Application of Two Mathematical Modelling Approaches for Real World Systems

Jessica Rowden

Thesis submitted to the University of Surrey for the degree of Doctor of Philosophy

Department of Mathematics
University of Surrey
Guildford GU2 7XH, United Kingdom

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E-mail address: J.Rowden@surrey.ac.uk
**Scientific abstract**

One of the biggest challenges in building intricate realistic real world models is to incorporate data and their subsequent analysis. When analysing such a system, researchers typically only use one of two modelling methodologies.

The first modelling methodology is “keep it simple stupid” (KISS), which aims to capture the simplified, sometimes extremely abstract behaviours of the real world. By not including all of the intricate features of a system, leads to the problem of having to justify an abstract model to represent the real world and for the results to be verified through theoretical reasoning. However, this method is often easier to construct and yields a clear overview of the system’s behaviour.

The second modelling approach is the “keep it descriptive stupid” (KIDS) approach that aims to include more vital features or behaviours of a system. The justification of using these highly descriptive models is easier, as it captures more intricate behaviours, but are often significantly more difficult to build and to analyse.

This thesis shows that by using the KISS methodology to analyse the system as a whole, vital information about the build of the KIDS model, i.e. which behaviours need to be simulated, can be obtained. This simplifies the process for building the KIDS model and ensures that the general behaviour of the system is included. The KIDS model is then used to analyse how the intricate behaviours influence the system.

I demonstrate this approach on two case studies, where the first investigates how impacts such as a leader’s reputation and family’s party preference influencing an individual voter alters the re-election rate of a leader or party. The second case study analyses how policies impact the UK phosphorus and nitrogen flows.
Lay summary

One of the biggest challenges in building intricate realistic real world models is to incorporate data and their subsequent analysis. In this context the “real world” is a network which has been established over time by nature and/or human evolution. When analysing such a system, researchers typically only use one of two modelling methodologies.

The first modelling methodology is “keep it simple stupid” (KISS), which aims to capture the simplified, sometimes extremely abstract behaviours of the real world. By not including all of the intricate features of a system, leads to the problem of having to justify an abstract model to represent the real world and for the results to be verified through theoretical reasoning. However, this method is often easier to construct and yields a clear overview of the system’s behaviour.

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Two case studies are analysed to demonstrate the application of both methodologies.

Case Study I

The first case study analyses, models mathematically, and compares national voting behaviours across seven democratic countries that have a long term election history. A KISS model is constructed to help analyse the election results of seven democratic countries, focusing on the election/re-election averages of a leader and political party. From this it was suggested that for one set of countries being in power prior to an election is beneficial as leaders have a high re-election rate, whereas for others it is a hindrance, as only a few leaders were re-elected. Furthermore, the model highlights that, when analysing voting
behaviour a distinction has to be made between electing a leader and electing a party, and that the number of years a leader has been in charge is not as significant as to how many times the leader has been elected. Finally, the information about who was in power before an election needs to be included in the second model. This second model based the KIDS methodology, is constructed to simulate a democratic voting system where individual voters are influenced by several factors ranging from social networks to global political leader influence. It is found that this statistical phenomenological model can fit the election statistics and shows that increasing the influence on voters of social neighbours leads to a decrease in the average re-election rate of leaders, but has a slight increase on the average amount of time the dominant party is in charge. Furthermore, the model supports the thesis that an unsuccessful leader has a greater influence on individual voters than a successful one, where both influences have to have a negative impact for the model to recreate the election statistics as observed from the data. Therefore, the interpretations concluded from both the KISS and KIDS models on how a leader impacts voters seem to disagree with each other and to understand further how the impact of a leader influences voters, further research would be needed.

Case Study II

The second case study analyses, models mathematically, and investigates the policy impacts on the UK phosphorus and nitrogen flows. The network layout of the metabolic flows were determined based on the literature and data. The network structure of the model is investigated by computing several network measures to determine the key nodes. Furthermore, the control nodes of the network are investigated. Two models of the KISS approach are then constructed, incorporating the data collected on the UK phosphorus and nitrogen flows. The first simplistic model analyses the metabolic flows based on the data. From this the long term distribution of the elements within the flows are shown and determines that both metabolic flows alter when the network structure is influenced. The model also showed that the quantity of nutrients to be recycled back onto soil from the waste sector was minimal. The second model shows the amount of phosphorus and nitrogen being lost from each sector. Based on these results from the KISS models three policies aiming to reduce the loss of elements were selected. A descriptive model using the KIDS methodology is created which simulates the metabolic flows with policies having an impact on the flows. It is found that the individual policies reduce the quantity of the elements lost, except for one policy aiming to reduce carbon emissions which increases
the phosphorus and nitrogen loss. Even though most policies have a positive impact on closing the cycles, they rely on human behaviour to drastically change or an increase in the quantity of nutrients in the soil is observed. By combining all policies together, the network showed in general that the loss of nutrients was reduced, while the need for human behaviour to change with respect to recycling food was minimal. Although these policies combined have a positive effect on the loss of nutrients in the system, a lot of it is stored in the soil. The nitrogen in the soil can react with air creating nitrogen oxides, thus impacting human health. There is therefore a greater need for collaboration between the different government sectors that have so far enforced the various policies in order to avoid an excess of nitrogen emissions.
Declaration

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1 Introduction

Analysing large intricate real world systems through various modelling techniques and verifying the results obtained can present a complicated problem. A typical approach to overcome this problem is to use one of two modelling methodologies.

The two methodologies are:

- to construct the model such that it is an extremely abstract representation of the real world, which simplifies the analysis of the problem but could disregard vital behaviours such that the model is a misrepresentation of the real system
- or, to include all the intricate details, for example behaviours or links, so that the model is a descriptive version of the system, which could lead to the analysis being more complicated and harder to understand.

Researchers have dubbed these two approaches respectively “keep it simple stupid” (KISS) and “keep it descriptive stupid” (KIDS) [53,131,132].

The traditional way of analysing real world problems is of the KISS approach, producing a simplified representation of the real world. Due to technological computer limitations, these models were usually based on some form of mathematical equations, thereby allowing the system to be methodologically tested in detail and hypotheses to be proven [53,132].

Even with an advancement in technology, which overcomes the dependence on mathematical tools, the KISS approach has its advantages. One advocate for this approach is Robert Axelrod, who believes that simplified models should not aim to provide an accurate representation of the real world, but instead simulate the fundamental process [16,17]. Complex results are easier to analyse and comprehend if the underlying rules of the model are simple and clearly described. Furthermore, fitting a simpler model with fewer parameters to data, describes the general behaviour of the system, whereas a complicated model, such as one containing more parameters could lead to the model to be overfitted. This means the model does not simulate the general behaviour of the system but instead describes the noise with in the data. This could potentially provide inaccurate predictive results. Yet, if the model is too simple or missing important behaviours, it can lead to the results not representing the general behaviour of the system. Another problem with this
approach is justifying the abstract models to represent real world systems, as the results are usually verified through theoretical reasoning [53]. Therefore, when using a model employing the KISS approach, a feasible justification is needed, for example by testing the model against data. Applying unjustified results from an abstract model to the real world can lead to misinterpretation [53].

For the KIDS approach, the model constructed is descriptive, allowing for easier verification of the model as it is a representation of the real world, i.e. the results do not as heavily depend on theoretical reasoning as KISS models [52,53]. However, this approach can be more complicated to construct, as it could be difficult to visualise which behaviours impact the whole system. Furthermore, the results can be hard to analyse and to comprehend if the underlying rules are described in a complex manner. Once the model has been built and the behaviour of the system is understood, the model can be simplified by disregarding irrelevant details. Therefore, the application of the KIDS approach has been encouraged as it provides a clearer understanding of the intricate behaviours of real world problems.

A distinction between the two modelling methodologies has been made, yet there seems to be no encouragement to apply both approaches to analyse a real world behaviour. This thesis shows that by using both methodologies can enhance the understanding of a system. The first step is to use the KISS methodology to analyse the system as a whole, which can provide vital information about the general behaviour of the system. Yet this model cannot explore how the intricate behaviours drive a system, therefore a KIDS model is needed. Based on the results from the KISS model, the KIDS model can be created. This approach simplifies the build of the descriptive model and assures that the general behaviour of the system is included. The KIDS model is then used to analyse how intricate behaviours drive the system and to test hypotheses.

For this research two different types of models are used when applying the two modelling methodologies: uni- and multi-level models. Here the names “uni” and “multi” are applied as the term “level” describes the organisational hierarchical structure. The KISS methodology uses uni-level models, which focus on one level of a system, thus ignoring any hierarchical structure. This allows for the whole system’s behaviour to be analysed. In comparison, the KIDS methodology uses multi-level models to analyse the micro and
macro behaviour of a system. Multi-level models consist of at least two levels where entities, each with their own characteristic or behaviour, are present in the micro level and are nested within contexts (also known as groups) in a macro level. There are at least two contexts in each macro level, whereby the nesting within a specific context influences the entity’s behaviour. This research does not use the common mathematical approach for multi-level models, which is a tool for linear regression data analysis, but instead creates a descriptive model as the basis. This means that the system usually cannot be described as one equation, but instead provides a more descriptive representation of the real world. Although this research uses these types of models, they will not be discussed in the main part of the thesis. For more information on this topic see the Appendix A.

To demonstrate how the two modelling methodologies provide a clearer understanding of the system, two case studies are presented.

The first case study analyses impacts on voters in a democratic system and, on the basis of data from seven countries, tests how these impacts affect the election of a leader. The KISS approach analyses how often a leader and a political party were in power for the seven countries. From this important voting mechanisms were observed, which were then included in the KIDS model. The descriptive model simulates the democratic voting process, where voters in electoral districts elect MPs. The elected MPs group together to form two political parties who in turn internally elect a partly leader. The leader of the party with a majority representation is selected as the leader of the political system. The leader’s term in office is then randomly selected to be either successful or unsuccessful, which in turn impacts the voters in the following election. Using a descriptive model allows impacts such as a leader’s reputation and social neighbours’ voting preferences, both influencing the voters and thereby also altering the national voting behaviour, to be analysed. Even though the individual voting behaviour is ignored, this model provides a phenomenological overview of national voting behaviour.

The second case study analyses the UK phosphorus and nitrogen flows. So far, researchers have been studying segments of these metabolic flows where proposed policies in reducing the elements’ loss within the cycle were only considered to impact one flow. A model based on the KISS approach depicts a clear distribution of the elements in the entire network, while the another KISS model highlights where in the system the loss of the vital nutrients
is greatest. Important information about the network structure and the quantity of the nutrients lost from each segment provides an insight into which policies should be included in the descriptive model. The policies aim to reduce the loss of the nutrients. The KIDS model simulates the UK phosphorus and nitrogen flows, where various policies influence the system at different stages. By testing the policies in conjunction with each other shows if these influences enhance or diminishes the aim of the policies.

This research is laid out as follows. Chapter 2 provides a quick introduction to all the methods and modelling tools used in both of the case studies described in the following chapters. In Chapter 3 the first case study, analysing the voting behaviour, is described. The second case study, analysing the UK phosphorus and nitrogen flows, is described in Chapter 4. A conclusion and further discussion is laid out in Chapter 5, which reiterates that by combining both modelling methodologies, a clearer understanding of how the intricate behaviours drive the whole system is achieved. Finally, Appendix A. discusses how uni- and multi-level models were used for the KISS and KIDS approach, and Appendices B. and C. describe the data and background information for Chapters 3 and 4 respectively.
2 Methods and Modelling Tools

As the two case studies in Chapters 3 and 4 use various techniques, this chapter looks at the methods and modelling tools employed. The methods are Network analysis and Model fitting, and the modelling tools applied are Markov chains, Input/Output models, System dynamics models, and Ising models.

