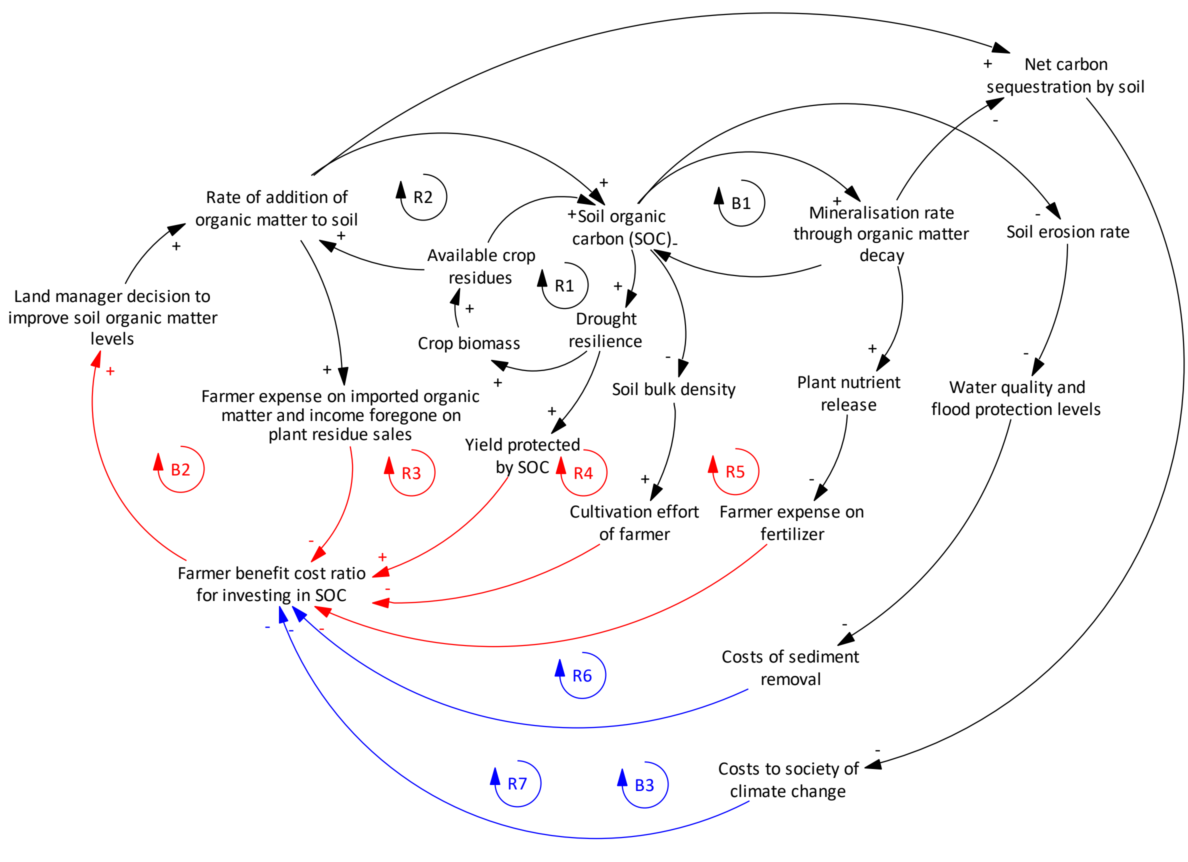


Figure 24: CLD showing the feedback loops introduced by Policy B.



5.3.2 Policy B Analysis

As shown in Figures 25a-25f, the effect of Policy B on SOC and the onsite and offsite ecosystem services benefits differed depending on whether the Policy was deployed in relation to plots with initially poor (Worst Case) SOC status or initially better (Best Case) SOC status. Without Policy B is the same as the runs without Policy A: SOC stocks decline away from the policy goal in both Cases with an exponential decay pattern that is more severe and rapid for Best Case plots. In contrast, introducing Policy B appears able to maintain SOC levels to achieve the policy goal on Best Case plots, leading to avoided cost savings over the 10-year simulation period for water quality and flood regulation to water companies and local authorities, and for climate regulation by society. Introducing Policy B also increased SOC levels on the Worst Case plots, but failed to reach the policy target for SOC stocks by 2030 despite improvements in water quality, flood regulation and climate regulation value during the 10-year simulation period.

For the Best Case plots, investment enabled the mitigation of almost all the potential costs posed by the No Policy simulation. The costs were highest during the first five years to ensure the “Farmer CB balance” for investing in OM was positive, which could then be reduced to the value of the offsite ecosystem services being provided by SOC. The assumption here is that farmers would continue investing in OM additions because the PES enabled the “Farmer CB balance for investing in OM” to stay positive. In dynamic terms, the reinforcing loops R3-R7 were able to exert enough influence despite the strong action of the balancing mechanisms of B2 and B3 (Figure 24). Despite this however, the overall value of offsite ecosystem services was still negative, with the natural capital investment only enabling the avoidance of additional costs compared to a situation without the investment. This is because the SOC stock cannot build to sufficiently high levels within the 10-year time period at the rate of organic matter being applied and the balancing mechanism of B1.

On Worst Case plots, the overall investment costs were higher because on these plots it was possible to achieve a large spike in initial ecosystem services benefits due to the sudden net gain in SOC sequestration, although these cost decreased over the course of the simulation as the net sequestration capacity of the soil declined as equilibrium was approached. This is the balancing feedback loop B3 in Figure 24. Despite improvements, however, the policy goal was not achieved.

The overall net present value (NPV) (excluding discounting factors) for Policy B are presented in Table 9. The results show that introducing Policy B on Best Case plots delivered overall net benefits through cost avoidances compared to not introducing it, whereas on Worst Case plots the costs outweighed the benefits.

Figure 25a: Policy B results SOC

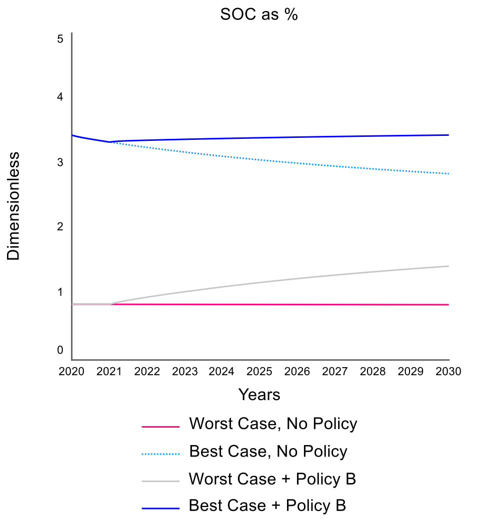


Figure 25b: Policy B results Farmer CB

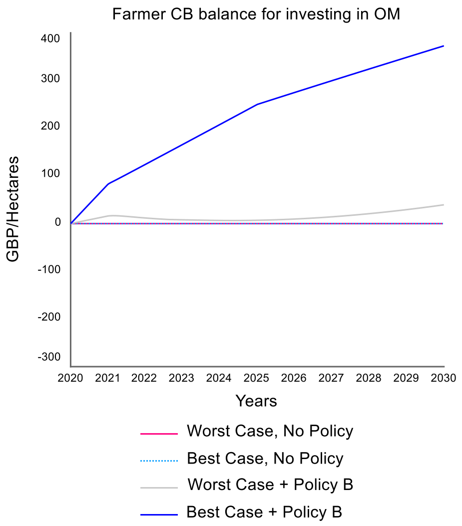


Figure 25c: Policy B results water and flooding

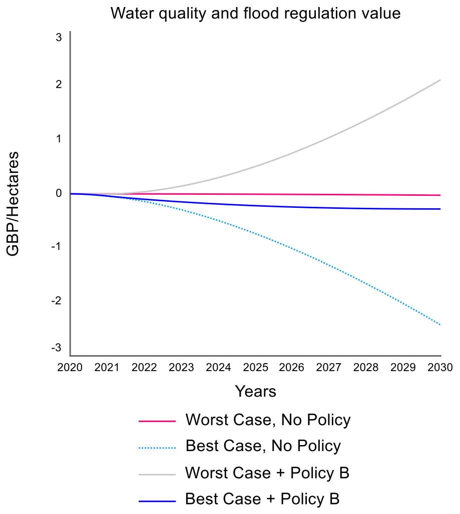
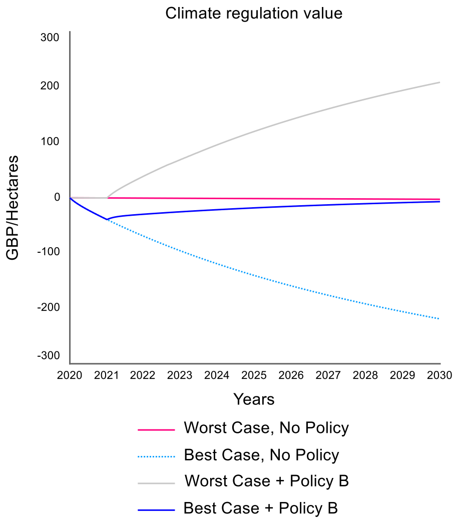
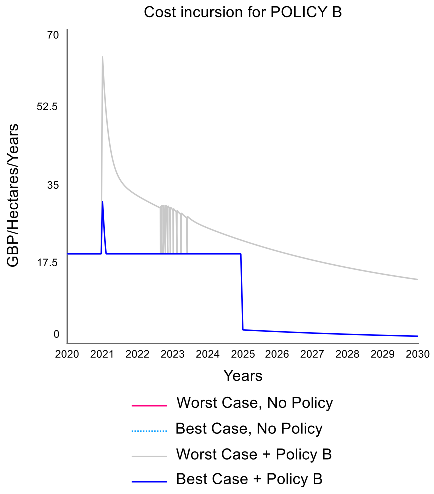


Figure 25d: Policy B results climate



Figude 25e: Policy B results costs over time



Figue 25f: Policy B results accumulated costs

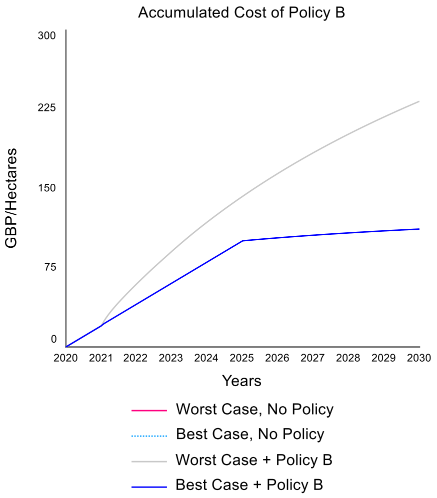


Table 9: Net present value (NPV) results (excludes discounting) for Policy B differentiating between plots will initially poor (Worst Case) and good (Best Case) SOC status. Values based on accumulated values over policy timeframe 2020-2030.

Initial SOC status	**Variables**	**No Policy A (GBP)**	**With Policy A (GBP)**	**Difference (GBP)**	**Policy A NPV (GBP)**
Worst Case	Benefit: water quality, flood and climate regulation value (sum)	-2.67	211.11	213.78	-19.22
	Cost: investment in policy	0	233.00	233.00	
Best Case	Water quality, flood and climate regulation value (sum)	-221.43	-7.27	214.16	102.16
	Investment in policy	0	112.00	112.00	

5.3.3 Policy B sensitivity

Sensitivity analysis was applied to the simulation runs including Policy B to further develop the preliminary answers to Research Questions 2.1-2.3 provided at the end of Chapter 4 and to test the extent to which Policy B could offer any improvements on Policy A.

Policy A was determined to be most sensitive to the parameter settings “Price per Mg of plant residue” and “Imported FYM or other organic amendment price per Mg”. Policy B was therefore simulated using these same settings to explore variations in their values. Figures 26a-26d show the results for initially poor SOC status plots (Worst Case). As in Policy A, these parameters influence the “Farmer CB balance for investing in OM” making it less attractive for land managers to invest in SOC even while receiving income from PES. The challenge is also that the PES benefits they generate are small because only small improvements in SOC are occurring through occasional organic inputs when the “Farmer CB balance for investing in OM” looks more positive. This highlights a potential disadvantage of determining PES based on the benefits being generated at the present time since small benefits will drive only smaller payments, hence the need for the “POLICY B First five years investment”.

Figure 26a: Policy B sens. Worst Case SOC

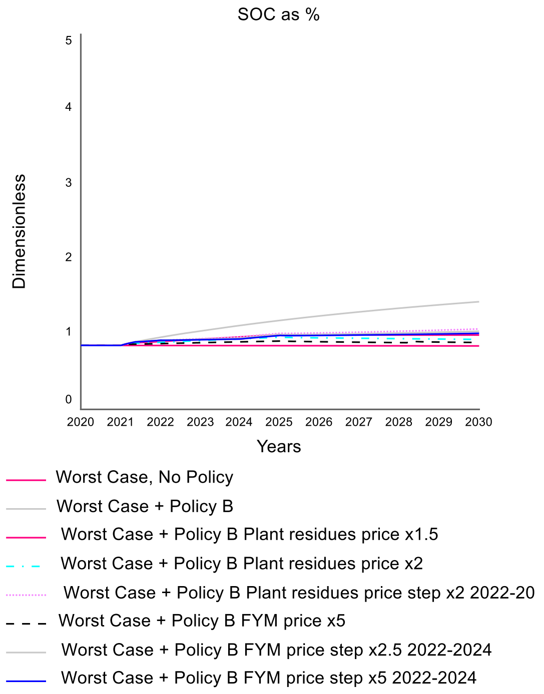


Figure 26b: Policy B sens. Worst Case CB

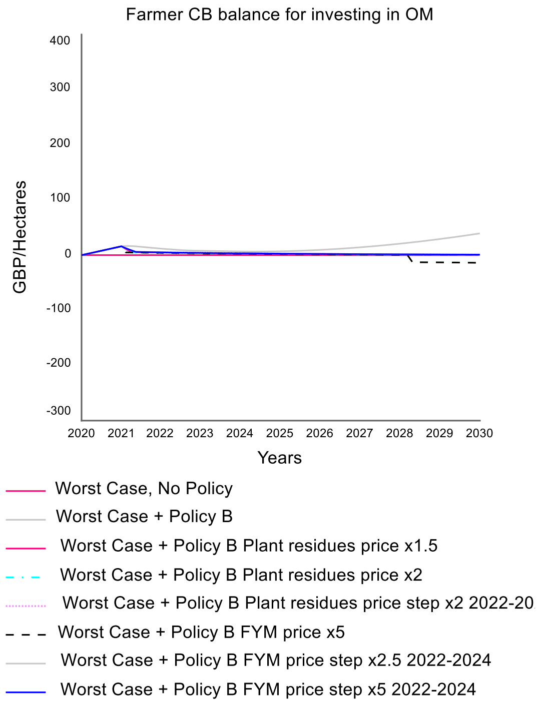


Figure 26c: Policy B sens. Worst Case climate

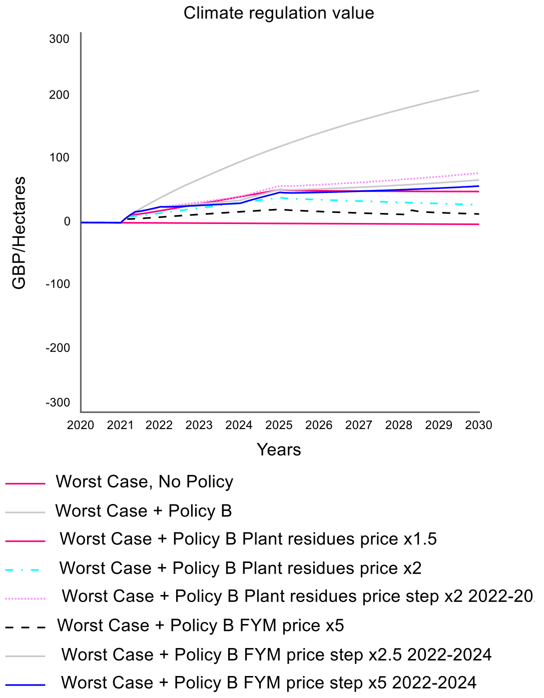
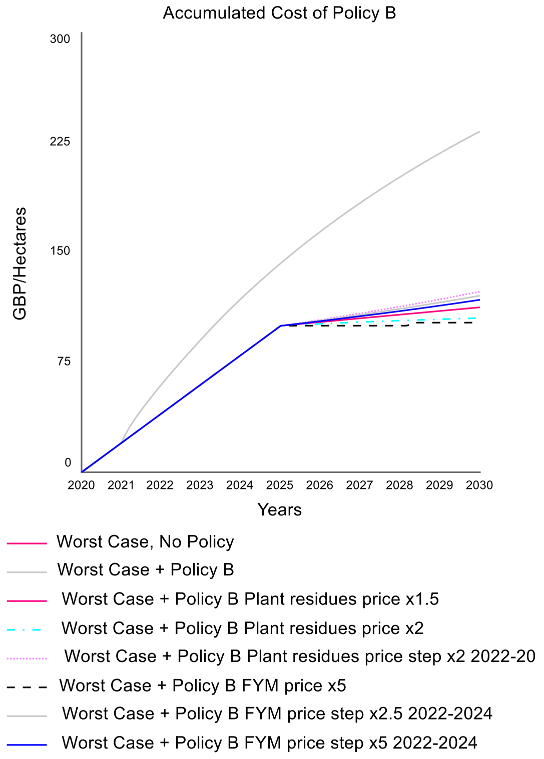


Figure 26d: Policy B sens. Worst Case acc. cost



Figures 27a-27d show the sensitivity results for initially good SOC status plots (Best Case) to which Policy B is applied. It can be seen that, as on initially poor SOC status plots, changes in these parameters influence the “Farmer CB balance for investing in OM” to make it less attractive for land managers to invest in SOC even while receiving PES. However, the policy is more robust on Best Case plots to ensuring the policy goal for SOC is met while returning a net positive return for the investor, except where the “Imported FYM or other organic amendment price per Mg” is five times the base cost of 2 £ Mg^{-1}. This is because in all other cases except this one, the benefits the farmer is receiving for their own operations sufficiently outweigh the costs, meaning that the PES is less important in their case. This analysis highlights that, where SOC status is already good, it is more the effect of the PES as a trigger for accounting for the costs and benefits of SOC that encourage farmers to continue investing in SOC rather than the PES amount itself. In dynamic terms, the feedback from onsite ecosystem services (R3, R4 and 45) is stronger than the feedback from offsite ecosystem services (R6 and R7), although for Policy B the latter is needed to initiate the former. Again, this illustrates the differences in policy outcomes for differential initial SOC conditions and the structural reasons behind them.

The simulation results for Policy B on plots with initially poor SOC status show that, although the policy might be able to exploit the leverage points to which it as targeted and initiate some improvements in SOC stocks and ecosystem services value, the target SOC levels of the policy goal cannot be achieved by 2030. This is because larger than normal organic matter additions would need to be made. The model was therefore used to determine under what conditions the policy goal could be reached. The aim was to provide insights using a “what if” scenario and gauge the level of policy effort that might be required. To achieve the policy goal, assuming all other parameters including the “Maximum potential harvested yield” and Policy B cost parameters remained constant, for plots with initially poor SOC status to achieve the policy goal, 55 Mg ha^{-1} of FYM would need to be added each year. For the investor, this would require funds of 971 GBP ha^{-1} over the 10-year period. Changing the parameters in the Policy B structure it was determined that these results for SOC could also be achieved with “POLICY PES proportion of value” set at 0.5 which would require the smaller investment of 503 GBP ha^{-1} while still providing a net positive return. However, whether such application rates can be achieved over the necessary temporal and spatial scales is questionable: this is a far higher than normal FYM application rate (KeySoil, 2010) and whether such quantities of available FYM can be sourced is doubtful. Such demand could also impact the FYM price. The use organic amendments other than FYM such as compost could be promising (Powlson et al., 2011), but whether this quantity is available is uncertain. These results illustrate the difficulty of achieving desirable SOC levels in the policy timeframe for plots with low initial soil status even with incentives that could change behaviour.

Figure 27a: Policy B sens. Best Case SOC

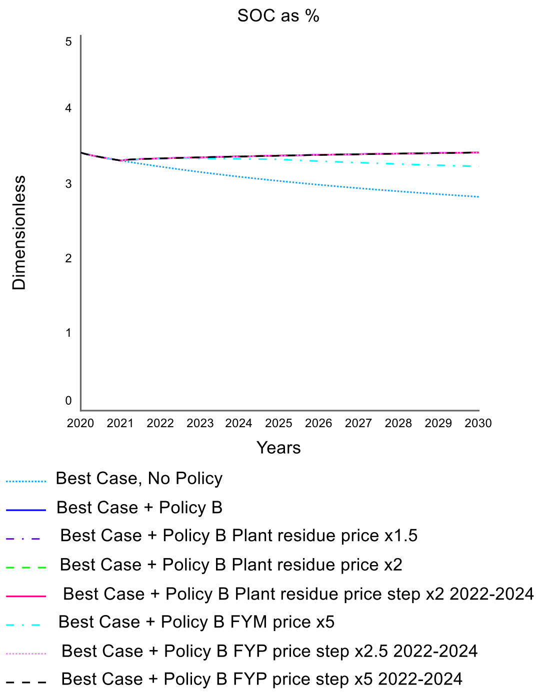


Figure 27b: Policy B sens. Best Case Farmer CB

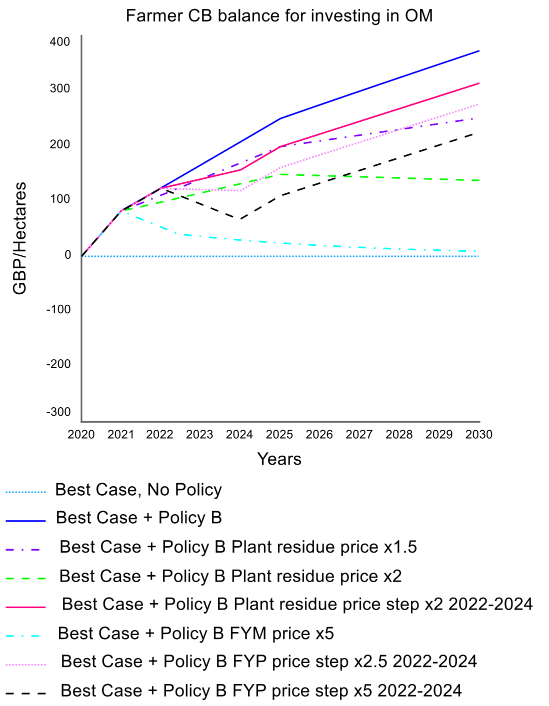


Figure 27c: Policy B sens. Best Case cliamte

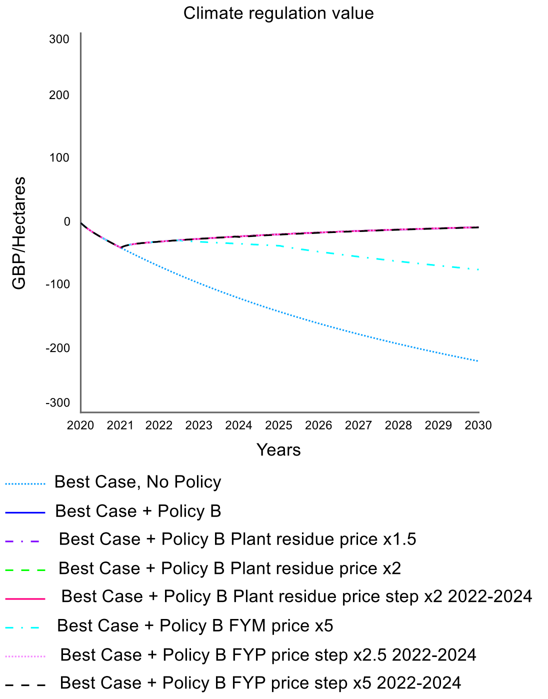
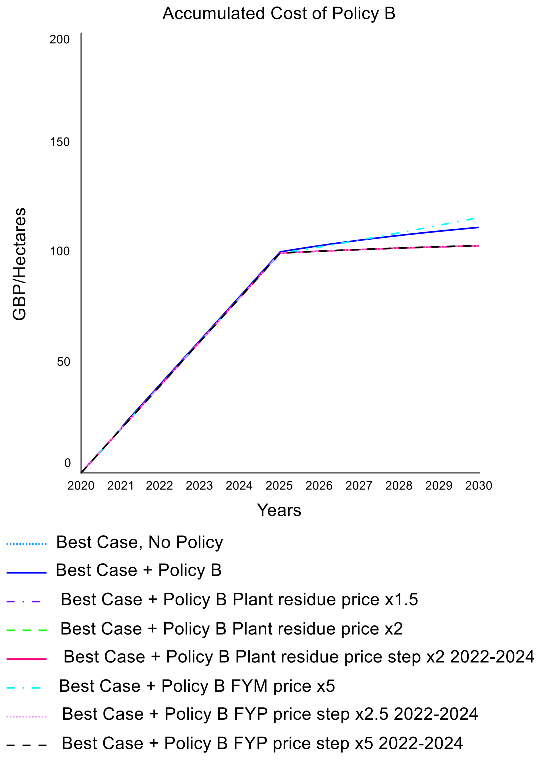


Figure 27d: Policy B sens. Best Case acc. cost



5.4 Main insights from policy analysis and testing

The insights generated during the policy analysis and sensitivity testing are discussed here in relation to the Research Questions 2.1-2.3 posed in Chapter 1 and the preliminary answers proposed in Chapter 4.

5.4.1 Leverage points for natural capital investment

Research Question 2.1 asks "What are the leverage points in the dynamic structures of the system for reversing the decline in soil natural capital in England using natural capital investments?" The model analysis and validation testing in Chapter 4 offered the preliminary answer that the land managers' lack of awareness about the potential economic benefits of SOC for their business could represent a potential leverage point. Policies A and B were therefore designed as natural capital investments which would introduce an information feedback mechanism focused on this leverage point (Figure 24).

Policy A was designed to advise farmers of the benefits of increasing SOC stocks and enable them to make a cost benefit assessment of adding more organic matter, initiating their awareness and operating on the assumption that farmers would act on the advice to continue investing in SOC if they could forecast a positive return after five years. Analysis and testing demonstrated that targeting this leverage point with Policy A was likely capable of achieving the policy goal on field plots with already good initial SOC levels at the beginning of the policy timeframe. This was because SOC levels were already sufficiently large to produce significant onsite ecosystem services, and land managers accounting for these pre-existing contributions presented an immediate positive net benefit which would likely encourage them to invest in SOC. However, analysis and testing of Policy A suggested that for field plots with initially poor SOC status, operating this leverage point was likely to require more than awareness raising and farmers accounting for the benefits of SOC. This was because farmers' activities to build SOC stocks would be unlikely to offer a net economic benefit within the 10-year policy timeframe due to the high costs involved.