Chapter 3 analyses the democratic political voting system of various countries, with the aim to understand the national voting behaviour. First, the KISS model analysing the whole system is built. The election results of seven countries were collected to which a Markov chain, with the aid of a Model fitting technique, is fitted. The Markov chain model determines a unique stationary probability distribution from the data. These distributions describe the probability of a leader and political party being elected, re-elected once or re-elected multiple times. This shows the historic national voting behaviour for each country. For the descriptive KIDS model, the Ising model is used to represent voters in their electoral districts, where impacts such as social neighbours’ party preference and the leader’s reputation have an influence on individual voters. The aim is to analyse how these impacts influence the national voting behaviour of a leader and party to be elected/re-elected.

The case study described in Chapter 4 analyses the UK phosphorus and nitrogen flows. Various Network analysis methods are employed to provide an understanding of the network structure. To analyse the network behaviour based on the data, two models based on the KISS approach are created. First, a discrete model for a system with conservation of mass, which will not be discussed in this chapter, provides an overview of the long term distribution of the UK phosphorus and nitrogen in various sectors. The second KISS model uses an Input/Output model to calculate the quantity of phosphorus and nitrogen being lost from each sector. Finally, a descriptive model based on the KIDS approach uses a System dynamics model to simulate the flows, where the unknown parameters are obtained by using a Model fitting technique to fit the model to the data. The aim is to understand how various policies impact these metabolic flows.
2.1 Network Analysis

A network consists of nodes, also known as vertices, which are joined together through links, also called edges. These links may represent information or material to flow from one node to another. In a directed network, the links constrain the direction of the flows, whereas for an undirected network the flows can go either way along the links. An example of a network is a social network, where people are the nodes. If two people have met then the link between them is undirected, as they both know each other. However, should a person have knowledge of another person, then the link between them is directed, as it may not be a mutual awareness.

Let $G(V, E)$ denote the network, where $V$ are the nodes, of which there are $N$ in total, and $E$ are the links. The adjacency matrix $A$ describes the links in the network, where $a_{ij}$ is the $i^{th}$, $j^{th}$ element of the matrix $A$. A link between node $i$ and node $j$ is denoted as $a_{ij} = 1$, or else $a_{ij} = 0$. The flow for an undirected network can go either way along a link, meaning the adjacency matrix for an undirected network is symmetric. For a directed graph, the flow is dictated by the direction of the link, giving rise to an asymmetric adjacency matrix [22,27].

Various methods are used for an analysis of the network structure providing diverse information of the system [24,27,55,56]. The network used in Chapter 4 relies on a directed network, where the degree, eigenvector, closeness and betweenness centrality measures are employed and the control nodes are found. These methods are discussed in §2.1.1 - 2.1.5.

GEPHI is an open source program which focuses on network analysis, which was used in Chapter 4 to analyse the UK phosphorus and nitrogen flows. By using traditional statistics, this tool provides not only the centrality measure results, but also is an interactive visual platform for the user. This program is free to download from the website URL: https://gephi.org/

To calculate all of the control node configurations a tool created by Knight was used. This tool was created for the ERIE (Evolution and Resilience of Industrial Ecosystems) project to provide stakeholders with an insight into how an outside influence can control a network [126].
2 Methods

2.1.1 Degree Centrality

The degree centrality, denoted as \( C_D \), describes the number of edges associated with a node, which is obtained by

\[
C_D(i) = \sum_{j}^{N-1} (a_{ij} + a_{ji}).
\]  

(2.1)

Here \( i \) is the node of interest and \( j \) are all other nodes. The equation is a combination of the sum of inbound links into node \( i \), given by \( \sum_{j}^{N-1} a_{i,j} \), and the total number of outbound links from node \( i \), as described by \( \sum_{j}^{N-1} a_{j,i} \). This centrality highlights which node is the most connected in the network, but only considers the local structure, i.e. it only takes the directly connected edges to node \( i \) into account [24,56].

2.1.2 Eigenvector Centrality

Unlike the degree centrality, the eigenvector centrality looks at each node and ranks them in order of the number of links associated with them or if they are connected with a node that has many links. Therefore, this centrality measure for node \( i \), denoted as \( C_E \), shows if the node is well connected within the whole network. This centrality is given by the corresponding eigenvector \( v \) of the largest eigenvalue \( \lambda_{\text{largest}} \) of the adjacency matrix \( A \), as shown by

\[
C_E(i) = \left( \frac{1}{\lambda_{\text{largest}}} A v \right) = v.
\]  

(2.2)

An eigenvector centrality closer to one highlights that the node is well connected within the whole network [22,55].

2.1.3 Closeness Centrality

The closeness centrality for node \( i \) is given by \( C_C \). This centrality measure looks at the average number of links from node \( i \) to all other nodes, as determined by

\[
C_C(i) = \frac{M}{\sum_{j=1}^{N-1} d_{ij}}.
\]  

(2.3)
where $M$ are the total number of links within the network, $d_{ij}$ is the smallest number of links between nodes $i$ and $j$, and $d_{ii} = 0$ [24,27]. As this centrality only considers links from node $i$ to all other nodes, this measure focuses on the outbound links of a node. Nodes containing of only inbound links will always have a closeness centrality of zero, thus meaning they cannot affect any other nodes. All other nodes which do have outbound links will have a measure of greater than one. The nodes with a measure closest to one will have the fastest impact on the other nodes.

2.1.4 Betweenness Centrality

This centrality measure looks at which nodes are the most important on bridging the network, which is obtained by assessing the flows having to pass through node $i$, whilst trying to proceed from node $j$ to $k$. The betweenness centrality for node $i$, denoted as $C_B$, is given by

$$C_B(i) = \sum_{j=1}^{N-2} \sum_{k=1}^{N-2} \frac{\sigma_{jk}(i)}{\sigma_{jk}}. \quad (2.4)$$

Here $i \neq j \neq k$, $\sigma_{jk}$ is the shortest path from node $j$ to node $k$, and $\sigma_{jk}(i)$ describes the shortest path from node $j$ to node $k$ via node $i$ [24,27].

2.1.5 Control Nodes

For an outside influence to drive the system into a specific state, not all of the nodes need to be controlled. By determining the control nodes of a network highlights the least number of nodes that would need to be influenced to alter the state of the system. A method created by Knight [126], highlights all possible combinations of control nodes, which is based on the Hopcroft-Karp algorithm and Liu et al.’s work [103].

The Hopcroft-Karp algorithm finds the maximum set of matchings in a bipartite graph. A bipartite graph is an undirected network, which consists of two disjointed sets $U$ and $V$, where the links within the network are between the two sets, i.e. there are links between the nodes in sets $U$ and $V$, and no links within one set. As this research relies on a directed graph, the network is duplicated in both sets, with the outbound links from a
node in the network leading from set $U$ to the inbound node in set $V$, see Figure 2.1 for an overview on how to change a directed network into a bipartite graph.

![Directed Network](image1.png) ![Bipartite Graph](image2.png)

**Figure 2.1:** In the figure on the left is an overview of a directed six node system. In the figure on the right is the equivalent bipartite graph of the directed network.

Matchings are selected links between nodes in set $U$ and $V$, where the nodes are allowed to be associated with only one matching. The aim is to find a configuration with the maximum set of matchings. The nodes containing a matching are referred to as being matched, whereas the nodes not containing a matching are free. Lui et al.’s work [103] showed the maximum set of matchings relates to the minimum size of the control configuration, which are the free nodes.

The Hopcroft-Karp algorithm uses the breadth-first search to find all the maximum set of matchings within the network. For this the shortest simultaneously increasing set of augment paths are created. Augment paths are a special type of alternating paths, where an alternating path is a path that consists of links that is alternatively connected to a matching and free node. Augment paths are alternating paths that start and end on free nodes. Therefore, the Hopcroft-Karp algorithm starts its algorithm with a free node in set $U$ and links with another free node in set $V$. After this first step the path has to alternate between matched and free nodes; always linking with a free node in set $U$ and a matched node in set $V$. Once the path has to link with a free node in set $V$ the algorithm terminates. This paths then shows the maximum set of matchings within the network. There can be multiple solutions of matchings, where Knight’s algorithm [126] uses an
efficiency search algorithm to find all solutions. In general, the free nodes are nodes that have no inputs from the rest of the network. This means that no other node can influence their state. However, for an external influence to impact these free nodes allows the state of the whole network to be controlled [103].

Example

Let a system consist of six nodes: $S$, $C$, $A$, $H$, $L$ and $SS$, each containing a quantity of stock. The links between the nodes allow the stock to move from one node to another, as shown in Figure 2.2.

![Figure 2.2: An overview of a six node system, where the links show the direction of the flow of stock between the nodes.](image-url)

The program GEPHI is used to calculate the degree, eigenvector, closeness and betweenness centralities and the tool created by Knight is used to obtain the control nodes. These results, as shown in Table 1 are used to analyse the network.

Degree Centrality: An analysis of the results for the degree centrality shows nodes $S$, $C$ and $L$ to be the most connect, with 5 links associated with each node. These three nodes have 3 inbound and 2 outbound links. Nodes $A$, $H$ and $SS$ have 3 links associated with each node, of which 1 is inbound and 2 are outbound.

Eigenvector Centrality: Unlike the degree centrality, the eigenvector centrality shows
<table>
<thead>
<tr>
<th></th>
<th>Degree (In/Out) Centrality</th>
<th>Eigenvector Centrality</th>
<th>Closeness Centrality</th>
<th>Betweenness Centrality</th>
<th>Control Node</th>
</tr>
</thead>
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<tr>
<td>S</td>
<td>5 (3/2)</td>
<td>0.71</td>
<td>1.6</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>5 (3/2)</td>
<td>1</td>
<td>1.8</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>3 (1/2)</td>
<td>0.5</td>
<td>1.8</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>3 (1/2)</td>
<td>0.5</td>
<td>1.8</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>5 (3/2)</td>
<td>0.86</td>
<td>1.6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>SS</td>
<td>3 (1/2)</td>
<td>0.43</td>
<td>1.6</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Network analysis results for all six nodes.

which nodes are well connected within the whole network by ranking the nodes on either the number of links associated with the node or if the node is linked to another node with many connections. The results show node C to be the most connected within the network, followed by nodes L and S. From the degree centrality nodes A, H and SS were ranked equally, as they have the same amount of links. For the eigenvector centrality node SS is ranked lower. This is due to the directed links from node C, the highest connected node, to nodes A and H, whereas node SS is only directly influenced by node L, the second highest connected node in the network. For node SS not to be directly linked with the highest connected node means its ranking within the network declines.

Closeness Centrality: The closeness centrality looks at the average sum of outbound links between the nodes. As in this network all nodes have at least one outbound link, all closeness centrality measures are greater than one. Nodes C, S and SS have the closest measure to one compared to all other nodes, thus leading these nodes having the fastest affect on all other nodes.

Betweenness Centrality: The betweenness centrality looks at the flows having to pass through node i to reach its desired destination, thus showing node C to be a critical node in bridging the network.

Control Nodes: To calculate the control node configurations, the network has to be turned into a bipartite graph, see Figure 2.3 for an overview. The none solid lines in the figure indicate the link to be a matching, where two maximum matchings configurations are
possible. The purple dashed lines are always matchings, therefore nodes $S$, $C$, $L$ and $SS$ are always matched for all solutions, whereas the red dotted lines indicate that only one of the links is a matching for one of the configurations. Therefore, depending on which configuration is chosen, either node $A$ or $H$ is free. As Liu et al.’s work [103] showed, the maximum matching leads to the minimum size of control node configurations. The control node configurations for this small network has two results, each only consisting of one node, $A$ or $H$, as shown in Table 1. Therefore, for an outside influence to control the system such that a desired state is achieved, for example reducing the quantity of stock in node $L$, either node $A$ or $H$ need to be influenced.