Policy B was designed as a stronger attempt to influence this leverage point through the introduction of an additional feedback structure in the form of a PES scheme. The aim of Policy B was to enable land managers internalise external ecosystem services costs and benefits of SOC in their decisions about how they use crop residues and organic amendments by being paid by offsite actors for the offsite benefits (or cost mitigations) SOC could generate. This included an initial five-year fixed payment to help land managers with initially poor status soils overcome the barrier of negative returns (counteracting balancing loop B2 in Figure 24) if they had to fund the SOC improvements themselves. Like Policy A, the analysis for Policy B confirmed managers' awareness of the cost benefit balance of maintaining and improving SOC levels could be a leverage point for achieving the policy goal on field plots with already good initial soil status. This is because Policy B would enable farmers to be further incentivised to continue investing in SOC because of the benefits they were not only receiving for their own business but also from the PES payment. In contrast to Policy A, Policy B demonstrated that farmer awareness and accounting of the economic benefits of SOC could also be used as a leverage point for improving SOC stocks on field plots with initially poor SOC status. This was because the initial five-year payment and subsequent receipt of the PES based on their offsite benefits from offsite sources could provide a sufficiently strong economic incentive. Nevertheless, despite the ability of Policy B in making use of this leverage point, in circumstances of initially poor soil status Policy B was still unable to reach the policy goal within the policy timeframe. This suggests that land manager awareness and accounting of the ecosystem services benefits of SOC does present a leverage point for behavioural change, but the success of using this leverage point and achieving the policy goal is dependent on the initial SOC status of the target field plot. That an investor with interests in multiple plots (e.g. at the catchment scale) might use the returns on investment on initially good SOC status plots to further incentivise those with poor initial SOC status could be explored in future work.

5.4.2 Strengths and opportunities of using natural capital investment

Research Question 2.2 asks "What are the strengths and opportunities for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?" In Chapter 4 it was proposed that natural capital investments could be used to create feedback mechanisms relating SOC as a soil health and natural capital indicator to its economic benefits and thereby influence the behaviour of the land manager. Policy A was designed to introduce such a feedback mechanism through farm advice whereby farmers would become aware of and account for the economic benefits of SOC for their own business. The strength of this type of natural capital investment is that for field plots with already good SOC status it could represent a "one off" investment for offsite actors since it is assumed farmers will be motivated to invest in SOC themselves once they recognise the benefits it already delivers for their business. The opportunity Policy A presents is that it is also a net positive investment for offsite actors since they can use it to mitigate potential costs they would incur if good soil status plots were allowed to degrade. Sensitivity testing revealed that for plots with initially good SOC status, Policy A was robust to some changes in plant residue prices, FYM prices and crop yields, indicating a further strength of the intervention. For plots with initially good SOC status Policy B was shown to be even more robust to more extreme changes in these parameters influences while still presenting a net positive investment for offsite actors compared to bearing the costs of soil degradation without such a policy. That both Policy A and B could achieve the policy goal of maintaining good SOC status on plots with initially good SOC status is another strength of both of these types of natural capital investments. For plots with initially poor SOC status, Policy A was not considered an effective intervention. At such locations Policy B could alter land manager behaviour to invest in SOC by providing a sufficient economic incentive and could improve SOC stocks, but failed to achieve the policy goal. These results suggest that under certain circumstances (most crucially the initial soil health conditions) both farm advice and PES natural capital investments can present the opportunity of achieving desired changes in SOC stocks and deliver positive returns on investments while being reasonable robust to changes in variables that can affect land managers' economic incentives.

5.4.3 Limitations and risks of using natural capital investment

Research Question 2.3 asks "What are the limitations and risks for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?" The preliminary analyses in Chapter 4 provided three initial responses: that natural capital investments might produce desired results on some plots of land but not on others, high sensitivity of financial indicators to price parameters such as "Price per Mg of plant residue", and the financial and practical challenges of ensuring sufficient organic matter inputs for achieving policy goals.

The policy analysis and sensitivity testing confirmed the first point: one limitation of using natural capital investments to exploit the farmer awareness leverage point was indeed dependent on the initial SOC status with greater investment effort needed for sites with initially poor SOC status than those with initially good SOC status, despite the ability of the former to produce improvements in ecosystem services value. The policy analysis and sensitivity testing also illustrated that, although PES investments (Policy B) were more likely to produce behavioural change and with greater robustness to sensitivity than those using farm advice (Policy A), these interventions might still be unable to achieve the policy goal on initially poor status plots despite some improvements in SOC levels. This is because of the delay in SOC accumulation and the diminishing rate of SOC accumulation (assuming a constant organic input) resulting from balancing loop B1. This limitation of natural capital investment relates to the fact that although incentives can be created through investment mechanisms and change land manager behaviour, the dynamic structure of biophysical processes may constrain the potential for achieving natural capital stock goals within the policy timeframe depending on the initial natural capital stocks of particular target sites.

The policy analysis and sensitivity testing also provided confirmation on the second point: the success of natural capital investments could indeed be sensitive to certain price parameters farmers consider in their cost benefit assessment of whether to improve SOC stocks or not. The policy testing in this Chapter was able to add value to this suggestion by quantifying and comparing sensitivities between different price variables and under different initial SOC conditions. The results demonstrated that farm advice (Policy A) was reasonably robust and PES (Policy B) highly robust to changes in “Price per Mg of plant residue” and “Imported FYM or other organic amendment price per Mg” for field plots with initially good soil status. This is because of the initially good SOC stock which provides a “buffer” against price and input fluctuations while providing a stronger supply of benefits to the farmer. In contrast, farm advice (Policy A) could only be effective on sites with initially low SOC status with constantly very low plant residue prices. PES (Policy B) proved to be more robust to crop residue and FYM prices than farm advice on initially low SOC status sites because it provided an economic incentive for overcoming the initially low SOC ecosystem services benefits to their business. These analyses highlight the risks posed by plant residue and FYM price fluctuations to the success of natural capital investments for both exploiting leverage points for behavioural change and influencing biophysical processes. Such risks need to be accounted for in the design of policies, such as the “PES first five years investment” as a stimulus to resist balancing loop B2. These analyses also confirm the initial conditions limitation discussed earlier. In the same way, plant residue and FYM prices present an additional spatial dimension, since these can vary locally and regionally (KeySoil, 2010).

The policy analysis and sensitivity testing also provided further insights into the potential financial and practical challenge to achieving policy goals as first posed in Chapter 4, such as ensuring sufficient organic matter inputs are available. Policy B was shown to be sensitive to changes in the “Maximum potential harvested yield” and the FYM supply available for the “Mean annual input of FYM or other organic amendment” which control organic inputs. Policy B was robust to these changes in terms of behavioural change on initially good SOC status sites. Policy B was also relatively robust here in achieving the target or close to the policy target for SOC by 2030. Again, this was due to the initially high SOC levels where larger natural capital stocks provided resilience against occasional fluctuations in inputs due to the stock accumulation-depletion delay. Policy B was also reasonably robust to these changes in terms of delivering behavioural change for the land manager of sites with initially poor SOC status. However, such fluctuations posed even greater challenges for SOC indicators which remained only a little higher than equilibrium. This highlights a potential risk for natural capital investments that although they might provide land managers with an economic incentive to change behaviour, they may be unable to produce or buy-in sufficient organic matter to increase their SOC stocks at a sufficient rate to achieve the policy goal within the policy timeframe. In England, FYM supplies are considered to be fully utilised, although there appears potential for using composted green waste (Powlson et al., 2011). Dynamic relationships between FYM supply, demand and prices were not included in the model structure, although such relationships could pose related risks between financial sensitivities and practical issues. For example, if FYM is in short supply, the price might increase, meaning there is less economic incentive for land managers to buy FYM to increase their SOC levels regardless of the PES payment available to them. Natural capital investment interventions should be designed to be resilient to such effects and this presents an opportunity for future research.

The policy analysis and sensitivity testing provided an additional insight regarding limitations and risks of natural capital investments for reversing soil degradation. This related to the value of SOC investment outcomes for the investor, here considered as an offsite entity (water company, local council, national government) benefiting from the offsite ecosystem services generated from SOC. The business case for these offsite entities investing in farm advice (Policy A) and PES (Policy B) to continue receiving the ecosystem services benefits of SOC and avoiding the costs of degradation is clear for plots with initially good SOC status, as indicated by the positive NPV of investment for these sites. However, the business case for offsite entities investing in farm advice on sites with initially poor SOC status unclear: such interventions are unlikely to produce the forecast benefits because the land manager does not receive a sufficient economic incentive. The NPV of investment in PES on these sites with is also less attractive than not deploying a policy because the costs of investment outweigh the benefits investors can expect to gain within the policy timeframe. Again, this is due to the slow accumulation of the SOC stock, feedback loops B1 and B2, and the requirement for the initial five-year payment for sites with initially poor status which increase the funding burden on the investor. The discussion reveals the limitation that, because natural capital investments operate on the basis of economic incentives for both the land manager and the offsite beneficiary, if there is no clear economic incentive for the investor then the investment is unlikely to be made. This is particularly problematic both in the context of Defra’s broader policy aim for ensuring sustainable soil management, since the business case for investing to maintain sites with currently good SOC status is clear, but the case for investing to increase SOC levels where the status is poor is not. These insights can be considered valuable from both a commercial investment perspective and from the perspective of public policy.

Chapter 6. Conclusions

6.1 Answers to Research Questions

The first three Research Questions 1.1-1.3 were focused on identifying the dynamic structures underlying soil natural capital degradation in England, and highlighting dynamics linking soil health metrics to systems of financial investments and incentives. Soil organic carbon (SOC) was the metric used. These questions were addressed through model analysis and validity testing from which the following conclusions were drawn.

Research Question 1.1: "Which dynamic structures could be responsible for promoting the decline of soil natural capital in England?"

- Stocks and flows: the stock and flow structure of accumulating cause and effect relationships are central to the historic decline in SOC. This is because SOC is a stock and therefore depletes if the inflows of adding organic carbon (e.g. from crop residues or farmyard manure) are smaller than the outflows of mineralisation during organic matter decay. Trends of declining SOC are due to smaller inflows of organic matter than outflows of decay in the long term.
- No feedbacks: feedback mechanisms between SOC, soil ecosystems services, land management decisions and existing policies are absent. The model provides an operational and quantified structure to support the market failure hypothesis proposed by Graves et al. (2015) and highlights the limitation of existing action-oriented agri-environment policy.

Research Question 1.2: "Which dynamic structures could be responsible for mitigating or slowing the decline in soil natural capital in England?"

- Balancing feedback loop: the outflow of SOC through organic matter decay is determined by the current SOC stock level via a first order control. This structure mitigates or slows the decline of SOC producing goal-seeking behaviour patterns of exponential decay.
- Exogenous influences: reasons unrelated to SOC are also responsible for mitigating or slowing the decline in SOC as well as promoting it due to the absence of feedback mechanisms. This means that factors not related to SOC are currently influencing land managers' decision processes about how to manage the SOC stock which slow the degradation process. Again, examples include action-oriented agri-environmental policies.

Research Question 1.3 “Which of these dynamic structures relate soil health to systems of financial incentives and investments?”

- They don’t: the costs of soil degradation and loss of soil ecosystem services due to declining SOC are currently externalities to land managers’ financial decision making. Changes in SOC present unrecognised potential economic benefits and costs to land managers’ businesses, while the offsite actors bearing the economic burden of declining water quality, loss of flood protection and reduced ability to regulate climate due to declines in SOC.

The last three Research Questions 2.1-2.3 were focused on identifying opportunities and limitations for the effectiveness of natural capital investments for regenerating soils in England. These questions were addressed by designing and testing two policies in the simulation model with the goal of achieving good SOC status by 2030 following their introduction in 2020. “Policy A” was an investment in farm advice which would activate an information feedback loop between the onsite ecosystem services benefits of SOC and land managers’ cost-benefit assessment of their organic matter related practices. “Policy B” was a payment for ecosystem services (PES) by which beneficiaries of SOC’s offsite ecosystem services paid farmers to maintain or improve SOC status. Policy sensitivities to initial SOC status, price variables and available organic matter supplies were compared. The results of the policy analysis enabled the following conclusions to be drawn.

Research Question 2.1 “What are the leverage points in the dynamic structures of the system for reversing the decline in soil natural capital in England using natural capital investments?”

- Land managers’ lack of awareness about the potential economic benefits of SOC for their own business: this was considered a suitable leverage point with which to target farm advice investments (Policy A) for land managers whose field plots had an initially good SOC status at the beginning of the policy timeframe. This is because the unrecognised economic contributions of already sufficient SOC levels already exceed the costs to the farmer of adding the necessary inputs to maintain them. This was not the case for plots with initially poor SOC status because the costs to the farmer of increasing SOC outweigh the benefits until a higher level of SOC is achieved.
- Land managers’ cost-benefit assessment of the ecosystem services value of SOC and organic matter inputs: this was considered a suitable leverage point with which to target PES investments (Policy B) by those benefiting from the offsite ecosystem services of SOC. Using this leverage point it is possible to change the behaviour of land managers to add more organic matter whose field plots had either an initially good or initially poor SOC status at the beginning of the policy timeframe. It works by increasing farm income from offsite actors who

benefit from SOC. However, targeting this leverage point could only succeed in achieving the policy goal for field plots with initially good soil status. Targeting this leverage point could not achieve the SOC policy target on plots with initially poor soil status due to the unrealistically high quantities organic material required to provide a sufficient inflow rate.

Research Question 2.2 “What are the strengths and opportunities for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?”

- Creating feedbacks: farm advisory and PES natural capital investments have the potential to create missing feedback mechanisms relating SOC to its economic benefits and influencing the behaviour of the land managers to increase organic matter applications.
- Achieve (or work towards) policy goals: for field plots with initially good SOC status both farm advisory and PES investments can initiate behaviour change and achieve the SOC policy target by 2030. For field plots with initially poor SOC status, a PES investment has potential to initiate behavioural change and can increase SOC stocks towards (but not reach) the policy goal by 2030.
- One-off investments: for plots with initially good soil status, farm advisory investments proved reasonably robust to changes in organic materials price and supply variables and might need only be made as a one-off investment. This is because land managers with already good SOC status may only need to be stimulated once to recognise the benefits of SOC to their business of improving SOC. For investors, this means that large or long-term capital expenditures are unlikely to be required for these sites.
- Net positive investments: for plots with initially good SOC status, benefits in advisory and PES investments for offsite funders yield a net positive return by 2030. This is because these investments mitigate the costs they would incur if initially good SOC status plots are allowed to degrade.

Research Question 2.3 “What are the limitations and risks for using natural capital investments to exploit these leverage points in the system structure for restoring soil natural capital?”

- Natural capital investments can produce desired results on some land plots but not others: farm advisory investments were only effective in exploiting farmer awareness of the economic benefits of SOC for plots with good initial SOC status. This is because land managers with plots of initially poor soil status are unlikely to have a positive cost-benefit analysis of increasing organic matter applications within the policy timeframe.
- Natural capital investments can be sensitive to price parameters depending on initial SOC conditions: policy analysis demonstrated that although farm advice and PES investments were

reasonably robust to changes in plant residue and imported FYM prices for field plots with good initial SOC status, they were less robust for plots with poor initial status. This is because initially high SOC stocks provide a “buffer” against fluctuations in prices and organic matter additions, whereas low SOC levels do not. PES investments were more robust than advisory investments overall.

- Insufficient supplies of organic matter could hinder efforts to achieve desired SOC levels: although PES investments may be more robust than advisory investments, both policies are susceptible to shortages in organic matter supply over the long term, and more so for plots with initially low SOC stocks. This is because although the policies could produce behavioural change by activating farmer awareness and providing additional income, if supplies of organic matter (either from crop residues due to low crop yields or due to high market demand for FYM) are not sufficient to at least maintain SOC equilibrium, over the long term the PES land managers can receive will decrease as SOC stocks decline following lower organic matter applications. This represents a negative consequence of reliance on a reinforcing feedback loop for natural capital investment mechanisms.
- Returns to the natural capital investor might not always be net positive: the business case for offsite entities (water companies, local councils, national governments) investing in farm advice and PES to continue receiving the ecosystem services benefits of SOC and avoiding the costs of degradation is clear for plots with initially good SOC status because financial gains are greater than costs. However, the business case for offsite entities investing in the farm advice or PES mechanisms on sites with initially poor SOC status are likely incapable of producing positive returns. This is because the land manager either does not receive a sufficient economic incentive or because of the long delay times in increasing SOC to sufficient levels with available organic matter supplies. The investor is therefore unable to receive a return within the policy timeframe under these circumstances, meaning that these investments are unlikely to be made in the first place, even though some improvements in SOC levels could be made. The potential for investors to use returns from investments in initially good status soils to subsidise improvements initially poor status soils was highlighted for further consideration in future research.

6.2 Broader implications and next steps

The insights produced in this thesis can also contribute to knowledge about and management of other natural capital assets, such as water and biodiversity. The work complements natural resources management literature which already recognises the importance of stocks, flows and feedback processes (Moxnes, 2000) by illustrating how management decisions can be linked to resource quality metrics and the ecosystem services value that natural capital stocks generate. The work also offers insights which are likely to be transferable to other sustainability issues to which natural capital investment could be applied, such as the importance of initial conditions, feedbacks (or their absence), and how such interventions can be designed and tested with the help of a simulation model. These contributions are relevant to both policy makers interested in the potential of natural capital investments, as well as investors and suppliers of ecosystem services, to help recognise the opportunities and risks of using natural capital investments to achieve desired outcomes. Perhaps most importantly, this thesis highlights that although there is promise for natural capital investment to harness the power of reinforcing feedback mechanisms to improve natural capital stocks, deliver greater ecosystem services benefits and generate positive returns on investment, this process can also work in reverse, while balancing feedback mechanisms can place limitations on how far and how quickly desired results can be achieved if at all.

Two recommendations are suggested for how the insights and simulation model developed in this thesis can be used and improved upon further. First, the model could be used as part of a participatory engagement effort including policy stakeholders. The model could be used in such a setting as both the basis for critical discussion and as a repository of existing knowledge. In this way the model could facilitate the improvement of collective understanding of the soil degradation problem and synthesise the tacit knowledge of stakeholders with the secondary data. This could help achieve the dual purpose of improving some of the uncertainties in the model structure highlighted by the analysis (Andersen et al., 2012; Richardson, 2013) while also facilitating the design, testing and evaluation of policies (Gilbert et al., 2018). Second, the model could be adapted to serve the purpose of a natural capital investment appraisal tool to be used by natural capital investors and suppliers. To enable this, it is recommended that the existing model and insights of this research should be demonstrated to potential users, such as policy analysts, natural capital investors and those with natural capital assets who are seeking investment. A survey of product user requirements should be a key component of this demonstration to understand what questions investors and suppliers would be interested in the tool being able to answer. The model's existing functionality and validity should then be reviewed against these requirements and a product development proposal can be devised.

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Appendix: model documentation

Three electronic Stella files are attached to this thesis:

- "RothC_Stella_rebuild_04.stmx" which is the quantified system dynamics model translated from the original RothC-26.3 model (set in equilibrium);
- "Model_Nichols2019_Soil_natural_capital_investment.stmx" which is the complete model built and used in this thesis (set with policy switches off, parameterised for "Worst Case" initial SOC stock conditions);
- "Model_Nichols2019_Soil_natural_capital_investment.isdb" which contains all the data from all of the model runs referred to in the text.

The remaining pages of this thesis provide the remaining model documentation. These notes are arranged in alphabetical order based on the names of the sectors in the model file.

****

Outside sectors:

****

Drought_conditions = IF(SWITCH_Drought_conditions=0) THEN 1 ELSE (1+PULSE(-0.5, 10, Potential_drought_frequency))

UNITS: Dimensionless

Potential_drought_frequency = 5 {every 5 years}

UNITS: Years

Ref_mode_intercept = 69.3

UNITS: Dimensionless

Ref_mode_slope = -0.0333

UNITS: Per Year

SWITCH_Drought_conditions = 0

UNITS: Dimensionless

Time_series_data_for_SOC_on_arable_land = Ref_mode_slope*TIME+Ref_mode_intercept

UNITS: Dimensionless

****

Decisions:

****

Carbon_fraction_of_FYM_or_other_organic_amenedment = 0.34 {0.34 for FYM from ADAS mean from straw and manure report}

UNITS: Dimensionless

Carbon_fraction_of_plant_residues = 0.4 {-Straw used for fuel purposes usually contains 14 – 20% moisture that vaporises during burning. The remaining dry matter consists of less than 50% carbon https://www.teagasc.ie/media/website/publications/2010/868_StrawForEnergy-1.pdf -These estimates assumed that half of the non-grain/seed biomass was returned in the stubble and chaff (Anon., 1997), that root dry matter production was equivalent to c.8% of shoot dry matter (Gregory et al., 1978) and that all dry matter contained 40% OC (Powlson et al., 1985). ADAS report on straw and manure SOC}

UNITS: Dimensionless

CHECK_Input_of_carbon_from_plant_residues = 1.91 {1.91 equilibrium setting}

UNITS: Mg/Hectares/Years

Check_proportion = 1

UNITS: Dimensionless

DECISION_Add_FYM_or_other_organic_amendment = IF(SWITCH_DECISION_Mean_annual_input_of_FYM_or_other_organic_amendment_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback=2) THEN DECISION_To_invest_in_OM ELSE SWITCH_DECISION_Mean_annual_input_of_FYM_or_other_organic_amendment_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback

UNITS: Dimensionless

DECISION_Proportion_of_recoverable_plant_residue_returned_to_field = IF (SWITCH_Proportion_of_recoverable_plant_residue_returned_to_field_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback = 1) THEN (Check_proportion) ELSE (Proportion_of_recoverable_plant_residue_returned_to_field)

UNITS: Dimensionless

DECISION_To_invest_in_OM = IF (SWITCH_1_Exogenous_reason_to_invest_in_SOM_2_Dynamic_reason_to_invest_in_SOM=1) THEN 1 ELSE (MAX(DYNAMIC_POLICY_A_Advice_to_farmer_on_benefits_of_investing_in_OM, Standard_practice_to_invest_in_OM))

UNITS: Dimensionless

DECISION_To_keep_investing_in_OM = IF(FORCST(Farmer_CB_balance_for_investing_in_OM, 1, 5)> 0) AND(TIME>(STARTTIME+1)) THEN 1 ELSE 0

UNITS: Dimensionless

DYNAMIC_POLICY_A_Advice_to_farmer_on_benefits_of_investing_in_OM = IF(DECISION_To_keep_investing_in_OM =0) THEN POLICY_A_Advice_to_farmer_on_benefits_of_returning_crop_residues ELSE 0

UNITS: Dimensionless

Farmer_Making_a_CBA(t) = Farmer_Making_a_CBA(t - dt) + (Initiating_awareness_for_making_CBA) * dt

INIT Farmer_Making_a_CBA = Initial_making_CBA

UNITS: Dimensionless

INFLOWS:

Initiating_awareness_for_making_CBA = ((DYNAMIC_POLICY_A_Advice_to_farmer_on_benefits_of_investing_in_OM-Farmer_Making_a_CBA)+SWITCH_POLICY_B)/Time_to_awareness {UNIFLOW}

UNITS: Per Year

FYM_or_other_organic_amendment_available = 1 {Poulton et al 2019 access to manure as potential limitation}

UNITS: Dimensionless

Harvested_plant_residue = Recoverable_crop_plant_residue*(1-DECISION_Proportion_of_recoverable_plant_residue_returned_to_field)

UNITS: Mg/Hectares/Years

Initial_making_CBA = 0

UNITS: Dimensionless

Mean_annual_input_of_FYM_or_other_organic_amendment = 55 {In eq for FYM use 8.82 for 3 Mg/Ha/Year with 34% C}

UNITS: Mg/Hectares/Years

Mean_annual_input_of_FYM_or_other_organic_amendment_when_on = DECISION_Add_FYM_or_other_organic_amendment*Mean_annual_input_of_FYM_or_other_organic_amendment*FYM_or_other_organic_amendment_available

UNITS: Mg/Hectares/Years

Mean_annual_input_of_plant_residues = (Recoverable_crop_plant_residue*DECISION_Proportion_of_recoverable_plant_residue_returned_to_field)+Unrecoverable_plant_residue

UNITS: Mg/Hectares/Years

Minimum_proportion_of_recoverable_plant_residue_being_returned = 0 {use 0.285 for RothC unmanured as Base Case, 0 for Worst Case}

UNITS: Dimensionless

Proportion_of_recoverable_plant_residue_returned_to_field = IF DECISION_To_invest_in_OM =1 THEN 1 ELSE Minimum_proportion_of_recoverable_plant_residue_being_returned

UNITS: Dimensionless

Standard_practice_to_invest_in_OM = DECISION_To_keep_investing_in_OM

UNITS: Dimensionless

SWITCH_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback = 2

UNITS: Dimensionless

SWITCH_1_Exogenous_reason_to_invest_in_SOM_2_Dynamic_reason_to_invest_in_SOM = 2

UNITS: Dimensionless

SWITCH_DECISION_Mean_annual_input_of_FYM_or_other_organic_amendment_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback = 2

UNITS: Dimensionless

SWITCH_Proportion_of_recoverable_plant_residue_returned_to_field_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback = 2

UNITS: Dimensionless

Time_to_awareness = DT

UNITS: Years

****

Offsite_Finance:

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Accumulated_net_CO2_seq_value(t) = Accumulated_net_CO2_seq_value(t - dt) + (Net_CO2_seq_value_accumulation) * dt

INIT Accumulated_net_CO2_seq_value = 0

UNITS: GBP/Hectares

INFLOWS:

Net_CO2_seq_value_accumulation = Annual_value_of_net_CO2_sequestration_in_soil_by_area

UNITS: GBP/Hectares/Years

Accumulated_value_of_change_in_nuisance_sediment_removal(t) = Accumulated_value_of_change_in_nuisance_sediment_removal(t - dt) + (Change_in_cost_of_nuisance_sediment_removal_during_simulation) * dt

INIT Accumulated_value_of_change_in_nuisance_sediment_removal = 0

UNITS: GBP/Hectares

INFLOWS:

Change_in_cost_of_nuisance_sediment_removal_during_simulation = Initial_Cost_of_nuisance_sediment_per_source_ha-Cost_of_nuisance_sediment_per_source_ha