![Figure 2.3: An overview of a six node system, which has been turned into a bipartite graph. There are two control node configurations for this network. The purple dashed lines are the matchings for both solutions, such that nodes $S$, $C$, $L$ and $SS$ are always matched. The red dotted lines are a solution for one of the configurations, thereby if node $A$ is a match, then node $H$ is free and vice versa.](image)

Figure 2.3: An overview of a six node system, which has been turned into a bipartite graph. There are two control node configurations for this network. The purple dashed lines are the matchings for both solutions, such that nodes $S$, $C$, $L$ and $SS$ are always matched. The red dotted lines are a solution for one of the configurations, thereby if node $A$ is a match, then node $H$ is free and vice versa.
2 Methods

2.2 Model Fitting

To carry out predictions on some given data, a mathematical model is frequently used to represent the system. The model is fitted to the data, thus determining the unknown parameters. A systematic method that carries out this task is to minimise the least square errors.

Let $y_i$ be the dependent variable and $x_i$ the independent variable describing $i$ collected data points, where $i = 1, ..., N$. A model, which can be a map or an ordinary differential equation (ODE), can then be fitted to the data points, with the solution of the model being described by $f(x_i, \alpha_j)$, where $\alpha_j$ are the parameters. The errors $E = \sum_{i=1}^N \epsilon_i$, describing the distance of the fitted model to the data points, are given by

$$E = \sum_{i=1}^N \epsilon_i = \sum_{i=1}^N ||y_i - f(x_i, \alpha_j)||^2,$$

(2.5)

where $||\cdot||$ is the vector norm. Squaring the errors in equation (2.5) has a larger emphasis on weighting the errors, as for example a data point with a larger distance to the fitted model will create a larger squared error in comparison to a data point close to the model. Therefore, by calculating the sum of squared errors allows for the noise in the data set to be included [157].

This approach assumes the distribution of the errors to be normal, thus meaning the errors $E$ are the logarithm of the likelihood of the data. To find the maximum likelihood parameter estimates is equivalent to minimising equation (2.5) over the parameters $\alpha_j$, i.e. to find the critical points of $E$, such that

$$\frac{\partial E}{\partial \alpha_j} = 0.$$

(2.6)

Therefore, solving equation (2.6) finds the optimal parameters $\alpha_j$ for the model to represent the system [45,157].

To estimate the parameters $\alpha_j$ for a model to represent a system over time, such that the results are described by $f(x_i, t_i, \alpha_j)$, the same method can be applied. Here $i$ are the data points $x$ measured at time $t$. In this case, the errors are
\[ E = \sum_{i=1}^{N} \epsilon_i = \sum_{i=1}^{N} ||y_i - f(x_i, t_i, \alpha_j)||^2, \tag{2.7} \]

where $||\cdot||$ is the matrix norm. To obtain the optimal parameters $\alpha_j$ for the model to represent the time dependent system, the squared errors are minimised, i.e.

\[ \frac{\partial E}{\partial \alpha_j} = 0. \tag{2.8} \]

Although this is a frequently used method in fitting a model to a data set, one problem needs to be highlighted. When fitting a nonlinear function to the data set, there could be a local and a global minimum within the fitted model. In this case, depending on the chosen initial points, two or multiple different results could be obtained.

Once the model has been fitted to the data various analysis can be done to estimate the sensitivity of the results of the model. Two types of analysis can occur, one which test the goodness-of-fit of a model to the data, for example using the R-square test to determine the variation of the results of the model to the data or the Chi-square test which compares the frequency of a model’s results to be in a certain state to the data. Another way to test the model is to apply a sensitivity analyses which determines the impact of certain inputs. For example a common approach to analyse non-linear models is use a variance-based global sensitivity analysis. This sensitivity analysis determines how much the sensitivity changes for a model when the inputs are varied [37]. This method in frequently applied when tuning a model or determining if a local or global optima within a non-linear model fitting has be found.
2.3 Markov Chain

A Markov chain describes the transition of a system’s state to another state space based on its current state. This method is useful to apply when analysing a system with a time series data set.

Let the system be in one of the finite set of states \( S = \{s_1, s_2, ..., s_k\} \). The current system’s state is denoted as \( s_i \), with the transition of the state in the following time step to be denoted as \( s_j \). Let \( x_t \) be a stochastic column vector whose entities correspond to the probability of the system to be in either of the states at time \( t \). The probability of the transition from state \( s_i \) to state \( s_j \) is defined in the transition probability matrix \( p_{ij} = P(x_{t+1} = s_j | x_t = s_i) \). Multiplying the stochastic vector at time \( t \) by the probability transition matrix describes the probability of the system to be in one of the states at the next time step, given by

\[
x_t = P^t x_1 = P x_{t-1}.
\] (2.9)

Markov Chains can also be described as being periodic or aperiodic. A periodic Markov chain is defined to have a period \( d_i \) if the initial state \( s_i \) can be achieved within a multiple of \( d_i \) time steps, i.e. \( d_i = gcd(t : P(x_t = i | x_0 = i) > 0) \), where \( gcd \) is the greatest common divisor. If \( d_i = 1 \) then the state is aperiodic. A Markov chain is aperiodic if all states are aperiodic. It can also be determined to be aperiodic if the network is represented by an aperiodic strongly connected graph, i.e. a directed network with all nodes connected with each other.

It can be shown that for periodic Markov chains, as \( t \to \infty \) the stochastic vector \( x_{t \to \infty} \) becomes stationary, i.e. tends to a constant stochastic vector \([138]\). This vector is called the stationary probability distribution, which is denoted by \( \pi \), satisfying the condition

\[
\pi = P \pi.
\] (2.10)

For aperiodic Markov chains a unique stationary probability distribution \( \pi \) exists only if \( x_t = \pi \) for all \( t \).

The Perron-Frobenius theorem, which provides properties of the eigenvalues and eigenvectors of irreducible square matrices, guarantees there to be a stationary probability
distribution [8, 81, 127, 143]. For a finite state Markov chain, evaluating the stationary probability distribution \( \pi \) is equivalent to calculating the unit eigenvector of the probability matrix \( P \). Unlike the eigenvector centrality measure as described in equation (2.2) the stationary probability measure \( \pi \) is normalised so that the sum of the components equals to one.

**Example**

This example analyses the probability of the weather in a chosen system to be in one of the following three states: sunny, foggy or rainy. The weather is measured each day and does not change within that time period. After each day the system’s weather changes to any of the three possible states with a given probability \( p \), as shown in Figure 2.4.

![Figure 2.4: An overview of the three states of a weather system and the possible transitions from one state to another.](image)

If the current weather is sunny then the following day has three options: to be either sunny again with probability \( p_1 \), foggy with probability \( p_2 \), or raining, which occurs with probability \( p_3 \), where \( p_3 = 1 - p_1 - p_2 \), as the system has to be in one of the three possible states. The same applies for the system to be either in a foggy or rainy state, such that \( p_6 = (1 - p_4 - p_5) \) and \( p_9 = (1 - p_7 - p_8) \). The probability matrix \( P \) for this system is given by
For this example some arbitrary data was chosen to describe the changes of the states of the previous weather conditions to be

\[ P = \begin{pmatrix}
    p_1 & p_4 & p_7 \\
    p_2 & p_5 & p_8 \\
    p_3 & p_6 & p_9
\end{pmatrix}.\]

Let the initial current weather be \( s_i = \text{sunny} \), such that the stochastic vector is \( x_{t=1} = (0.3, 0.2, 0.5)^T \), where \( T \) is the transpose of the vector. By using the Markov model as shown by the equation

\[ x_{t=2} = Px_{t=1}, \quad (2.11) \]

the weather on the following day can be estimated to be \( x_{t=2} = (0.18, 0.37, 0.45)^T \). Hence, there is an 18% chance that the following day is sunny, a 37% chance for it to be foggy and a 45% chance for it to be rainy.

*Use in case studies*

By fitting the transition probability matrix to the data, Chapter 3 uses the Markov chain to analyse the election history of seven countries, where the states refer to the leader or political party being elected, re-elected once or re-elected multiple times. By plotting the stationary probability distribution after each election shows the historic national voting behaviour of each country.
2.4 Input/Output Model

Input/Output models capture the interconnecting flows between sectors in a large network, thus allowing for each sector to analyse the total output needed to produce to satisfy the in between sector and the end consumer demand.

Let a system be made up of \( i \) number of sectors, where \( i = 1, ..., N \). Some sectors interact with each other, for example for material or financial exchange, but also have to supply some of their goods to end consumers. The entities in the state variable \( \mathbf{x} \) correspond to the total quantity of output needed for each sector. The interacting demand of the products between the industries is described by the matrix \( \mathbf{A} \), with \( a_{ij} \) indicating the ratio of each sector \( i \) inputing its product into sector \( j \). Therefore, \( \mathbf{Ax} \) describes the intermediate demand between sectors. The end consumer demand sector is defined as \( \mathbf{d} \), which also requires some of the products of the sectors from the network, but does not interfere with the in between network flow. The output of each sector is

\[
\mathbf{x} = \mathbf{Ax} + \mathbf{d},
\]

which is satisfying the requirements for the other industries and the end consumer demand [94].

The Input/Output model is widely used in economics analysing the need of financial investments in industrial sectors, but has also been widely applied in life-cycle assessments where the inputs are the flows of a raw material and the vector \( \mathbf{d} \) represents the environmental burden, such as hazardous waste [51, 83, 94, 101].

Example

This example is based on San Jose State University Department of Economics work [47].

Let there be two industrial sectors, coal and steel industry, aiming to analyses the necessary outputs of their industries to satisfy the in between and consumer demand. Figure 2.5 shows an overview of the system, with the links describing the interdependency of the industry, where each sector also provides its stock to consumers.
The state variables $x$ for this example are the total outputs of the coal and steel industry. Let the in between sector demand be the coal industry needing 10% of steel for its production, i.e. for tools, and the steel industry needing 20% of coal for its production, with the consumer’s demand of coal and steel being 25,000 tonnes and 20,000 tonnes respectively, such that $d = [25,000, 20,000]^T$, where $T$ is the transpose of the vector. Rearranging equation (2.12) to

$$x = (I - A)^{-1}d,$$  \hspace{1cm} (2.13)

allows each sector to calculate the total quantity of its product needed to satisfy the industrial and consumer demand, where the in between industry demand matrix is

$$A = \begin{pmatrix} 0 & 0.1 \\ 0.2 & 0 \end{pmatrix}.$$ 

Here $I$ is the identity matrix. It is noted that $A \neq I$, i.e. some of the product has to be available for the consumers. This gives the total production of coal and steel, satisfying all the demand, to be 27,551 tonnes of coal and 15,510 tonnes of steel, i.e. $x = [27,551, 15,510]^T$. 

Figure 2.5: An overview of an industrial system. Here the output of each sector either supplies another industrial sector or consumers.
Use in case study

Chapter 4 analyses the UK phosphorus and nitrogen flows where the state variables describe the stock of each element at each node, for example soil or animal consumption. For this research the vector $d$ is the loss, thus showing the quantity of phosphorus and nitrogen to be lost from each node in one year.
2.5 System Dynamics Model

A system dynamics model simulates the dynamics of a system where feedback loops are incorporated. By including the dynamics of the system, changes over time can be analysed [71].