UNITS: GBP/Hectares/Years

Annual_cost_of_building_sediment_removal_capcaity = Nuisance_sediment_removal_capacity_building*Cost_per_ton_of_new_nuisance_sediment_removal_capacity

UNITS: GBP/Years

Annual_cost_of_nuisance_sediment_removal = Nuisance_Sediment_Removal_Capacity*Cost_per_ton_of_nuisance_sediment_removal

UNITS: GBP/Years

Annual_value_of_net_CO2_sequestration_in_soil_by_area = Net_C_sequestration_by_soil*CO2_price*Conversion_to_measure_cost_of_C_rather_than_CO2

UNITS: GBP/Hectares/Years

Climate_regulation_value = Accumulated_net_CO2_seq_value

UNITS: GBP/Hectares

CO2_price = 51 {CO2 e } {Graves et al 2015 For the purpose here, however, a policy based MAC price of £51 CO2e t−1 is used as the best single estimate to reflect the 2009 'business as usual' case It is noted that the economic price of carbon has a significant effect on total soil degradation costs given the scale of potential soil carbon loss.}

UNITS: GBP/Mg

Conversion_to_measure_cost_of_C_rather_than_CO2 = 0.273

UNITS: Dimensionless

Cost_of_nuisance_sediment_per_source_ha = Universal_Soil_Loss_Equation_USLE*Cost_per_ton_of_nuisance_sediment_removal*Proportion_of_sediment_deposited_in_unwanted_locations

UNITS: GBP/Hectares/Years

Cost_per_ton_of_new_nuisance_sediment_removal_capacity = 5.15

UNITS: GBP/Mg*Years

Cost_per_ton_of_nuisance_sediment_removal = 5.15 {Graves p6 ref to Anthony et al 2009}

UNITS: GBP/Mg

Desired_nuisance_sediment_removal_capacity = (Nuisance_sediment_gap/Sediment_management_period)+Sediment_deposition

UNITS: Mg/Years

Initial_Cost_of_nuisance_sediment_per_source_ha = INIT(Cost_of_nuisance_sediment_per_source_ha)

UNITS: GBP/Hectares/Years

Initial_Nuisance_Sediment = 27.3

UNITS: Mg

Initial_Nuisance_Sediment_Removal_Capacity = 100

UNITS: Mg/Years

Nuisance_sediment(t) = Nuisance_sediment(t - dt) + (Sediment_deposition - Sediment_removal_and_drain_clearance) * dt {NON-NEGATIVE}

INIT Nuisance_sediment = Initial_Nuisance_Sediment

UNITS: Mg

INFLOWS:

Sediment_deposition = Universal_Soil_Loss_Equation_USLE*Total_area_of_farmland_in_catchment_of_interest*Proportion_of_sediment_deposited_in_unwanted_locations

UNITS: Mg/Years

OUTFLOWS:

Sediment_removal_and_drain_clearance = Nuisance_Sediment_Removal_Capacity

UNITS: Mg/Years

Nuisance_sediment_gap = Nuisance_sediment-Nuisance_sediment_target

UNITS: Mg

Nuisance_Sediment_Removal_Capacity(t) = Nuisance_Sediment_Removal_Capacity(t - dt) + (Nuisance_sediment_removal_capacity_building - Nuisance_sediment_removal_outdating) * dt

INIT Nuisance_Sediment_Removal_Capacity = Initial_Nuisance_Sediment_Removal_Capacity

UNITS: Mg/Years

INFLOWS:

Nuisance_sediment_removal_capacity_building = Nuisance_sediment_removal_capacity_expansion_needed

UNITS: Mg/Years/Years

OUTFLOWS:

Nuisance_sediment_removal_outdating = Nuisance_Sediment_Removal_Capacity/Nuisance_Sedimental_Removal_lifetime

UNITS: Mg/Years/Years

Nuisance_sediment_removal_capacity_build_time = 5

UNITS: Years

Nuisance_sediment_removal_capacity_expansion_needed = (Nuisance_sediment_removal_capacity_gap/Nuisance_sediment_removal_capacity_build_time)+Nuisance_sediment_removal_outdating

UNITS: Mg/Years/Years

Nuisance_sediment_removal_capacity_gap = Desired_nuisance_sediment_removal_capacity-Nuisance_Sediment_Removal_Capacity

UNITS: Mg/Years

Nuisance_sediment_target = 0

UNITS: Mg

Nuisance_Sedimental_Removal_lifetime = 40

UNITS: Years

Proportion_of_sediment_deposited_in_unwanted_locations = 1

UNITS: Dimensionless

Sediment_management_period = 1

UNITS: Years

Sum_of_annual_costs_related_to_nusiance_sediment_removal = (Annual_cost_of_building_sediment_removal_capcaity+Annual_cost_of_nuisance_sediment_removal)/Total_area_of_farmland_in_catchment_of_interest

UNITS: GBP/Hectares/Years

Supply_chain_risk_indicator = SOM_influence_on_mean_yield_variability/100 {Simple linear indicator expressing how change in potential yield variability due to influence of SOC could present supply chain risk e.g. for retailer of farm produce}

UNITS: Dimensionless

Total_area_of_farmland_in_catchment_of_interest = 330 {330 ha is the size of the Rothamsted Research site where RothC applied}

UNITS: Hectares

Water_quality_and_flood_regulation_value = Accumulated_value_of_change_in_nuisance_sediment_removal

UNITS: GBP/Hectares

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Onsite_Finance:

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Accumulated_ROI(t) = Accumulated_ROI(t - dt) + (ROI_Accumulation) * dt

INIT Accumulated_ROI = 0

UNITS: Dimensionless

INFLOWS:

ROI_Accumulation = Farm_ROI_for_investing_in_SOM/ROI_spread_period

UNITS: Per Year

Actual_income_from_plant_residue_sales_by_area = Harvested_plant_residue*Price_per_Mg_of_plant_residue

UNITS: GBP/Hectares/Years

Actual_K_inorganic_fertilizer_cost = K_inorganic_fertilizer_price*K_inorganic_fertilizer_demand

UNITS: GBP/Hectares/Years

Actual_N_inorganic_fertilizer_cost = N_inorganic_fertilizer_price*N_inorganic_fertilizer_demand

UNITS: GBP/Hectares/Years

Actual_P_inorganic_fertilizer_cost = P_inorganic_fertilizer_price*P_inorganic_fertilizer_demand

UNITS: GBP/Hectares/Years

Additional_annual_onsite_cost_for_investing_in_SOM_per_area = Annual_FYM_or_other_organic_amendment_handling_and_spreading_costs+ Annual_imported_FYM_or_other_organic_amendment_cost+Cost_of_additional_weed_management+Cost_of_additional_slug_management+Cost_of_ploughing_in_recoverable_plant_residues+Potential_income_foregone_from_plant_residue_sales

UNITS: GBP/Hectares/Years

Additional_annual_weed_management_cost_per_area = 2.50 {KeySoil Case 27}

UNITS: GBP/Hectares/Years

Additional_slug_management_cost_per_area = 0 {12.5 KeySoil Case 9 and 18 additional slug burden when adding crop residues or FYM}

UNITS: GBP/Hectares/Years

Annual_cost_of_ploughing_in_recoverable_plant_residues_per_area = 0 {KeySoil Case 9 refs to "small cost of ploughing in" and does not report therefore assumed to be covered in same as normal cultivation activity}

UNITS: GBP/Hectares/Years

Annual_FYM_or_other_organic_amendment_handling_and_spreading_costs = SWITCH_Additional_costs_of_using_FYM_or_other_organic_amendment*FYM_or_other_organic_amendment_handling_and_spreading_costs_per_area

UNITS: GBP/Hectares/Years

Annual_imported_FYM_or_other_organic_amendment_cost = SWITCH_Additional_costs_of_using_FYM_or_other_organic_amendment*(Mean_annual_input_of_FYM_or_other_organic_amendment_when_on*Imported_FYM_or_other_organic_amendment_price_per_Mg)

UNITS: GBP/Hectares/Years

Annual_number_of_soil_cultivation_treatments = 4 {Select 4 for conventional tillage (2x2 treatments), 2.5 for reduced tillage (2x1 treatments), and 0 for no-till} {Powlson et al 2011 "Recent surveys in England and Wales (Anon, 2006) show that c.50% of primary tillage practices used mouldboard ploughing ('conventional tillage') and c.43% used reduced tillage methods (i.e. heavy discs, tines or powered cultivators), with direct drilling/broadcasting (i.e. no cultivation) occurring on only c.7% of the tillage area. The reason that zero tillage has been less popular in the UK and northwest Europe, compared to the Americas and Australia, has been the build-up of grass weeds, crop disease problems and soil compaction, all of which decrease crop yields and appear to be more prevalent in a moister climate. Also the larger crop yields achieved in northwest Europe (often 8-10 t grain ha−1) leads to a larger quantity of straw which can cause problems of seedling emergence if left on the surface. The relatively small area that is under zero tillage in the UK is mainly calcareous clay soils that self-mulch as a result of wet-dry and freeze-thaw cycles, producing good tilth in a way not occurring on other soil types."}

UNITS: Treatments/Years

Annual_onsite_benefits_of_SOM_per_area = (Inorganic_P_cost_saving+Inorganic_K_cost_saving+Inorganic_N_cost_saving+Cost_saving_on_compaction_relief_cultivation_due_to_influence_of_SOM+Drought_resilience_value_of_SOM_for_yield_income_protection+POLICY_B_PES_to_Farmer)

UNITS: GBP/Hectares/Years

Base_fuel_consumption_per_treatment_per_hectare_of_cultivation = 30 {Ploughing up to 30 litres per ha https://www.swarmhub.co.uk/energy-efficiency-master/fuel-saving-stragies/}

UNITS: Litres/Treatments/Hectares

Base_fuel_costs_for_cultivation_by_area = Annual_number_of_soil_cultivation_treatments*Base_fuel_consumption_per_treatment_per_hectare_of_cultivation*Fuel_price

UNITS: GBP/Hectares/Years

Cost_of_additional_slug_management = IF(SWITCH_Additional_costs_of_ploughing_in_recoverable_plant_residues>0) THEN (SWITCH_Additional_costs_of_ploughing_in_recoverable_plant_residues*Additional_slug_management_cost_per_area) ELSE SWITCH_Additional_costs_of_using_FYM_or_other_organic_amendment*Additional_slug_management_cost_per_area

UNITS: GBP/Hectares/Years

Cost_of_additional_weed_management = SWITCH_Additional_costs_of_using_FYM_or_other_organic_amendment*Additional_annual_weed_management_cost_per_area

UNITS: GBP/Hectares/Years

Cost_of_ploughing_in_recoverable_plant_residues = SWITCH_Additional_costs_of_ploughing_in_recoverable_plant_residues*Annual_cost_of_ploughing_in_recoverable_plant_residues_per_area

UNITS: GBP/Hectares/Years

Cost_saving_on_compaction_relief_cultivation_due_to_influence_of_SOM = Base_fuel_costs_for_cultivation_by_area*Cost_saving_on_compaction_relief_cultivation_due_to_influence_of_SOM_as_proportion_of_base

UNITS: GBP/Hectares/Years

Cost_saving_on_compaction_relief_cultivation_due_to_influence_of_SOM_as_proportion_of_base = 1-(Fuel_cost_for_compaction_relief_cultivation_by_area_with_efficiency/Base_fuel_costs_for_cultivation_by_area)

UNITS: Dimensionless

Drought_resilience_value_of_SOM_for_yield_income_protection = Yield_protected_by_SOM*Price_per_crop_ton

UNITS: GBP/Hectares/Years

Farm_ROI_for_investing_in_SOM = 0 { ((Annual_onsite_benefits_of_SOM_per_area/(Additional_annual_onsite_cost_for_investing_in_SOM_per_area)*100)-100)}

UNITS: Dimensionless

Farmer_CB_balance_for_investing_in_OM(t) = Farmer_CB_balance_for_investing_in_OM(t - dt) + (Farmer_Net_benefit_of_OM_per_hectare) * dt

INIT Farmer_CB_balance_for_investing_in_OM = 0

UNITS: GBP/Hectares

INFLOWS:

Farmer_Net_benefit_of_OM_per_hectare = (Annual_onsite_benefits_of_SOM_per_area-Additional_annual_onsite_cost_for_investing_in_SOM_per_area)*Farmer_Decision_to_make_CBA_switch

UNITS: GBP/Hectares/Years

Farmer_Decision_to_make_CBA_switch = IF(Farmer_Making_a_CBA=1) THEN 1 ELSE 0

UNITS: Dimensionless

Fuel_cost_for_compaction_relief_cultivation_by_area_with_efficiency = MAX(0, Base_fuel_costs_for_cultivation_by_area*Effect_of_SOM_compaction_regulation_on_cultivation_efficiency)

UNITS: GBP/Hectares/Years

Fuel_price = 0.502 {2017 annual average https://www.statista.com/statistics/527997/annual-average-price-of-red-diesel-in-the-united-kingdom-uk/}

UNITS: GBP/Litres

FYM_or_other_organic_amendment_handling_and_spreading_costs_per_area = 13 {Keysoil case 27 collection and spreading costs £13/ha}

UNITS: GBP/Hectares/Years

Imported_FYM_or_other_organic_amendment_price_per_Mg = 2 {For price only use £2/Mg Set at £7/Mg for imported and spread turkey manure from KeySoil Case 20 for imported delivery and spread}

UNITS: GBP/Mg

Inorganic_K_cost_saving = K_inorganic_fertilizer_cost_if_all_K_input_to_come_from_fertilizer-Actual_K_inorganic_fertilizer_cost

UNITS: GBP/Hectares/Years

Inorganic_N_cost_saving = N_inorganic_fertilizer_cost_if_all_N_input_to_come_from_fertilizer-Actual_N_inorganic_fertilizer_cost

UNITS: GBP/Hectares/Years

Inorganic_P_cost_saving = P_inorganic_fertilizer_cost_if_all_P_input_to_come_from_fertilizer-Actual_P_inorganic_fertilizer_cost

UNITS: GBP/Hectares/Years

K_inorganic_fertilizer_cost_if_all_K_input_to_come_from_fertilizer = K_input_needed_to_maintain_cereal_yield*K_inorganic_fertilizer_price

UNITS: GBP/Hectares/Years

K_inorganic_fertilizer_demand = MAX(0, (K_input_needed_to_maintain_cereal_yield-K_release_from_OM))

UNITS: Mg/Hectares/Years

K_inorganic_fertilizer_price = 279 {AHDB GB Fertilizer Price Market Update April 2019 for Murate of Potash, price for March 2019 https://ahdb.org.uk/fertiliser-information}

UNITS: GBP/Mg

K_input_needed_to_maintain_cereal_yield = 0.03 {Cereals approx 5 year averageFrom Defra fertilizer study https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712349/fbs-fertiliseruse-statsnotice-31may18.pdf}

UNITS: Mg/Hectares/Years

N_inorganic_fertiliser_demand_sensitivity_to_N_release_from_OM = 0.05 {Experimental variable to simplify model structure since modelling soil N dynamics is itself a project with existing models and complex system dynamics - purpose of this variable is to enable accounting for savings on N fertiliser approximating those reported in relevant KeySoil case studies. Variable can be considered to account for processes such as leaching, nitrification/denitrification, mineralisation and N availability}

UNITS: Dimensionless

N_inorganic_fertilizer_cost_if_all_N_input_to_come_from_fertilizer = N_input_needed_to_maintain_cereal_yield*N_inorganic_fertilizer_price

UNITS: GBP/Hectares/Years

N_inorganic_fertilizer_demand = MAX(0, (N_input_needed_to_maintain_cereal_yield-(N_release_from_OM*N_inorganic_fertiliser_demand_sensitivity_to_N_release_from_OM)))

UNITS: Mg/Hectares/Years

N_inorganic_fertilizer_price = 264

UNITS: GBP/Mg

N_input_needed_to_maintain_cereal_yield = 0.156 {N inorganic fertilizer mean application rate for cereal crops of ~0.156 Mg/Ha https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712349/fbs-fertiliseruse-statsnotice-31may18.pdf}

UNITS: Mg/Hectares/Years

P_inorganic_fertilizer_cost_if_all_P_input_to_come_from_fertilizer = P_input_needed_to_maintain_cereal_yield*P_inorganic_fertilizer_price

UNITS: GBP/Hectares/Years

P_inorganic_fertilizer_demand = MAX(0, (P_input_needed_to_maintain_cereal_yield-P_release_from_OM))

UNITS: Mg/Hectares/Years

P_inorganic_fertilizer_price = 332 {AHDB GB Fertilizer Price Market Update April 2019 for TripleSuperPhosphate, price for March 2019 https://ahdb.org.uk/fertiliser-information}

UNITS: GBP/Mg

P_input_needed_to_maintain_cereal_yield = 0.029 {Cereals approx 5 year averageFrom Defra fertilizer study https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712349/fbs-fertiliseruse-statsnotice-31may18.pdf}

UNITS: Mg/Hectares/Years

Perception_delay_for_CB_balance = DELAYN(Farmer_CB_balance_for_investing_in_OM, 1, 1, 0)

UNITS: GBP/Hectares

POLICY_B_PES_to_Farmer =
SWITCH_POLICY_B*(MAX(((Change_in_cost_of_nuisance_sediment_removal_during_simulation+Net_CO2_seq_value_accumulation)*POLICY_B_PES), POLICY_B_First_five_years_investment))

UNITS: GBP/Hectares/Years

Potential_income_foregone_from_plant_residue_sales =
Potential_income_from_plant_residue_sales_by_area-
Actual_income_from_plant_residue_sales_by_area

UNITS: GBP/Hectares/Years

Potential_income_from_plant_residue_sales_by_area =
Recoverable_crop_plant_residue*Price_per_Mg_of_plant_residue

UNITS: GBP/Hectares/Years

Price_per_crop_ton = 190 {190 barley, 25 for grass}
{https://www.farminguk.com/MarketData/Cereals/MALTING-BARLEY_19.html}

UNITS: GBP/Mg

Price_per_Mg_of_plant_residue = 6 {6 barley, 25 grass} {6 GBP/Mg Usual price per Mg according to KeySoil cases but thought to be overestimate due to costs of collection}

UNITS: GBP/Mg

ROI_spread_period = 1

UNITS: Years

SWITCH_Additional_costs_of_ploughing_in_recoverable_plant_residues =
IF(Mean_annual_input_of_plant_residues>Unrecoverable_plant_residue) THEN 1 ELSE 0

UNITS: Dimensionless

SWITCH_Additional_costs_of_using_FYM_or_other_organic_amendment =
IF(Mean_annual_input_of_FYM_or_other_organic_amendment_when_on>0) THEN 1 ELSE 0

UNITS: Dimensionless

Unrecorded_CB(t) = Unrecorded_CB(t - dt) + (Unrecorded_net_benefit) * dt

INIT Unrecorded_CB = 0

UNITS: GBP/Hectares

INFLOWS:

Unrecorded_net_benefit = Annual_onsite_benefits_of_SOM_per_area-Additional_annual_onsite_cost_for_investing_in_SOM_per_area

UNITS: GBP/Hectares/Years

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Policies:

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Accumulated_Cost_of_Policy_A(t) = Accumulated_Cost_of_Policy_A(t - dt) + (Cost_incursion_for_POLICY_A) * dt

INIT Accumulated_Cost_of_Policy_A = 0

UNITS: GBP/Hectares

INFLOWS:

Cost_incursion_for_POLICY_A = ((DYNAMIC_POLICY_A_Advice_to_farmer_on_benefits_of_investing_in_OM*Cost_per_hectare_of_POLICY_A)/Policy_A_cost_period)*Auto_instigation_of_POLICY_A_without_cost_when_POLICY_B_activated

UNITS: GBP/Hectares/Years

Accumulated_Cost_of_Policy_B(t) = Accumulated_Cost_of_Policy_B(t - dt) + (Cost_incursion_for_POLICY_B) * dt

INIT Accumulated_Cost_of_Policy_B = 0

UNITS: GBP/Hectares

INFLOWS:

Cost_incursion_for_POLICY_B = POLICY_B_PES_to_Farmer

UNITS: GBP/Hectares/Years

Auto_instigation_of_POLICY_A_without_cost_when_POLICY_B_activated = IF(SWITCH_POLICY_B=0)THEN 1 ELSE 0

UNITS: Dimensionless

Conversion_acres_to_hectares = 2.471

UNITS: Acres/Hectares

Cost_per_acre_for_farm_advisor = 7 {https://thefarmingforum.co.uk/index.php?threads/agronomy-fees.31195/}

UNITS: GBP/Acres

Cost_per_hectare_of_POLICY_A = Cost_per_acre_for_farm_advisor*Conversion_acres_to_hectares

UNITS: GBP/Hectares

Discount_factor = 1

UNITS: Dimensionless

Introduction_year_POLICY_A = 2020

UNITS: Years

Introduction_year_POLICY_B = 2020

UNITS: Years

NPV_Policy_A_based_on_offsite_benefits(t) = NPV_Policy_A_based_on_offsite_benefits(t - dt) + (change_in_NPV_Policy_A) * dt

INIT NPV_Policy_A_based_on_offsite_benefits = 0

UNITS: GBP/Hectares

INFLOWS:

change_in_NPV_Policy_A = Policy_A_Net_offsite_benefits*Discount_factor

UNITS: GBP/Hectares/Years

NPV_Policy_B_based_on_offsite_benefits(t) = NPV_Policy_B_based_on_offsite_benefits(t - dt) + (change_in_NPV_Policy_A_1) * dt

INIT NPV_Policy_B_based_on_offsite_benefits = 0

UNITS: GBP/Hectares

INFLOWS:

change_in_NPV_Policy_A_1 = Policy_B_Net_offsite_benefits*Discount_factor*SWITCH_POLICY_B

UNITS: GBP/Hectares/Years

POLICY_A_Advice_to_farmer_on_benefits_of_returning_crop_residues = 0+STEP(SWITCH_POLICY_A, Introduction_year_POLICY_A)

UNITS: Dimensionless

Policy_A_annual_costs = Cost_incursion_for_POLICY_A

UNITS: GBP/Hectares/Years

Policy_A_annual_offsite_benefits = Change_in_cost_of_nuisance_sediment_removal_during_simulation+Annual_value_of_net_CO2_sequestration_in_soil_by_area

UNITS: GBP/Hectares/Years

Policy_A_cost_period = 1

UNITS: Years

Policy_A_Net_offsite_benefits = Policy_A_annual_offsite_benefits-Policy_A_annual_costs

UNITS: GBP/Hectares/Years

Policy_B_annual_costs = POLICY_B_PES_to_Farmer

UNITS: GBP/Hectares/Years

Policy_B_annual_offsite_benefits = Change_in_cost_of_nuisance_sediment_removal_during_simulation+Annual_value_of_net_CO2_sequestration_in_soil_by_area

UNITS: GBP/Hectares/Years

POLICY_B_First_five_years_investment = 20+STEP(-20, 2025)

UNITS: GBP/Hectares/Years

Policy_B_Net_offsite_benefits = Policy_B_annual_offsite_benefits-Policy_B_annual_costs

UNITS: GBP/Hectares/Years

POLICY_B_PES = 0+STEP((SWITCH_POLICY_B*POLICY_PES_proportion_of_value), Introduction_year_POLICY_B)

UNITS: Dimensionless

POLICY_PES_proportion_of_value = 1

UNITS: Dimensionless

SWITCH_POLICY_A = 0

UNITS: Dimensionless

SWITCH_POLICY_B = 0

UNITS: Dimensionless

****

RothC_Constants:

****

Decomposition_rate_constant_BIO = (1/0.66) {0.66 per year}

UNITS: Years

Decomposition_rate_constant_DPM = (1/10) {10 per year}

UNITS: Years

Decomposition_rate_constant_HUM = (1/0.02) {0.02 per year}

UNITS: Years

Decomposition_rate_constant_RPM = (1/0.3) {0.3 per year}

UNITS: Years

Proportion_of_decaying_C_PM_BIO_rather_than_HUM = 0.46

UNITS: Dimensionless

Rate_modifying_factor_Soil_cover = IF(Soil_cover_average_over_year>0.99)THEN 1 ELSE 0.6 {as in RothC - decided to keep as is}

UNITS: Dimensionless

Rate_modifying_factor_Temperature = 47.91/(1+2.71828^(106.06/(Mean_annual_air_temp+18.27)))

UNITS: Dimensionless

Rate_modifying_factor_Topsoil_Moisture_Deficit = GRAPH(Topsoil_Moisture_Deficit)

(0.00, 1.000), (5.00, 1.000), (10.00, 1.000), (15.00, 1.000), (20.00, 1.000), (25.00, 0.850), (30.00, 0.700), (35.00, 0.550), (40.00, 0.400), (45.00, 0.200), (50.00, 0.200)

UNITS: Dimensionless

Soil_texture_adjustment_calculation = 1.67*(1.85 + 1.60*EXP(-0.0786*Soil_clay_content)) {the ratio CO2 / (BIO+HUM)}

UNITS: Dimensionless

Topsoil_Moisture_Deficit = IF (Mean_annual_rainfall-(0.75*Mean_annual_evaporation)) > 0 THEN 0 ELSE ((Mean_annual_rainfall-(0.75*Mean_annual_evaporation))*-1) {coefficient of 0.75 does not change with CC is constant used in calc of topsoil moisture deficit - important thing that can change are rainfall and evap which can already use in developing scenarios, coefficient does not have real world equivalent, is only a constant in the calculation for convention} {"In the original RothC version the model is primed to run open panevaporation data, which was multiplied internally by 0.75 to give actual evapotranspiration. This scaling factor of 0.75 basically also accounts for the transfer of potential evapotranspiration to actual evapotranspiration. Herbst et al 2018" }

UNITS: Dimensionless

****

RothC_Inputs:

****

Decomposability_of_incoming_plant_material_DPMRPM_ratio = 0.59

UNITS: Dimensionless

Mean_annual_air_temp = 9 {average monthly temperature Degrees C from RothC guide Fig 2 }

UNITS: Dimensionless

Mean_annual_evaporation = 49.8 {monthly mm from RothC guide p.13 averaged for year}

UNITS: Dimensionless

Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment = Mean_annual_input_of_FYM_or_other_organic_amendment_when_on*Carbon_fraction_of_FYM_or_other_organic_amenedment

UNITS: Mg/Hectares/Years

Mean_annual_input_of_carbon_from_plant_residues = IF(SWITCH_1_CHECK_constant_input_break_feedback_2_Automated_via_feedback=2) THEN (Mean_annual_input_of_plant_residues*Carbon_fraction_of_plant_residues) ELSE CHECK_Input_of_carbon_from_plant_residues