When creating a system dynamics model, the most important features within the system and their boundary conditions need to be determined. From this the dynamics within the system can be drawn out, highlighting the links within the network. Based on these links, the ordinary differential equations (ODEs) can be created, describing the instantaneous rate of change of the product in each sector over time. Integrating these equations gives the product’s layout within the network at time $t$, such that the dynamics of the system can be understood.

ODEs and Markov chains are not too dissimilar from one another, such that their results are an approximation of one another. When deciding which approach to use their pros and cons should be considered. For example, Markov chains rely on eigenvalues to be calculated from stochastic probability matrices, whereas ODEs provide an overview of the system for a specific time frame but relies on inputs such as boundary conditions and initial values. Furthermore, in a linear ODE case with constant coefficients the results will be in an exponential form, i.e.

$$\frac{dx}{dt} = Ax(t), \quad (2.14)$$

where $x$ describes the function of the system over time $t$ and $A$ is a matrix with constant values, the general solution of the system is

$$x = c_1 e^{\lambda_1 t} v_1 + c_2 e^{\lambda_2 t} v_2 + \ldots + c_n e^{\lambda_n t} v_n. \quad (2.15)$$

Here $n$ is the size of the matrix $A$, $\lambda_{1,...,n}$ its eigenvalues, $v_{1,...,n}$ the corresponding eigenvectors, and $c_{1,...,n}$ are constants. In this case the solution could have a drastic impact on the results for a large $t$. 
Example

Let there be six entity types: $S$, $C$, $A$, $H$, $L$ and $SS$, which are shown as the nodes in the system and are connected together through links. Each node contains a quantity of stock, where the links allow some of the stock to flow from one entity to another, as shown in Figure 2.6.

![Diagram showing the flow of stock between six entities](image)

*Figure 2.6: An overview of a six entity system, illustrated here as nodes, where the links show the flow of a stock between the entities.*

A data set, shown in Table 2, describes the quantity of the stock in each entity measured at four different time points.

<table>
<thead>
<tr>
<th>Time points</th>
<th>$t = 1$</th>
<th>$t = 2$</th>
<th>$t = 3$</th>
<th>$t = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>30</td>
<td>35</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>C</td>
<td>25</td>
<td>26</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>A</td>
<td>10</td>
<td>12</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>H</td>
<td>6</td>
<td>5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>L</td>
<td>15</td>
<td>18</td>
<td>24</td>
<td>11</td>
</tr>
<tr>
<td>SS</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

*Table 2: Stocks of each node taken at four different time points.*

From the diagram it can be determined that the flows describing the movement of the
stock between the nodes to be

\[ \alpha_1 A + \alpha_2 + \alpha_3 SS \rightarrow S \]
\[ \alpha_4 S + \alpha_8 SS + \alpha_{11} L \rightarrow C \]
\[ \alpha_6 C \rightarrow A \]
\[ \alpha_7 C \rightarrow H \]
\[ \alpha_5 S + \alpha_9 A + \alpha_{10} H \rightarrow L \]
\[ \alpha_{12} L \rightarrow SS. \]

Here \( \alpha_i \), where \( i = 1, \ldots, 12 \), indicate the ratio of the stock being transported along the link. From this, the ordinary differential equations (ODEs) describing the instantaneous rate in change of the stock in each node, can be determined to be

\[ \frac{dS}{dt} = \alpha_1 A + \alpha_2 + \alpha_3 SS - \alpha_4 C - \alpha_5 L \]
\[ \frac{dC}{dt} = \alpha_4 S + \alpha_8 SS + \alpha_{11} L - \alpha_6 A - \alpha_7 H \]
\[ \frac{dA}{dt} = \alpha_6 C - \alpha_1 S - \alpha_9 L \]
\[ \frac{dH}{dt} = \alpha_7 C - \alpha_2 S - \alpha_{10} L \]
\[ \frac{dL}{dt} = \alpha_5 S + \alpha_9 A + \alpha_{10} H - \alpha_{11} C - \alpha_{12} SS \]
\[ \frac{dSS}{dt} = \alpha_{12} L - \alpha_3 S - \alpha_8 C. \]

Here a positive quantity highlights the addition of the stock from the specified node, whereas the minus sign shows the loss of the stock to a certain entity.
To obtain the parameters $\alpha_i$, the model is fitted to the data, as described in §2.2. In this case, and in the case used in Chapter 4 a non-linear method was employed where the minimum of the sum of squares of the function $F(t) = \{S(t), C(t), A(t), H(t), L(t), SS(t)\}$ is found, such that

$$
\min_i \|F(t)\|_2 = \min_i (S(t)^2 + C(t)^2 + A(t)^2 + H(t)^2 + L(t)^2 + SS(t)^2).
$$

Let the initial conditions for the parameters $\alpha_i$ be set to 1, with the condition $\alpha_i > 0$, for all $i = 1, ..., 12$, as the flows are directed. This gives rise to the optimised parameters being $\alpha = [0, 0.38, 0.74, 0, 1.8, 0.06, 0.5, 0, 0, 0, 0.27, 1.37]^T$. Integrating the ODEs with the first time point being the initial condition and using the evaluated $\alpha_i$, shows how the system evolves over time, as shown in Figure 2.7.

![Figure 2.7: An overview of the results from the system dynamics model showing how the stock in each entity changes over time.](image)

**Use in case study**

Chapter 4 uses this method for the descriptive model to simulate the UK phosphorus and nitrogen flows. The aim is to analyse how various policies impact the flows.
2.6 Ising Model

The Ising model is a simple method to describe the behaviour of electrons, which can be in one of two states, spinning up or down. The spin of the electron creates an energy, which is greater if two neighbouring electrons are spinning in different directions. The collective behaviour of electrons, i.e. if they are spinning in the same direction as their neighbours or not, defines which of the three possible states the whole system is in: opposite, random or emerging state, as shown in Figures 2.8-2.10 [80]. As a system with no external influence always tries to be in the state requiring the minimal energy, the Ising model tries to minimise the energy within the system by getting the electrons to spin in the same direction.

More generally, the Ising model simulates the binary choice of an entity. Each entity is influenced by its closest neighbours, where the strength of this influence is defined as the coupling constant $J$. A phase transition of the system changing states can be seen by varying this coupling constant. Because of its generic behaviour, the model has been used to describe a variety of phenomenas, where the three different states the system can be in are described below.

Opposite state: Here the entities try to be in the opposite state to their neighbours to the north, east, south and west, as shown in Figure 2.8. In the figure, the entities are set up in a square lattice of the size 30 x 30, thus representing 900 entities. Each entity is in one of the two possible states, which is represented by the black or white filling.

Random state: Here the system has the entity’s state randomly distributed, as shown in Figure 2.9. Again, the figure shows the states of 900 entities, where each entity is in one of the two states highlighted by the black or white filling.
Figure 2.8: Opposite system; entities are in an opposite state to their neighbours, where each square represents an entity which are in one of the two states shown by the black and white filling.

Figure 2.9: Random system; entity’s states are randomly distributed in the system, where each square represents an entity which are in one of the two states shown by the black and white filling.
Emerging state: In this state, clusters of entities in the same state appear, leading to an emerging property in the system, as shown in Figure 2.10. The black and white fillings again show the states of the 900 entities in the system.

The idea of using the Ising model to represent voters was suggested by Serge Galam as a quantitative metaphor [65], which is used in this research in Chapter 3 to simulate voters in an electoral district. The voters are in one of two states, electing a politician from one of the two possible political parties. The coupling constant $J$ is used to determine how much the individual is influenced by its neighbour’s party preference, which for this research are referred to as the individual’s social neighbours, i.e. friends and family. As this research only considers the random and emerging states of the system, the phase transitions into an opposite state is from now on ignored.

The first part of this section in §2.6.1, evaluates where the system’s phase transitions occur by estimating the critical coupling constant $J$ using the mean field approximation. The mean field approximation assumes all entities to be in the same state, thus having the same effect as if there is only one entity in the system. The Boltzmann distribution [57, 100] contains the Boltzmann factor, describing the probability of the entities to be in one of the two states, and the detailed balance, implicating for a system at equilibrium the transition from one state to another and its reverse to occur at equal rates, can be applied to describe the change of the whole systems’s behaviour. This distribution is used as it aims to maximise the transitions of the states, thus leading to a minimisation in state

Figure 2.10: Emerging system; system shows emerging behaviour, as clusters of entities in the same state are formed, where each square represents an entity which are in one of the two states shown by the black and white filling.

The figure shows a system of entities where clusters of entities in the same state appear, leading to an emerging property in the system. The black and white fillings again show the states of the 900 entities in the system.
differences between the entities. From this the critical coupling constants $J_c$, at which a phase transition occurs, can be found to be at $J_c \sim 0.5$, with

$$\text{System’s state} = \begin{cases} 
\text{Random} & \text{if } J \lessgtr 0.5 \\
\text{Emerging} & \text{if } J \gtrless 0.5.
\end{cases}$$

The second part of this section in §2.6.2, describes the simulation of the Ising model, which uses the energy difference to simulate the change of states for each entity. This model also simulates where the phase transition occur, as determined in §2.6.1.

### 2.6.1 Mean Field Approximation

**Notation**

- $s_i = \text{Individual voter’s state, electing one of the two political parties}$
- $s_j = \text{Neighbour’s voting state}$
- $z = \text{The number of neighbours influencing the individual voter } i$
- $J = \text{Coupling constant, defining the strength of an individual voter to be influenced by its neighbours’ states}$
- $H = \text{External influence impacting the individual}$
- $T = \text{Tension between voters. If a voter is electing a different political party to its neighbours, then there is a larger tension between them, whereas if they are all similar minded, then there is no tension. The Ising model tries to minimise this tension in the system.}$

#### 2-D Ising Model with no External Influence

Let $L$ be the number of voters in an electoral district set up on a lattice $S$. Each voter can be in one of two states $s_i = \pm 1$, voting for one of the two political parties, where $i$ is a specific individual voter. Let the lattice be square $S = N^2$, where $N$ is the size of the array such that $N^2 = L$ [108].

The total tension between voters in the system $T$ is defined as
Here \( <im> \) defines each voter as only interacting with its \( z = 4 \) closest neighbours to its north, east, south and west. \( J \) is the coupling constant, defining the strength of the individual to be influenced by its neighbours. The second part of the equation is given by an external influence, which only impacts the individual voter.

The tension for the \( i^{th} \) voter is defined as

\[
t_i = -\frac{J}{2} s_i \sum_{<im>} s_m - H s_i,
\]

where the coupling constant \( J \) is halved to satisfy the condition \( T = \sum_{i=1}^{L} t_i \), so that neighbours are not counted twice.

Through definition, let the effective field \( H_{eff} \) be

\[
H_{eff} = H + \frac{J}{2} \sum_{<im>} s_m.
\]

In this section the system is not impacted by an external influence, therefore \( H = 0 \). Substituting the effective field as described in equation (2.19) into equation (2.18) simplifies the individual’s tension to be

\[
t_i = -H_{eff} s_i.
\]

With the assumption that all voters have an unanimous opinion on which party to elect, such that the mean vote is \( \bar{s} = \pm 1 \), Boltzmann established the Boltzmann factor \( p(\bar{s}) \) to be

\[
p(\bar{s} = \pm 1) = \frac{1}{Z} e^{\alpha t_i},
\]

where \( \alpha = \frac{1}{k_B \tau} \), \( k_B \) is the Boltzmann constant and \( \tau \) the temperature of the system, which is proportional to the coupling constant \( \tau \sim \frac{1}{J} \). For simplicity, the Boltzmann constant and temperature will be from now on set to unity. \( Z = \sum_{s \in [-1,1]} e^{\frac{1}{\tau} s} \) is the normalising or partition function.
The detailed balance condition describes the transition from one state to other, where for a system in equilibrium, the transition from one state to another and its reverse transition should occur at equal rates [7, 108]. Applying this to the Boltzmann factor gives rise to the Boltzmann distribution, describing the state of the voters in the system, to be

\[ \bar{s} = \frac{p(\bar{s} = 1)}{p(\bar{s} = -1)} = \frac{1}{Z} \frac{e^{H_{eff}}}{e^{H_{eff}} + e^{-H_{eff}}} = \frac{e^{H_{eff}} - e^{-H_{eff}}}{e^{H_{eff}} + e^{-H_{eff}}} = \tanh(H_{eff}). \] (2.22)

As all voters are similar minded, the mean vote is \( \bar{s} = \pm 1 \), and the sum of all the neighbours’ votes is \( \sum_{i=1}^{z} s_i = z\bar{s} \). The effective field in equation (2.19) can thus be rewritten as

\[ H_{eff} = \frac{zJ\bar{s}}{2}. \] (2.23)

Substituting equation (2.23) into equation (2.22) gives rise to

\[ \bar{s} = \tanh\left(\frac{zJ\bar{s}}{2}\right). \] (2.24)

To find the critical gradient of where the two intercept, the line \( y = \bar{s} \) and the function \( y = \tanh\left(\frac{zJ\bar{s}}{2}\right) \) are differentiated with respect to \( \bar{s} \) and set equal to each other, such that

\[ 1 = \frac{zJ}{2} \text{sech}^2\left(\frac{zJ\bar{s}}{2}\right). \]

Setting \( \bar{s} = 0 \) such that \( \text{sech}^2(0) = 1 \), gives rise to the equation determining the critical point for a phase transition to be

\[ J_c = \frac{2}{z}. \] (2.25)

Thus far, there has only been one system where the critical coupling constant has been analytically solved. For a system with no external influence and each voter interacting with its four closest neighbours, i.e. \( z = 4 \), the critical coupling constant has been analytically been solved to be

\[ J_c = \frac{\ln(1 + \sqrt{2})J_o}{2} = 0.44J_o, \] (2.26)
where $J_o = k_B \tau$ is a constant [123].

In a 1-D Ising model there are no phase transitions, whereas a phase transition is possible for a 2-D lattices. It has not been proven that a phase transition is guaranteed to occur in a 3-D system [38,125].

### 2.6.2 Model Build

For the simulation of the Ising model [150], which uses the Metropolis-Hastings algorithm, the difference between each voter’s state $\Delta T$ is used to determine the probability of an individual to change their mind on who to elect.

Let all voters be in a square lattice with double periodic boundary conditions, where each voter’s current state $s_i = \pm 1$, is randomly determined. The tension $T$ in the system is given in equation (2.17), where the tension difference between the voters $\Delta T$ is

$$\Delta T = \sum_{<im>} 2J s_i s_m + 2H \sum_i s_i. \quad (2.27)$$

Here $<im>$ again indicates that the individual voter is influenced by its closest neighbours in the direction of north, east, south and west.

For this section the model simulates a system with no external influence, therefore $H = 0$. For simplicity, let the temperature and Boltzmann constant be $\tau = k_B = 1$.

The change in states for an individual is determined randomly as given by

$$Transition of voter = Transition \times Noise\ Controller \times (-2) + 1, \quad (2.28)$$

where

$$Transition = \begin{cases} 
1 & \text{if } R < (e^{-\Delta T}) \\
0 & \text{else}
\end{cases}$$

$$Noise\ Controller = \begin{cases} 
1 & \text{if } R < RandTol \\
0 & \text{else.}
\end{cases}$$
The first part of the equation (2.28) *Transition* defines the transition of the voter, where the exponential of the negative tension difference is compared to a random number $R$. If the exponential is larger than the random number, which is indicated by the result 1, the voter changes their state, whereas, if the random number is larger, indicated by 0, the voter stays in their original state. The second part of the equation *Noise Controller* allows for only certain number of transitions to occur. The noise controller $RandTol$ is compared to a random number $R$, only allowing voters to change states if the noise controller is larger than the random number $R$. Again, 1 indicates that the transition occurs and 0 that voters do not change their mind. Finally, the equation for transitions of voters is multiplied by $-2$ and $+1$ is added to each state, to ensure that each voter is in either one of these states $s_i = \pm 1$. The model then updates the voter’s states in the lattice by multiplying the *Transition of voters* matrix by the lattice of current voters’ states.

**Example**

The algorithm explained in the previous section was implemented in Matlab with $RandTol = 0.1$. Let the lattice size be $L = 10,000$, with the voter’s state $s_i = \pm 1$ being randomly determined, thus giving the mean vote to be $\bar{s} \sim 0$. The coupling constant is set at $J = 0$, such that voters are not influenced by their neighbours’ party preference. The algorithm is run 4,000 times before the coupling constant $J$ increases by 0.1.

![Figure 2.11](image)

*Figure 2.11: In the figure on the left the mean vote for all coupling constants is shown. In the figure on the right the tension between the voters for all coupling constants is pictured.*

In Figure 2.11 the results of the effect of an increasing coupling constant on the mean vote and tension in the system are visualised. In the figure on the left, the mean vote $\bar{s}$ versus
the coupling constant $J$ is pictured. It can be seen that around $J \sim 0.5$ a bifurcation occurs, as proven by Onsager or determined by the mean field approximation. It can also be seen that for a very small coupling constant $J \sim 0$ the mean vote is around $\bar{\sigma} \sim 0$. Only for the coupling constant to be further away from the critical coupling constant $J \gg 0.5$ does the mean vote tend to $\bar{\sigma} \to -1$ (could have been $+1$, as either happens with equal probability). In the figure on the right, the greater the number of similar minded voters, the lower the tension is in the whole system.
3 Political Voting Behaviour


Understanding national voting behaviour and analysing various influences on voters has a long history of research in terms of developing fair election systems [102,111,133,144]. In order to explore various influences on voting systems, several models have been proposed looking at basic forms and constitutions of Government [20,26,44,82,95] and voter systems [25,36,66–68,137,139]. This chapter analyses and compares different national voting behaviours across seven democratic countries with a long term election history focusing on re-election rates of leaders and political parties and the indirect impacts of a leader’s reputation and friends’ or family’s party preference on voters.

There are various forms of government, the most common being democracy, monarchy and authoritarian. This research focuses on a democratic system, as some countries have a near universal suffrage, therefore allowing external impacts on voters to be analysed. A democratic system is divided into three powers: legislative, executive and judiciary. Part of the legislative power consists of legislators representing their political parties, who are elected by the voters in electoral districts. The leader of the country is a member of the executive council and is the party leader whose political party has the most representatives in the legislative. The final power, which is not represented in this research, is the judiciary, who interprets the laws of the country.

This chapter is organised as follows:

A brief introduction on previous research on voting behaviour is described in §3.1, highlighting that differences in national voting behaviour have been observed.

Section 3.2 provides an overview of the data collected from seven countries. Five of the countries chosen are from the Commonwealth, as these countries have similar parliamentary systems, and the other two, France and the USA, have a long established democratic voting system. Although not all of the countries use the terms “MP” and “Prime Minister”, throughout this research the term “MP” is used to define a person who is elected into the legislature, also known as the legislator, and the term “Prime Minister” is the leader of the
executive council. Each country’s government system is simplified to a two-party system, where the two parties are the dominant party and the opposition. For some countries like the USA, only two parties have been in power, therefore making their political system a good fit for this research. Other countries for example France, have had numerous political parties in charge throughout history and to fit the classification of a two-party system to the French voting history, the parties have been subjectively classified to have either left or right wing political views\textsuperscript{1}. Doing so allows this research to fit the multiple-party led countries to a two party system. The party in charge for more than 50% of the time is defined as the dominant party.

In §3.3 a KISS model analyses the general voting mechanism for seven countries based on their historic election results. A Markov chain is fitted to the election results of the seven countries, calculating the probability of a Prime Minister or political party being in one of three states; newly elected, re-elected once or re-elected multiple times. These results highlight which behaviours impact national voting behaviour and should therefore be included in the KIDS model.

Section 3.4 describes the KIDS model which simulates the election process of a Prime Minister. The aim of this model is to determine how influences such as leader’s reputation and friends’ and family’s party preference, which are referred to as social neighbours, impacting individual voters which could alter the national voting behaviour.

A summary and conclusion of this chapter are laid out in §3.5.

3.1 Political Voting Behaviour

This section looks at previous research on voting behaviour, highlighting the differences observed between countries.

Research on voting behaviour [21, 32, 84, 85, 97, 134, 158] has shown that the reputation of a leader has an influence on voters, where voters perceive the leader to be either successful or unsuccessful [32]. Studies have frequently shown that a leader’s unsuccessful reputation has a stronger impact on voters than a successful one [32, 34, 85, 134].

\textsuperscript{1} See Appendix B. for each country’s party classification.
Differences between voting behaviour in various countries have also been observed due to a variety of cultural and constitutional differences. In the past, voters in the United Kingdom and Australia have tended to be more influenced by factors including class, age, gender, religion and ethnicity [9, 77, 98], whereas western European voters are inclined to elect parties that present clear political alternatives [92]. In comparison, throughout history, American voters were strongly influenced by their family’s party preference [18]. The type of election process in place for each country can also have an impact on voter behaviour [36]. Hence, there is a complex interaction of factors and influences determining the outcome of individual elections.

In order to untangle the intricate mix of reasons for voter behaviour, several simple conceptual voting models have been proposed. One of the first was proposed by Campbell et al. [30], who used the layout of the funnel of causality model to describe voting behaviour in a two-party system at a point in time, such that current understanding of voting influences can be understood. In Campbell et al.’s model, voters inherit their political party preference from their parents, which influences the individual’s future affiliation to a party. This model was able to predict 87% of voting decisions, suggesting that American voters are significantly more influenced by their families than by party policy. However, Campbell et al.’s conclusions have been criticised on the grounds that they used unrepresentative election results from the 1950s and that voters are modelled as uninformed and lacking interest in politics. This results in that every voter’s party preference was represented as being entirely dependent on loyalty towards a party to the exclusion of other individual influences, such as class, age and gender [128]. Furthermore, national influences such as the perception of a leader or media are not included but are known to have an impact on voter behaviour [32]. Despite all these issues, Campbell et al.’s model is widely used due to it explaining a large part of American voter behaviour and supporting the argument that American voters are likely to be influenced by their immediate social network.

Galam [65–68] proposed several simple mathematical voter models in order to investigate the effect of various individual influences on group decision and voting behaviour. Instead of analysing party preferences, his hierarchical model analyses the election process where voters choose one of the two proposed policies. Random voters are then selected to represent the policy in the above hierarchical level, where they gather together to form
various groups. Each voter selected keeps their policy preference, but again, one of the
elected in each group is randomly chosen and put forward into the following level. This
process continues until only one member is elected to represent their policy [65, 66]. One
model Galam proposed using is the statistical physics Ising model to describe how voters
make policy choices [68]. In the simplest form of a 2-D Ising model, voters can choose
between one of two policies and a voter’s preference is influenced by an initial choice and
the votes of their closest neighbours, e.g. family/friends. It is observed that depending
on the strength of the influence of a voter’s immediate social network, voters either select
a policy with a 50% preference or regions of voters all electing one policy occurs, such
that emerging clusters are created.