UNITS: Mg/Hectares/Years

Mean_annual_rainfall = Roth_mean_annual_rainfall*Drought_conditions

UNITS: Dimensionless

Roth_mean_annual_rainfall = 58.7 {monthly mm from RothC guide p.13 averaged for year}

UNITS: Dimensionless

Soil_clay_content = 23.4 {percentage}

UNITS: Dimensionless

Soil_cover_average_over_year = 0.34

UNITS: Dimensionless

Topsoil_depth = 23 {cm}

UNITS: Dimensionless

```
**********
"RothC_simplification_-_in_progress":
**********
"1-Cover_crop" = 1
   UNITS: Dimensionless
"2-Cereal_crop" = 0.85 {"The calculated GB and regional straw production figures derived by this
study represent potential straw production (t/ha @ 85% dry matter) assuming that all straw is
harvestable" 85% of dry matter
http://www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf}
   UNITS: Dimensionless
"3-Fallow_No_residues_intended_to_be_returned" = 0.1
   UNITS: Dimensionless
Arable(t) = Arable(t - dt) + (Rotate_to_arable - Rotate_to_grass) * dt
   INIT Arable = 750
   UNITS: Hectares
   INFLOWS:
      Rotate_to_arable = Rotate_to_grass
         UNITS: Hectares/Years
   OUTFLOWS:
      Rotate_to_grass = ((Arable+Grassland)*Proportion_to_convert_to_grass)/Conversion_interval
         UNITS: Hectares/Years
Conversion_interval = 1
   UNITS: Years
Grassland(t) = Grassland(t - dt) + (Rotate_to_grass - Rotate_to_arable) * dt
   INIT Grassland = 250
   UNITS: Hectares
```

INFLOWS:

Rotate_to_grass = ((Arable+Grassland)*Proportion_to_convert_to_grass)/Conversion_interval

UNITS: Hectares/Years

OUTFLOWS:

Rotate_to_arable = Rotate_to_grass

UNITS: Hectares/Years

National_Arable_Land(t) = National_Arable_Land(t - dt)

INIT National_Arable_Land = 6011000 {Total arable land in UK}

UNITS: Hectares

National_food_production = Actual_harvestable_crop_yield*National_Arable_Land

UNITS: Mg/Years

Proportion_of_crop_biomass_as_plant_residue = IF(SWITCH_Crop_choice=1)THEN"1-Cover_crop"ELSE(IF(SWITCH_Crop_choice=2)THEN"2-Cereal_crop"ELSE"3-Fallow_No_residues_intended_to_be_returned")

UNITS: Dimensionless

Proportion_to_convert_to_grass = 0.25

UNITS: Dimensionless

Soil_Organic_Carbon(t) = Soil_Organic_Carbon(t - dt) + (OM_add - OM_decomp) * dt

INIT Soil_Organic_Carbon = 33.8

UNITS: Mg/Hectares

INFLOWS:

OM_add = (Mean_annual_input_of_carbon_from_plant_residues+Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment)*Soil_texture_adjustment_decays_to_BIO_and_HUM

UNITS: Mg/Hectares/Years

OUTFLOWS:

OM_decomp = (Soil_Organic_Carbon*Rate_modifying_factors)/Time_to_decomposition

UNITS: Mg/Hectares/Years

SWITCH_Crop_choice = 2

UNITS: Dimensionless

Time_to_decomposition = Decomposition_rate_constant_DPM+Decomposition_rate_constant_RPM+Decomposition_rate_constant_BIO+Decomposition_rate_constant_HUM

UNITS: Years

****

RothC_Simplifying_calcs:

****

IOM = 2.7

UNITS: Mg/Hectares

Rate_modifying_factors = Rate_modifying_factor_Temperature*Rate_modifying_factor_Topsoil_Moisture_Deficit*Rate_modifying_factor_Soil_cover

UNITS: Dimensionless

Soil_texture_adjustment_decays_to_BIO_and_HUM = 1/(Soil_texture_adjustment_calculation+1) {1 / (x + 1) is formed as BIO + HUM}

UNITS: Dimensionless

Soil_texture_adjustment_evolves_to_C_emissions = Soil_texture_adjustment_calculation/(Soil_texture_adjustment_calculation+1) {x / (x + 1) is evolved as CO2}

UNITS: Dimensionless

****

RothC_SOC_SHI_Monitor:

****

BD_in_Grams_per_cmcb = Soil_Bulk_Density*Conversion_Tonnes_per_m3_to_Grams_per_cmcb

UNITS: Grams/cmcb

Conversion_cmcb_to_cmsq = 1

UNITS: cmcb/cmsq/Dimensionless

Conversion_cmsq_per_hectare = 100000000

UNITS: cmsq/Hectares

Conversion_Grams_per_cmsq_to_kg_per_cmsq = 0.001

UNITS: kg/Grams

Conversion_kg_to_g = 1000

UNITS: Grams/kg

Conversion_Tonnes_per_m3_to_Grams_per_cmcb = 1

UNITS: (Grams/cmcb)/(Mg/mcb)

Conversion_tonnes_to_kg = 1000

UNITS: kg/Mg

SOC_as_% = SOM_as_%*(1/SOC_to_SOM_conversion_factor)

UNITS: Dimensionless

SOC_in_g_per_kg = SOM_in_g_per_kg*(1/SOC_to_SOM_conversion_factor)

UNITS: Grams/kg

SOC_per_area = (RPM+DPM+BIO+HUM)+IOM {Intrepet with ref to Minasny et al 2017 Soil carbon 4 per mile - levelling off of seq beenefits as reach new equilibrium}

UNITS: Mg/Hectares

SOC_to_SOM_conversion_factor = 1.9 {https://www.researchgate.net/post/How_can_I_convert_percent_soil_organic_matter_into_soil_C and paper https://www.sciencedirect.com/science/article/pii/S0016706110000388 }

UNITS: Dimensionless

Soil_mass_Grams_per_cmsq = BD_in_Grams_per_cmcb*Topsoil_depth*Conversion_cmcb_to_cmsq

UNITS: Grams/cmsq

Soil_mass_in_kg_per_cmsq = Soil_mass_Grams_per_cmsq*Conversion_Grams_per_cmsq_to_kg_per_cmsq

UNITS: kg/cmsq

SOM = SOC_per_area*SOC_to_SOM_conversion_factor

UNITS: Mg/Hectares

SOM_as_% = (SOM_mass_in_kg_per_cmsq/Soil_mass_in_kg_per_cmsq)*100 {https://www.researchgate.net/post/How_does_one_convert_Soil_Organic_Carbon_SOC_from_to_Kg_Ha}

UNITS: Dimensionless

SOM_in_g_per_cmsq = SOM_mass_in_kg_per_cmsq*Conversion_kg_to_g

UNITS: Grams/cmsq

SOM_in_g_per_kg = SOM_in_g_per_cmsq/Soil_mass_in_kg_per_cmsq

UNITS: Grams/kg

SOM_mass_in_kg_per_cmsq = SOM_mass_in_kilos_per_hectare/Conversion_cmsq_per_hectare

UNITS: kg/cmsq

SOM_mass_in_kilos_per_hectare = SOM*Conversion_tonnes_to_kg

UNITS: kg/Hectares

****

RothC_structure:

****

BIO(t) = BIO(t - dt) + (BIO_input - BIO_decay) * dt

INIT BIO = Initial_BIO

UNITS: Mg/Hectares

INFLOWS:

BIO_input = (RPM_decay+DPM_decay+HUM_decay+BIO_decay)*Soil_texture_adjustment_decays_to_BIO_and_HUM*Proportion_of_decaying_C_PM_BIO_rather_than_HUM

UNITS: Mg/Hectares/Years

OUTFLOWS:

BIO_decay = (BIO*Rate_modifying_factors)/Decomposition_rate_constant_BIO

UNITS: Mg/Hectares/Years

C_emissions = (RPM_decay+DPM_decay+BIO_decay+HUM_decay)*Soil_texture_adjustment_evolves_to_C_emissions

UNITS: Mg/Hectares/Years

DPM(t) = DPM(t - dt) + (DPM_C_inputs - DPM_decay) * dt

INIT DPM = Initial_DPM

UNITS: Mg/Hectares

INFLOWS:

DPM_C_inputs = (Mean_annual_input_of_carbon_from_plant_residues*Decomposability_of_incoming_plant_material_DPMRPM_ratio)+(Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment*Proportion_of_FYM_DPM_and_RPM)

UNITS: Mg/Hectares/Years

OUTFLOWS:

DPM_decay = (DPM*Rate_modifying_factors)/Decomposition_rate_constant_DPM

UNITS: Mg/Hectares/Years

HUM(t) = HUM(t - dt) + (HUM_input - HUM_decay) * dt

INIT HUM = Initial_HUM

UNITS: Mg/Hectares

INFLOWS:

HUM_input = ((RPM_decay+DPM_decay+BIO_decay+HUM_decay)*Soil_texture_adjustment_decays_to_BIO_and_HUM*(1-Proportion_of_decaying_C_PM_BIO_rather_than_HUM))+(Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment*Proportion_of_FYM_already_HUM)

UNITS: Mg/Hectares/Years

OUTFLOWS:

HUM_decay = (HUM*Rate_modifying_factors)/Decomposition_rate_constant_HUM

UNITS: Mg/Hectares/Years

Initial_BIO = 0.393 {0.656 for eq and model analysis, 0.393 for Worst case policy from 2020, 1.96 for Best case policy at 2020 }

UNITS: Mg/Hectares

Initial_DPM = 0.115 {0.195 for eq and model analysis, 0.115 for Worst policy start in 2020, 0.542 for Best Case policy at 2020}

UNITS: Mg/Hectares

Initial_HUM = 16.9 {25.4 for eq, 16.9 for Worst Case start in 2020, 71.5 Best Case policy start in 2020} {Herbst et al 2018 The only difference was that we did not assume steady-state equilibrium for the TOC stocks at the LE sites. This might be explained by the fact that the soils of the IM data set were actually not in carbon turnover equilibrium, even though the sites were explicitly chosen since they were under agricultural practice for at least 50 years. Experimental evidence exists indicating that it takes> 50 years to reach TOC equilibrium, even under continuous crop regime (Odell et al., 1984).}

UNITS: Mg/Hectares

Initial_RPM = 2.66 {4.52 for eq and start, 2.66 for Worst Case policy at 2020, 15.1 for Best Case policy at 2020}

UNITS: Mg/Hectares

PM_decay = RPM_decay+DPM_decay

UNITS: Mg/Hectares/Years

Proportion_of_FYM_already_HUM = 0.02

UNITS: Dimensionless

Proportion_of_FYM_DPM_and_RPM = (1-Proportion_of_FYM_already_HUM)/2

UNITS: Dimensionless

Proportion_of_PM_that_is_FYM = Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment/Total_organic_C_inputs

UNITS: Dimensionless

Proportion_of_PM_that_is_plant_residues = Mean_annual_input_of_carbon_from_plant_residues/Total_organic_C_inputs

UNITS: Dimensionless

RPM(t) = RPM(t - dt) + (RPM_C_inputs - RPM_decay) * dt

INIT RPM = Initial_RPM

UNITS: Mg/Hectares

INFLOWS:

RPM_C_inputs = (Mean_annual_input_of_carbon_from_plant_residues*(1-Decomposability_of_incoming_plant_material_DPMRPM_ratio))+(Mean_annual_input_of_carbon_from_FYM_or_other_organic_amendment*Proportion_of_FYM_DPM_and_RPM)

UNITS: Mg/Hectares/Years

OUTFLOWS:

RPM_decay = (RPM*Rate_modifying_factors)/Decomposition_rate_constant_RPM

UNITS: Mg/Hectares/Years

Total_organic_C_inputs = DPM_C_inputs+RPM_C_inputs

UNITS: Mg/Hectares/Years

****

SOC_Offsite_ecosystem_services:

****

a_component = SOM_as_%

UNITS: Dimensionless

b_component = 2 {b = structure code: (1) very structured or particulate, (2) fairly structured, (3) slightly structured and (4) solid Structure not described so assume 2}

UNITS: Dimensionless

c_component = 2 {c = profile permeability code: (1) rapid, (2) moderate to rapid, (3) moderate, (4) moderate to slow, (5) slow and (6) very slow. Batcombe Soil Series From ERA http://www.era.rothamsted.ac.uk/Hoos/hfsoils#SEC2 and LandIS http://www.landis.org.uk/services/soilsguide/series.cfm?serno=109&sorttype_series=series_name }

UNITS: Dimensionless

C_Crop_management_factor = 0.1 {barley 0.1, grass 0.004} {Morgan 2005 from NDR report p. 56 - for Barley 0.1-0.2}

UNITS: Dimensionless

Conversion_to_K_units_for_Soil_erodability = 1

UNITS: Mg*Hectares*Hours/(MJ*Hectares*mm)

Conversion_USLE_to_annual = 1

UNITS: Years

Initial_Topsoil_in_catchment = Initial_topsoil_on_site*Total_area_of_farmland_in_catchment_of_interest

UNITS: Mg

Initial_topsoil_on_site = 2.62 {Top 23 cm of soil (i.e. soil depth) according to http://www.era.rothamsted.ac.uk/Hoos/hfsoils#SEC2 }