While these voting models have allowed researchers to investigate some of the fundamental
underlying mechanisms for voter behaviour, the models generally only capture local indi-
vidual influences on voter behaviour and ignore the national influence of media/leaders.
There is a need to develop models that explore conceptual mechanisms for voter behaviour
while also being able to reproduce gross averages of the election data.

3.2 Election Statistics

This section presents and analyses the election results of seven democratic countries. The
focus of the data collected was on the election results for the executive council from seven
democratic countries, in particular on the status of each country’s leader and political
party, whether newly elected, re-elected once or re-elected multiple times, which are col-
lected up until the election year 2011. As the leader in the year 2011 had not finished
their term in office, their status of being elected/re-elected is not included in the data.

The countries chosen for this research have had at least 20 democratic elections and have
a near universal suffrage. Two of the oldest democratic voting systems are France and
the USA allowing a large number of election results to be analysed. The five original
Commonwealth countries, Australia, Canada, Republic of Ireland, New Zealand and the
UK, were selected as they all have a similar government structure; for the sources of
the election results for each country see [78, 11, 23, 40, 44, 54, 73, 82, 87–90, 96, 114, 117,
119, 120, 124, 155]. Although South Africa was part of the original Commonwealth,
apartheid system throughout the 20th century led to it being excluded from this research. Other democratic countries were not considered, as their democratic voting systems were established quite recently.

From the data the percentage of the dominant party in charge and the re-election rate of a leader are calculated in terms of number of elections held for the original Commonwealth countries, France and the USA, as listed in Tables 3 and 4.

<table>
<thead>
<tr>
<th>Year first election held</th>
<th>Australia</th>
<th>Canada</th>
<th>Rep. of Ireland</th>
<th>New Zealand</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elections held</td>
<td>1901</td>
<td>1867</td>
<td>1922</td>
<td>1891</td>
<td>1801</td>
</tr>
<tr>
<td>Dominant party in charge (%)</td>
<td>61</td>
<td>57</td>
<td>58</td>
<td>62</td>
<td>60</td>
</tr>
<tr>
<td>PMs being re-elected (%)</td>
<td>51</td>
<td>63</td>
<td>53</td>
<td>66</td>
<td>47</td>
</tr>
</tbody>
</table>

Table 3: Listed are the calculated percentages for the election results from the five original Commonwealth countries.

<table>
<thead>
<tr>
<th>Year first election held</th>
<th>France</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elections held</td>
<td>1848</td>
<td>1789</td>
</tr>
<tr>
<td>Dominant party in charge (%)</td>
<td>52</td>
<td>66</td>
</tr>
<tr>
<td>PMs being re-elected (%)</td>
<td>21</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4: Listed are the calculated percentages from the election results from France and the USA.

It can be seen that in both Tables 3 and 4 that the dominant party was elected between 52-66% of the time for all countries. However, the biggest differences in the election data can be seen from the re-election percentages of the Prime Minister varying from 47-66% for the five original Commonwealth countries and between 21-30% for France and the USA. Even though the leaders of the USA can only be re-elected once since the 1950s, prior this only President Roosevelt was re-elected multiple times.
It is perhaps not unexpected that the election percentages for the five original Commonwealth countries are almost identical given that they have similar election systems. However, that France and the USA have a dominant party in charge with a percentage similar to the five original Commonwealth countries, but have a significantly lower re-election percentage for a leader highlights that the voters are being impacted in a different manner. Before exploring the differences seen in the re-election percentages, a KISS model analysing the general mechanism for national voting behaviour is carried out.

3.3 KISS Approach

To investigate the data and identify possible underlying mechanisms for the voting behaviour observed in §3.2, a three-state Markov model describing the time evolution from one election to the next keeping track of the probabilities of a Prime Minster and political party to be elected, re-elected once or re-elected multiple times, is constructed. A Markov chain, as described in §2.3, looks at the transition of a system’s state based on its current state.

3.3.1 Markov Model

In §3.2, the election statistics showed that the seven selected countries have the dominant party in charge for a similar amount of time, yet two types of voting behaviour can be seen: the original Commonwealth countries have a high re-election rate of their leaders and France and the USA are more likely to elect a new leader. A three-state Markov chain is fitted to the data, aiming to uncover some basic voting behaviour mechanisms. From this the stationary probability distribution describing the long term trends of the historic national voter behaviour in each country can be analysed. Finally, the Chi-square test investigates the goodness-of-fit of the model’s results to the data.

Figure 3.1 shows an overview of the model depicting the transition probabilities from each of the three states. Let $x_n \in \mathbb{R}^3$ describe the probability of a leader or party to be newly elected, re-elected once and re-elected multiple times at each election $n$, where $n = 1, 2, 3, \ldots$, such that

$$x_n = [p\{\text{newly elected}\}, p\{\text{re-elected once}\}, p\{\text{re-elected multiple times}\}]^T,$$
Figure 3.1: An overview of the KISS model. This Markov model shows the three states of a leader or party and their corresponding probabilities for moving from one state to another.

where $T$ denotes the transpose of the vector. The probabilities $x_n$ are updated at each election via the Markov model based on the previous election, i.e.

$$x_n = P x_{n-1},$$  \hspace{1cm} (3.1)

where $P$ is a probability matrix describing the transition probabilities between the three states, given by

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & p_{1,3} \\ p_{2,1} & p_{2,2} & p_{2,3} \\ 0 & p_{3,2} & p_{3,3} \end{bmatrix}.$$  

The probability matrix and diagram are chosen to reflect the options of the possible outcomes for a leader or party at each election, which will be briefly explained in terms
of the election of a Prime Minister. At the start of each election history $x_1$, a Prime Minister will always be newly elected. In the following election, with probability $p_{1,1}$ a new Prime Minister is elected or the current leader is re-elected with probability $p_{2,1}$, where $p_{2,1} = (1 - p_{1,1})$, since there are only two possibilities. Once a leader has been re-elected for the first time three outcomes are possible in the following election, namely a new Prime Minister is elected with probability $p_{1,2}$, the leader is re-elected once with probability $p_{2,2}$, or the once re-elected Prime Minister is re-elected with probability $p_{3,2}$. As these are the only three possibilities for the outcome, $p_{3,2} = (1 - p_{1,2} - p_{2,2})$. The transition of $p_{2,2}$ describes when a leader has already been re-elected once, but cannot finish their term, then an unelected leader takes their place. If this unelected leader is elected in the following election, it is considered they are re-elected for the first time, not just elected, as they were already in power before the election. Once the Prime Minister has been re-elected more than once, the following three outcomes are possible: the leader is re-elected again with probability $p_{3,3}$, which is given by $(1 - p_{1,3} - p_{2,3})$, a leader goes to being just re-elected once with probability $p_{2,3}$ (which occurs when an unelected leader comes to power during a term), or a new leader is elected with probability $p_{1,3}$. This model is also suitable to analyse the election/re-election of the dominant and opposition party.

In order to fit and calculate the probability transition matrix $P$, for each country, the entries of $p_{ij}$ are calculated via equation

$$p_{ij} = \frac{m_{ij}}{m_i},$$

(3.2)

where $i$ and $j$ each denote one of the three states, $m_{ij}$ is the total number of leaders or parties in power up to a certain election $n$ who made the transition from state $i$ to state $j$ based on the data and $m_i$ is the total number of leaders or parties in state $i$, also obtained from the data [93]. This calculation is done up to an election $n$, leading to a maximum likelihood fit of the Markov model to the data and is equivalent to carrying out a standard Least-squares fit of the model with the data [93].

As the probability matrix $P$ is column stochastic, the standard fix point theorem guarantees a fixed point to exist, i.e. as the number of elections held tends to infinity ($n \to \infty$) the steady state equilibrium distribution is achieved, as described by the steady state probability vector $\pi$. This satisfies the steady state relation
\[ \pi = P\pi. \] (3.3)

Solving equation (3.3) is equivalent to finding the normalised unit eigenvector of the probability matrix \( P \). The probability matrix \( P \) is re-computed after each election using equation (3.2). By evaluating the steady state equilibrium of the probability matrix at a certain election and by plotting each result provides a sensitivity analysis of the model.

To evaluate the suitability of using a three state Markov model, the Pearson’s Chi-square test is performed [64]. The Chi-square test \( \chi^2 \) looks at the expected frequencies of leaders and parties being elected/re-elected generated by the model and compares them with the frequencies of the data, as shown in

\[ \chi^2 = \sum_{l=1}^{k} \frac{(O(l) - NP_{ij}(l))^2}{NP_{ij}(l)}. \] (3.4)

Here \( O(l) \) are the total number of leaders in state \( l \) observed from the data, \( NP_{ij}(l) \) the total number of leaders in the same state \( l \), as obtained from model. This test is performed for a two-state up to eight-state system, as from the data it was observed that a leader was elected/re-elected at most eight times. For a two-state Markov chain the states are \( x_n = \text{[elected, re-elected]} \), for a higher \( k \)-state Markov chain the states correspond to \( x_n = \text{[elected, re-elected once, ..., re-elected (}k-1\text{) times, re-elected }k\text{ times]} \).

### 3.3.2 Markov Model Results

This section presents the results obtained from the Markov model. In Figure 3.2, the steady state equilibrium distribution from the Markov model for a leader to be newly-elected, re-elected once and re-elected multiple times are plotted, which are shown by the solid, asterisk and dashed lines respectively. The highlighted areas indicate the elections that took place during a World War, and the solid black line in the France figure denotes the interruption to French government due to the German invasion of France during World War II.
Figure 3.2: An overview of the steady state equilibrium distribution describing the historic national voting behaviour of leaders in the five original Commonwealth countries, France and the USA.
For all countries in Figure 3.2, an initial transience of the computed steady state equilibrium distribution is seen, but as the number of elections increases beyond ten then the mean probabilities start to converge. In order to see if the drastic change in the mean of the voting behaviour of each country in the first few results is due to the small number of elections used, the same method, but reversing the data points by using the most recent election as the initial election, is computed. It showed in this case that the voting behaviour converged again after few elections, indicating that the initial instabilities are due to a small numbers issue rather than any changes involving behaviours. Therefore, this sensitivity analysis highlights that by including more election results to the model leads to stable outcomes.

From the results, the computed probabilities highlight some countries with similar and different voting behaviours. In general, all countries apart from the USA remain largely unaffected by the World Wars. In the USA’s case, the spike in the re-election probability was due to the multiple re-elections of Franklin D. Roosevelt. Canada and New Zealand have steady state equilibrium distribution of being newly elected, re-elected once and re-elected multiple times roughly equal at a third. For all other countries the steady state equilibrium distribution of a newly elected leader is higher than the other two probabilities. Especially for France and the USA the probability of a newly elected leader is very high (~ 60%), but a negligible probability of a leader being re-elected multiple times. If the probabilities of re-elected once and multiple times are summed up, then for all of the original Commonwealth countries the chance of a Prime Minister remaining in power is greater than a new Prime Minister being elected, as observed in the election statistics in §3.2.

In order to test the goodness-of-fit of the Markov model and the choice of a three-state model, a Chi-square test was performed on all of the calculated steady state equilibrium distribution results for a two- up to eight-state Markov model, see Figure 3.3 for an overview of the results. The maximum number of states considered is eight, as no leader was elected/re-elected more than eight times. It is found that a two-state Markov model poorly captures the voter behaviour with the goodness-of-fit for New Zealand evaluated at $p \sim 0.1$. For a three-state Markov model the goodness-of-fit jumps to $0.88 < p < 1$ for all countries. As expected, the goodness-of-fit improves as the number of states increased, but this is only minimal. Hence, the three-state Markov model is chosen as it suitably
captures the key features of all the countries’ voting behaviours, whilst also remaining simple enough to yield some fundamental mechanisms for national voting behaviour.