UNITS: Mg/Hectares

K_Soil_erodability_dynamic = ((2.1 * 10^-4 * (12-a_component) * M_component^1.14 +3.25 * (b_component-2) +2.5 * (c_component-3)) /759)*Conversion_to_K_units_for_Soil_erodability {After Renard et al 1997 and from InVEST guide http://releases.naturalcapitalproject.org/invest-userguide/latest/sdr.html#sediment-export}

UNITS: Mg*Hectares*Hours/(MJ*Hectares*mm)

LS_Slope_length_gradient_factor = 1

UNITS: Dimensionless

M_component = 52 * (100-20) { (silt% + very fine sand%) * (100-clay%) From http://www.era.rothamsted.ac.uk/Hoos/hfsoils#SEC2}

UNITS: Dimensionless

Net_C_sequestration_by_soil = Total_organic_C_inputs-C_emissions {need to differentiate C storage and Cseq Chenu et al 2019 Increasing O stocks in agri soils knowledge gaps and potential innovations}

UNITS: Mg/Hectares/Years

Normal_Topsoil_formation_rate = 0.612 {For starting in equilibrium} {Global av is 0.7 https://www.sciencedirect.com/science/article/pii/001670619290040E}

UNITS: Mg/Hectares/Years

P_Support_practice_factor = 1

UNITS: Dimensionless

R_Rainfall_erosivity = 190

UNITS: MJ*mm/(Hectares*Hours)

Total_Topsoil_in_catchment(t) = Total_Topsoil_in_catchment(t - dt) + (Topsoil_formation - Topsoil_erosion) * dt

INIT Total_Topsoil_in_catchment = Initial_Topsoil_in_catchment

UNITS: Mg

INFLOWS:

Topsoil_formation = Normal_Topsoil_formation_rate*Total_area_of_farmland_in_catchment_of_interest

UNITS: Mg/Years

OUTFLOWS:

Topsoil_erosion = Universal_Soil_Loss_Equation_USLE*Total_area_of_farmland_in_catchment_of_interest {Not robust to extreme conditions - but this is more of a "check structure" to see if the rest makes sense e.g. will look at the stock to see if it goes negative, since if it does all of the topsoil on site will be gone. Structure is a way to check for extreme conditions}

UNITS: Mg/Years

Universal_Soil_Loss_Equation_USLE = R_Rainfall_erosivity*K_Soil_erodability_dynamic*LS_Slope_length_gradient_factor*C_Crop_management_factor*P_Support_practice_factor/Conversion_USLE_to_annual

UNITS: Mg/Hectares/Years

****

"SOC_on-site_ecosystem_services":

****

Actual_harvestable_crop_yield = Maximum_potential_harvested_yield*Drought_effect_on_yield_given_SOM_status

UNITS: Mg/Hectares/Years

BIO_CN_ratio = 8 {The aerobic heterotrophic bacteria are primarily responsible for the decay of the large amount of organic compounds generated on the earth's surface. These organisms typically have a C:N ratio of about 8:1 https://www.encyclopedia.com/environment/encyclopedias-almanacs-transcripts-and-maps/c-n-ratio}

UNITS: Dimensionless

BIO_nutrient_release = BIO_decay/BIO_CN_ratio

UNITS: Mg/Hectares/Years

Compaction_management_period = 1 {Time period in which farmer will try to get BD under control. Assume 1 year}

UNITS: Years

Crop_plant_residue_Harvest_Index = 0.5 {McCartney et al 2006 approx for Barley % estimated from HI Additionally, in Saskatchewan HI is typically 400 to 450 g kg–1 for wheat, 450 to 500 g kg–1 for oat, and 500 to 550 g kg–1 for barley; although, depending on the cultivar, wheat can be greater than 500 g kg–1, and barley greater than 600 g kg–1 (B. Rossnagel, personal communication, University of Saskatchewan, Saskatoon, SK). }

UNITS: Dimensionless

Crop_plant_residue_production = (Actual_harvestable_crop_yield/((1-Crop_plant_residue_Harvest_Index)*100))*(Crop_plant_residue_Harvest_Index*100)

UNITS: Mg/Hectares/Years

Decompaction_effort_by_farmer = Decompaction_needed*Effect_of_SOM_compaction_regulation_on_cultivation_efficiency

UNITS: (Mg/mcb)/Years

Decompaction_needed = Soil_compaction+(Soil_Bulk_Density_gap/Compaction_management_period)

UNITS: (Mg/mcb)/Years

Difference_in_yield_variability = Initial_SOM_influence_on_mean_yield_variability-SOM_influence_on_mean_yield_variability

UNITS: Dimensionless

Drought_condition_indicator = IF(Topsoil_Moisture_Deficit > 0) THEN 1 ELSE 0

UNITS: Dimensionless

Drought_effect_on_yield_given_SOM_status = IF (Drought_condition_indicator = 0) THEN 1 ELSE (1-(SOM_influence_on_mean_yield_variability/100))

UNITS: Dimensionless

Drought_probability = Drought_years_during_frequency_time/Potential_drought_frequency

UNITS: Dimensionless

Drought_years_during_frequency_time = 1

UNITS: Years

Effect_of_SOM_compaction_regulation_on_cultivation_efficiency = 1-(Soil_compaction_regulation_by_SOM/(Decompaction_needed+0.00000000001))

UNITS: Dimensionless

FOR_CHECK_Recoverable_plant_residue_production_based_on_Hoosfield_correlation = 0.362*Actual_harvestable_crop_yield-0.0974 {y = 0.3626x - 0.0974 and R² = 0.9399 based on Hoosfield5 straw collected from Rothamsted } {McCartney et al 2006 Harvest index (HI) is the proportion of grain yield to total above-ground biomass of a cereal crop. Harvest index allows for estimation of total straw, chaff and stubble yield from grain yield data. https://www.nrcresearchpress.com/doi/pdf/10.4141/A05-092 }

UNITS: Mg/Hectares/Years

FYM_CN_ratio = 12.7 {For FYM 12.7 from ADAS manure and SOC report Appendix 3 Table 1 For Green compost 11.4 same source Table 3}

UNITS: Dimensionless

Gap_between_SOM_Bulk_Density_predictor_and_Soil_Bulk_Density = Soil_Bulk_Density-SOM_Bulk_Density_predictor

UNITS: (Mg/mcb)

HUM_CN_ratio = 12 {the figure for humus being roughly 10:1 although values from 5: 1 to 15: 1 are generally found in most arable soils http://www.soilmanagementindia.com/organic-matter-in-soil/notes-on-the-carbon-nitrogen-c-n-ratio-in-soil/2524}

UNITS: Dimensionless

HUM_nutrient_release = HUM_decay/HUM_CN_ratio

UNITS: Mg/Hectares/Years

Initial_Soil_Bulk_Density = 1.16 {UK soil observatory for Harpenden cell as 1.16 http://mapapps2.bgs.ac.uk/ukso/home.html}

UNITS: (Mg/mcb)

Initial_SOM_influence_on_mean_yield_variability = INIT(SOM_influence_on_mean_yield_variability)

UNITS: Dimensionless

K_content_of_FYM = 0.00839 {For FYM 0.00839 from ADAS manure and SOC report Appendix 3 Table 1 For Green compost 0.00334 same source Table 3}

UNITS: Dimensionless

K_release_from_OM = (PM_decay)*Proportion_of_PM_that_is_FYM*((1/Carbon_fraction_of_FYM_or_other_organic_amenedment)*K_content_of_FYM)

UNITS: Mg/Hectares/Years

Maximum_potential_harvested_yield = 7 {barley 7, grass 13} {Use 4.78 for equilibrium model set up when residues can be returned not accounted for Pan influence of SOM on yield, Use 6.2 for 5 year average, use 7 for maximum "The combined total yield (winter and spring) for barley sits at 5.7 tonnes per hectare for 2018, below the five year average of 6.2 tonnes per hectare, 7.0 tonnes per hectare in 2017" https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/747210/structure-jun2018prov-UK-11oct18.pdf} {Corresponds with max yields at Hoosfield http://www.era.rothamsted.ac.uk/Hoos/hoos_open_access } {7 is the one to use for text runs} {8.35 for eq run}

UNITS: Mg/Hectares/Years

Minimum_Soil_Bulk_Density_for_UK_mineral_soils = 0.4

UNITS: (Mg/mcb)

N_release_from_OM = PM_N_release_via_plant_residues+PM_N_release_via_FYM+BIO_nutrient_release+HUM_nutrient_release

UNITS: Mg/Hectares/Years

OM_BD_predictor_unit_conversion = 1

UNITS: (Grams/cmcb)/(Grams/kg)

P_content_of_FYM = 0.00228 {For FYM 0.00228 from ADAS manure and SOC report Appendix 3 Table 1 For Green compost 0.00112 same source Table 3}

UNITS: Dimensionless

P_release_from_OM = (PM_decay)*Proportion_of_PM_that_is_FYM*((1/Carbon_fraction_of_FYM_or_other_organic_amenedment)*P_content_of_FYM)

UNITS: Mg/Hectares/Years

Plant_residues_CN_ratio = 80 {80 barley straw, 20 grass} {Straw is 80:1 http://www.ecofarmingdaily.com/carbon-nitrogen-ratio/} {Will need to set at another ratio if considering different types of crops e.g. beans, or use of cover crops to add more N}

UNITS: Dimensionless

PM_N_release_via_FYM = (PM_decay/FYM_CN_ratio)*Proportion_of_PM_that_is_FYM

UNITS: Mg/Hectares/Years

PM_N_release_via_plant_residues = (PM_decay/Plant_residues_CN_ratio)*Proportion_of_PM_that_is_plant_residues

UNITS: Mg/Hectares/Years

Recoverable_crop_plant_residue = Crop_plant_residue_production*Residue_recovery_efficiency

UNITS: Mg/Hectares/Years

Residue_recovery_efficiency = 0.6 {barley} {Copeland & Turley Typically around 60% of the straw produced in-field can be recovered for other uses. http://www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf and sense check "Recoverable cereal straw biomass on UK farms typically ranges from 2.75 – 4 t/ha depending upon crop type. Any remaining straw stubble is incorporated back into soil" }

UNITS: Dimensionless

Soil_Bulk_Density(t) = Soil_Bulk_Density(t - dt) + (Soil_compaction - Soil_decompaction) * dt

INIT Soil_Bulk_Density = Initial_Soil_Bulk_Density

UNITS: (Mg/mcb)

INFLOWS:

Soil_compaction = (Soil_compacting_land_use_activities)*SWITCH_Soil_compacting_land_use_activities_0_off_1_on

UNITS: (Mg/mcb)/(Years)

OUTFLOWS:

Soil_decompaction = Soil_compaction_regulation_by_SOM+Decompaction_effort_by_farmer

UNITS: (Mg/mcb)/(Years)

Soil_Bulk_Density_gap = Soil_Bulk_Density-Soil_Bulk_Density_goal

UNITS: (Mg/mcb)

Soil_Bulk_Density_goal = 1.16 {should be lower than 1.6 max as this is where restricts root growth}

UNITS: (Mg/mcb)

Soil_compacting_land_use_activities = 0.36/12 {For PULSE USE " PULSE(0.36, 0.9, 1) " } {For Average over year use " 0.36/12" } {Value of 0.36 is used as maximum change in BD with <1%OM on Soane 1990 - limitation is that this is linear function }

UNITS: (Mg/mcb)/(Years)

Soil_compaction_regulation_by_SOM = (Gap_between_SOM_Bulk_Density_predictor_and_Soil_Bulk_Density/SOM_time_to_BD_rebound_following_disturbance)

UNITS: (Mg/mcb)/(Years)

SOM_Bulk_Density_predictor = MAX((((-0.0039*SOM_in_g_per_kg+1.2301)*OM_BD_predictor_unit_conversion)/Conversion_Tonnes_per_m3_to_Grams_per_cmcb), Minimum_Soil_Bulk_Density_for_UK_mineral_soils) {regression BD and OM line equation from Yang et al. 2014 Figure 4}

UNITS: (Mg/mcb)

SOM_influence_on_mean_yield_variability = 23.626*2.71828^(-0.414*SOM_as_%) {Pan et al 2009 Figure 4 "normal climate region"}

UNITS: Dimensionless

SOM_time_to_BD_rebound_following_disturbance = 3 {Experimental variable Sensitivity analysis for cultivation efficiency suggested soil rebound time with incorporation of 2.8 plant carbon (straw added only as KeySoil Case 2) able to produce 20-30% cost saving on cultivation cost after 5 years}

UNITS: Years

SWITCH_Soil_compacting_land_use_activities_0_off_1_on = 1

UNITS: Dimensionless

Unrecoverable_plant_residue = Crop_plant_residue_production*(1-Residue_recovery_efficiency) {Copeland & Turley Typically around 60% of the straw produced in-field can be recovered for other uses. http://www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf and sense check "Recoverable cereal straw biomass on UK farms typically ranges from 2.75 – 4 t/ha depending upon crop type. Any remaining straw stubble is incorporated back into soil" }

UNITS: Mg/Hectares/Years

Yield_protected_by_SOM = Maximum_potential_harvested_yield*(Difference_in_yield_variability/100)*Drought_probability

UNITS: Mg/Hectares/Years

{ The model has 300 (300) variables (array expansion in parens).

In root model and 0 additional modules with 12 sectors.

Stocks: 22 (22) Flows: 30 (30) Converters: 248 (248)

Constants: 116 (116) Equations: 162 (162) Graphicals: 1 (1)

There are also 15 expanded macro variables.

}

---END---