Listed in Tables 5 and 6 are the steady state equilibrium distributions $\pi$ calculated by the three-state Markov chain, the re-election percentages from the data from §3.2 and the goodness-of-fit $p$ evaluated from the Chi-square test. As expected, a comparison of the two re-election statistics shows that there is not much variance in the results.

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>Canada</th>
<th>Rep. of Ireland</th>
<th>New Zealand</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime Minister’s re-election probability given by the probability vector $\pi$ (%)</td>
<td>52</td>
<td>65</td>
<td>57</td>
<td>68</td>
<td>50</td>
</tr>
<tr>
<td>Prime Minister’s re-election percentages from the election statistics (%)</td>
<td>51</td>
<td>63</td>
<td>53</td>
<td>66</td>
<td>48</td>
</tr>
<tr>
<td>$p$</td>
<td>0.99</td>
<td>0.97</td>
<td>0.88</td>
<td>0.97</td>
<td>0.93</td>
</tr>
</tbody>
</table>

*Table 5: Listed are the re-election probabilities of a leader for the original Commonwealth countries calculated from the steady state equilibrium distributions $\pi$, the re-election rates collected from the data and the $p$ value which describe the goodness-of-fit of the three-state Markov model to the data.*
Figure 3.3: An overview of the goodness-of-fit given by the p value and the number of states used in the Markov model to evaluate the re-election rates for leaders.
Table 6: Listed are the re-election probabilities of a leader for France and the USA calculated from the steady state equilibrium distribution $\pi$, the re-election rates collected from the data and the $p$ values which describe the goodness-of-fit of the three-state Markov model to the data.

<table>
<thead>
<tr>
<th></th>
<th>France</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prime Minister’s re-election probability from the probability vector $\pi$ (%)</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>Prime Minister’s re-election percentages from the election statistics (%)</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td>$p$</td>
<td>0.92</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Finally, the election/re-election of the political parties are analysed. In Figure 3.4 the steady state equilibrium distribution from the Markov model fit for a party being elected, re-elected once and re-elected multiple times are plotted, which once again is shown by the solid, asterisk and dashed lines respectively. As in the Figure 3.2, the fit and corresponding steady state equilibrium distribution are re-computed after every election using the data up to that election to form the probability matrix and calculated the resulting probabilities for each state via solving equation (3.3). The highlighted areas indicate the elections that took place during a World War.

For France and New Zealand the steady state equilibrium distribution does not seem to have converged due to a large variance in the results, whereas the party election rates for all the other countries has converged. It can be seen that the parties are more likely to be re-elected multiple times, except for the UK and the USA. For the UK there is a higher chance of the opposition party being elected, whereas for the USA the election of the opposition party and a party being re-elected multiple times occurs at a similar rate.

The goodness-of-fit is again calculated for all countries for a two- to eight-state Markov model, see Figure 3.5 for an overview of the results. It can again be seen that the two-state Markov model poorly fits the data, as, for example the goodness-of-fit for the Republic of Ireland is evaluated at $p \sim 0.5$. The goodness-of-fit for a three-state Markov model increases to the values between $0.87 < p < 0.98$. There is only a slight increase for the
Figure 3.4: An overview of the steady state equilibrium distribution describing the historic national voting behaviour for political parties in the five original Commonwealth countries, France and the USA.
Figure 3.5: An overview of the goodness-of-fit given by the p value and the number of states used in the Markov model to evaluate the re-election rates for parties.
results of higher states. Therefore, the results of a three-state Markov model are still sufficient in representing the data.

Listed in Tables 7 and 8 are the steady state equilibrium distributions $\pi$ for a party calculated by the three-state Markov chain, the re-election percentages from the data from §3.2 and the goodness-of-fit $p$ results. As expected, a comparison of the two party election statistics shows that there is not much variance in the results.

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>Canada</th>
<th>Rep. of Ireland</th>
<th>New Zealand</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Party’s re-election statistic from the probability vector $\pi$</td>
<td>70</td>
<td>67</td>
<td>61</td>
<td>76</td>
<td>56</td>
</tr>
<tr>
<td>Party’s re-election statistic given in percentages (%)</td>
<td>68</td>
<td>66</td>
<td>57</td>
<td>74</td>
<td>55</td>
</tr>
<tr>
<td>$p$</td>
<td>0.97</td>
<td>0.97</td>
<td>0.87</td>
<td>0.92</td>
<td>0.95</td>
</tr>
</tbody>
</table>

*Table 7: Listed are the re-election probabilities of the dominant party for the original Commonwealth countries calculated from the steady state equilibrium distributions $\pi$, the re-election rates collected from the data and the $p$ value which highlight the goodness-of-fit.*

Overall, this KISS model highlighted that the number of years a leader has been in charge is not as significant as to how many times the leader has been elected. Furthermore, as the Markov model provided a suitable representation of the system suggests that an underlying fundamental mechanism for national voter behaviour is based on who was in power prior to an election. Comparing Figure 3.4 to Figure 3.2 shows the historic national party elections to differ to the elections of Prime Ministers. Therefore, when analysing national voting behaviour a distinction between electing a leader and party election needs to be made.

As an underlying fundamental mechanism for national voter behaviour is based on who was in power prior to an election, leads to the current leader’s state to have an impact on voters. This could be one explanation as to why differences in national voting behaviour are observed in the data. Given that the French and the USA re-election rate of a leader
Table 8: Listed are re-election probabilities of the dominant party for France and the USA calculated from the steady state equilibrium distributions $\pi$, the re-election rates collected from the data and the $p$ value which highlight the goodness-of-fit.

<table>
<thead>
<tr>
<th></th>
<th>France</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Party’s re-election statistic from the probability vector $\pi$</td>
<td>69</td>
<td>61</td>
</tr>
<tr>
<td>Party’s re-election statistic given in percentages (%)</td>
<td>67</td>
<td>60</td>
</tr>
<tr>
<td>$p$</td>
<td>0.93</td>
<td>0.97</td>
</tr>
</tbody>
</table>

is significantly lower than the chance of a leader being elected, seems to suggest that for a leader already in power has a negative impact on voters, whereas for the original Commonwealth countries, being in power prior to an election has a positive influence on voters. This could be based on the impact of the leader’s reputation perceived by voters. Or, as suggested by Pomper [128] further possibilities, such as family/friends/social class could also be having an influence on the re-election rate of a leader. In order to examine these impacts, a model that incorporates the fundamental voter behaviour mechanism described by the three-state Markov model and the influence of friends’ and family’s party preference on individual voters needs to be constructed.

3.4 KIDS Approach

In the previous section, the voting behaviour of each county was analysed, showing the Commonwealth countries to have similar voting behaviour, as do France and the USA. A possible explanation of these similarities and differences of voter behaviour could be due to the impacts of the Prime Minister’s reputation and friends’ and family’s party preference, which are referred to as social neighbours, on individual voters. Hence, in order to explain the differences seen in the election statistics, a model that incorporates these influences on an individual voter but also has the underlying mechanism that voters decide on who to elect based on who was previously in power is needed. Since these mechanisms operate at different stages in an election, a descriptive model simulating the
3.4.1 Political Voting Model

A descriptive model is created in order to explain the differences observed in the election statistics, by incorporating the influences of social neighbours’ party preference and the Prime Minister’s reputation on voters, see Figure 3.6 for an overview of the model.

![Diagram](image)

**Figure 3.6:** A schematic overview of the descriptive model. There are an odd number of electoral districts where individuals vote for an MP. The elected MPs are grouped into the legislative power, creating two political parties, where they internally vote for a party leader. The executive council consists of the Prime Minister who is selected on the basis of the size of the political parties in the legislature. The success score of the Prime Minister’s term in office, $\beta$, is fed back to the electoral districts.
The actions taken place in the model can be divided into four sections:

- Electoral districts put forward an MP
- Assigning characteristics to the MPs
- Choosing party leaders
- Selecting a Prime Minister

**Electoral districts put forward an MP**

Individual voters are grouped into $D_c$ equal-sized electoral districts, where $D_c$ is an odd number in order to avoid a hung parliament. As proposed by Galam [65], this research on a two-party voting system uses a 2-D Ising model [57, 108, 150], as explained in §2.6, to represent each electoral district in which the voters are set up in a square lattice with double periodic boundary conditions. The voters are in one of two states, voting for one of the two political parties. A tension $t_i$, defined by

$$ t_i = -\frac{J}{2} s_i \sum_{<im>} s_m - H s_i, \quad (3.5) $$

is created between the individual voter and its social neighbours, where $s_i = \pm 1$ describes the vote of each voter $i$, $J$ the strength of the nearest social neighbours’ influence and $< im >$ restricts the individual voter $i$ to be influenced by its $z$ closest neighbours. $H$ is the strength of the external influence, which impacts only the individual’s party preference. This impact is chosen to reflect how the electoral district voted previously, the current leader’s political party and their reputation denoted as $\beta$. In particular, if an electoral district voted the same way as the overall outcome of the election, then the tension in the system decreases. On the other hand, if an electoral district voted counter to the overall outcome of the election then there is an increased tension for the voters to choose the opposition. Hence, the external influence $H$ for an electoral district is defined as

$$ H = \text{sign}(\bar{s}^{prev}) - \beta \text{ sign} \sum_{d=1}^{D_c} (\bar{s}_d^{prev}), \quad (3.6) $$
where $\bar{v}^{\text{prev}}$ is the electoral district’s mean vote of the previous election, $\sum_{d=1}^{D_c}(\bar{v}_d^{\text{prev}})$ is the overall mean vote of all electoral districts $D_c$ from the previous election, which therefore describes the current leader’s political party, and $\beta$ is the current leader’s reputation. Only two types of reputations are considered, as research has shown that voters perceive the leader’s term in office to be either successful or unsuccessful [32]. Therefore, the Prime Minister’s reputation $\beta$ is one of two values:

$$
\beta = \begin{cases} 
\beta_{\text{suc}} & \text{Prime Minister’s term was successful} \\
\beta_{\text{unsuc}} & \text{Prime Minister’s term was unsuccessful.}
\end{cases}
$$

The implementation of this feedback of the current leader’s success is how the descriptive model takes the underlying mechanism of voter’s being influenced based on who was previously in power into consideration. If a leader is elected and has a negative impact on voters then in the following election their support will decrease.

The Boltzmann distribution is used to determine the probability that an electoral district is in a certain configuration, which is based on the Boltzmann factor $p(s)$, which is defined as

$$
p(s) = \frac{e^{-\sum_{i=1}^{D_v} t_i}}{\sum_{s=\pm 1} e^{-t_i}}, \quad (3.7)
$$

where $D_v$ is the number of voters in an electoral district. The “temperature” and “Boltzmann constant” in the Boltzmann distribution are set to unity. The Boltzmann distribution is chosen, as the most likely voter configuration is found by maximising the probability of equation (3.7), which is equivalent to minimising the total tension ($\sum_{i=1}^{D_v} t_i$) for each electoral district. This minimisation is carried out using the Metropolis-Hastings algorithm. The overall vote of each electoral district is counted, thus determining the elected MP’s political party.

Assigning characteristics to the MPs

The elected MPs are placed into one of two groups in the legislative power, creating two political parties. Each MP has two characteristics: a political complexion and a leadership skill. An MP’s political complexion is given by the absolute mean of the overall vote of their electoral district, therefore highlighting the mean political complexion
of their district. Initially, all MPs’ leadership skills are defined randomly, where thus far, a Uniform random distribution has been used, ranging from 0 to 1, with 0 indicating an incompetent leader and 1 a highly skilled one. This is only re-assigned if a new MP is elected, i.e. there has been a change of party in an electoral district. For the first election there are initial MPs, all of whom, for simplicity, are defined as being from one party.

Choosing party leaders

The political party in charge before the election keeps the Prime Minister as the party leader only if their term was successful; the success of a leader’s term in office is randomly scored to be either successful or unsuccessful. If it was unsuccessful, the party votes for a new party leader. A leadership battle is then carried out, where the candidates are the two MPs with the highest leadership score. All the other MPs vote for the candidate who has the closest political complexion to their own, where the candidate with the most votes wins the leadership battle. This leadership battle allows for the strongest leader not to be elected if their political views differs too much from the mean view of the party.

Selecting a Prime Minister

The Prime Minister is the party leader whose party has a majority representation in the legislative power. The success score of the Prime Minister is randomly determined by comparing the Prime Minister’s leadership skill to a random number. If their leadership skill is greater than a randomly generated number, then their term is deemed to be a success. This success score is fed back into the electoral districts, which in turn influences the voters in the following election.

For the first two elections, the external influence $H$ is set to zero so that voters are only influenced by their neighbours, as in the first election there is no leader to impact on the voters.

3.4.2 Political Voting Model Results

Before the descriptive model is analysed, the impact of the parameters $J$, $\beta_{suc}$ and $\beta_{unsuc}$ needs to be understood. Therefore, the mean field approximation, as described in §2.6, is applied to evaluate the influence of the parameters on the system.
**Mean Field Approximation**

To understand how the parameters $J$, $\beta_{suc}$ and $\beta_{unsuc}$ impact the voting system, the mean field approximation is applied. For this research voters are influenced by their four closest social neighbours to the north, east, south and west, denoted as $z = 4$.

For a small coupling constant $J$, it is expected that the tension of each voter to be governed mostly by the leader’s influence. Starting from a uniform random distribution of voters, the mean vote $\bar{s}$ in an electoral district will be approximately zero, leading to the external influence also to be close to zero. Therefore the mean vote in an electoral district stays unchanged in the following election. For a large coupling constant $J$, the influence of the leader can be neglected leading to clusters of similar minded voters. In this case, it is expected that the dominant party is in charge all the time. The aim is to analyse the point at which a bifurcation occurs, where the mean vote of an electoral district turns form 0 to $\pm 1$. For a system with no external impacts the critical coupling constant is set at $J_c \sim \frac{2}{z}$, but the influence of the leader $\beta_{suc}$ and $\beta_{unsuc}$ will change the value of the $J_c$ and to estimate how this critical value changes, the mean field approximation is applied.

A single electoral district is considered leading to the electoral district’s elected MP to also be the Prime Minister. Therefore, the tension within the district and the external impact influencing the voters is

$$t_i = \left(\frac{J}{2} z \bar{s} + H\right) s_i, \quad (3.8)$$

where

$$H = \text{sign}(\bar{s}_{\text{prev}}) - \beta \text{sign}(\bar{s}_{\text{prev}}) = (1 - \beta) \text{sign}(\bar{s}_{\text{prev}}). \quad (3.9)$$

Here $\bar{s}_{\text{prev}} = \pm 1$ denotes the electoral district’s previously elected MP’s political party.

From this the effective field, impacting the system’s behaviour, can be defined as

$$H_{\text{eff}} = \frac{J}{2} z \bar{s} + (1 - \beta) \text{sign}(\bar{s}_{\text{prev}}). \quad (3.10)$$

The probability for a single voter $s_i$ to be in one of the two states $s_i = \pm 1$ is given by by

the Boltzmann factor $p(s_i)$, i.e.
\[ p(s_i) = \frac{e^{-H_{\text{eff}} s_i}}{e^{H_{\text{eff}}} + e^{-H_{\text{eff}}}}, \quad (3.11) \]

and applying the Boltzmann distribution, which leads to the voters changing their states with equal probability, gives rise to the mean field equation

\[ \bar{s} = \frac{e^{H_{\text{eff}}} - e^{-H_{\text{eff}}}}{e^{H_{\text{eff}}} + e^{-H_{\text{eff}}}} = \tanh(H_{\text{eff}}) = \tanh\left(\frac{J_z}{2}\bar{s} + (1 - \beta) \text{sign}(\bar{s}^{\text{prev}})\right), \quad (3.12) \]

that needs to be solved.

The effect of the external influence \( H = (1 - \beta) \text{sign}(\bar{s}^{\text{prev}}) \), will lead to a mean vote \( \bar{s} \) that is the same sign as the external influence \( H \); see Figure 3.7 for a graphical sketch of the solutions of equation (3.12) for \( H > 0 \) and \( H < 0 \) and \( J_z \) small/large. Hence, for small \( \beta \), there is an increased preference to vote for the same overall outcome \((\pm 1)\) as before and a constantly elected dominant party is expected to occur. It is also observed that as the coupling constant increases the non-trivial mean solutions of equation (3.12) tend to \( \pm 1 \).

Next, the case where all the electoral district votes with the same mean \( \bar{s} = \pm 1 \) is considered, with the effect of multiple runs of the model. By approximating \( H \) by the smooth function

\[ H = (1 - \beta)\bar{s} \approx \tanh(\alpha\bar{s})(1 - \beta), \quad \alpha \in \mathbb{R}^+, \quad (3.13) \]

where \( \alpha \gg 1 \), gives rise to the mean field equation

\[ \bar{s} = \tanh\left(\frac{J_z}{2}\bar{s} + \tanh(\alpha\bar{s})(1 - \beta)\right), \quad (3.14) \]

that needs to be solved.

A necessary condition for a non-trivial solution of equation (3.14) is that the derivative of the righthand side of equation (3.14) at the origin \( \bar{s} = 0 \) is greater than unity. This leads to the condition

\[ \frac{J_z}{2} + \alpha(1 - \beta) > 1. \quad (3.15) \]
Figure 3.7: A graphical sketch of the solutions of equation (3.12). The blue line is the left hand side of equation (3.12) and the red line is the right hand side of equation (3.12). A solution of equation (3.12) corresponds to intersections of the two graphs denoted by circles for (a) \( Jz < 1 \) and \( H > 0 \) (b) \( Jz < 1 \) and \( H < 0 \) (c) \( Jz > 1 \), \( H > 0 \) and (d) \( Jz > 1 \), \( H < 0 \). Linear stability is denoted by full circles and linear instability is denoted by empty circles.

Provided \( 0 < \beta < 1 \) and \( \alpha \) sufficiently large the model will always attain this condition irrespective of the value of the coupling constant \( J \). Correspondingly, if \( \beta > 1 \) then for \( \alpha \) sufficiently large it is expected to never attain this condition. Hence, a critical value of the coupling constant is not expected in the numerical simulations but the coupling constant may still have an effect on the re-election rates.

Overall, equation (3.15) highlights that varying the value of the coupling constant \( J \) and reputation \( \beta \) to both have a clear impact on the system. Through the external influence in equation (3.6), it can be seen for a reputation \( \beta > 0 \) has a negative impact of voters, thus reducing the chance of a leader to be re-elected, whereas for \( \beta < 0 \) increases their chance.
Voting Model Results

In the previous section it was shown that both the reputation $\beta$ and the influence of social neighbours $J$ impact the system’s behaviour. This section aims to determine the strength of these impacts for the model to reproduce the two different voting behaviours as observed in the Markov model in §3.3.1.

The model uses $D_c = 11$ number of electoral districts, where each district is represented by a 2-D Ising model of the size $D_v = 100 \times 100$. The voters are set up on a torus, i.e. a 2-D lattice with double periodic boundary conditions, where each voter is influenced by the four closest social neighbours to the north, east, south and west, such that $z = 4$.

In order to yield one election average for a leader and party, 50 sequential elections are simulated. This is then repeated 20 times to create an election history, which are then also averaged to provide the average number of times a leader was re-elected and how long the dominant party was in charge. The standard deviation (taken from the 20 simulations) for all the results lies between 0-0.24 for the re-election of a leader and between 0-0.19 for how often a party was in charge. Computing the standard error of the mean yields at worse a standard error of approximately 3.5%. Hence, when analysing the results a difference in the re-election averages of greater that 7% could be expected. However, it is rare to see such high deviations in the results, where the mean of the standard deviation for the re-election rates of a leader is 0.03 and for party election 0.02, yielding a standard error of approximately 0.5%.

Parameter sweep of the influence of $J$, $\beta_{suc}$ and $\beta_{unsuc}$

To understand which impacts affect the national voting behaviour a parameter sweep for $J$, $\beta_{suc}$ and $\beta_{unsuc}$ on the descriptive model is performed.

In Figure 3.8 a three parameter plot of the results of the re-election rates of a leader with varying parameters of the successful and unsuccessful reputation and coupling constant is shown. Each colour in a square represents the value of the axis label and not the value in between, where blue indicates that no leaders are re-elected. The closer the colour is to red more leaders are being re-elected. It can be seen that there is a smooth transition of how often a leader is being re-elected by varying the parameters, i.e. there are no multiple parameter combinations to get the same re-election rate.
Figure 3.8: A plot of the average re-election rates for leaders with varying impacts of the successful and unsuccessful reputations and coupling constant.

To understand further how $J$, $\beta_{\text{suc}}$ and $\beta_{\text{unsuc}}$ impact the re-election rates of a leader, parameter plots with two varying parameters and one parameter fixed are analysed.

In Figure 3.9 a two parameter plot of the results of the re-election rate of a leader with varying parameters of the successful reputation $\beta_{\text{suc}}$ and the coupling constant $J$ is shown. In this figure the unsuccessful reputation is set to $\beta_{\text{unsuc}} = 1$, i.e. an unsuccessful leader has a strong negative impact on the voters. To counteract the influence of the unsuccessful leader, the successful reputation $\beta_{\text{suc}}$ is set to have a positive impact on voters ranging from 0, such that the successful reputation has no impact on voters, to $-0.9$ leading to the successful reputation having a strong impact on the re-election of the leader. It is noted that the successful reputation is not as strong as the unsuccessful one, as determined from research [32, 34, 85, 134]. In the Figure 3.9, each square represents the value of the axis label and not the value in between. It can be seen that most leaders have a re-election chance of 61%, where no matter how strong the negative impact is on voters, it does not seem to have an influence on the re-election rate of a leader. From the
election data it is known that on average only 58% of Commonwealth leaders and 26% of French or American leaders are re-elected. Hence, in order for the descriptive model to produce re-election rates similar to the France or the USA, the successful reputation cannot have a positive influence on voters.

In Figure 3.10, the results again show the re-election rate of a leader, where the successful reputation is set to be a constant at $\beta_{\text{suc}} = 0$, such that a successful leader has no impact on the voters, while the unsuccessful reputation $\beta_{\text{unsuc}}$ and coupling constant $J$ vary. Again, each square represents the value of the axis label and not the value in between. It can be seen that for the unsuccessful reputation to have no impact, i.e. $\beta_{\text{unsuc}} = 0$, around 60% of leaders are consistently re-elected. In particular the results show that a successful and unsuccessful leader can be re-elected multiple times. For $\beta_{\text{unsuc}} = 0.1$ there is a drop to around 50% in the leader’s re-election rate, as there is a higher chance for a random voting pattern. An analysis of the election histories show that for the case when $\beta_{\text{unsuc}} = 0.1$ an unsuccessful leader was able to be re-elected once, but this was a rare occasion. For a stronger unsuccessful reputation, i.e. $\beta_{\text{unsuc}} > 0.1$, there is an increase in the leader’s being re-elected. This is due to voters not re-electing an unsuccessful leader, whereas a successful leader is re-elected multiple times. Therefore, there were more successful leaders. As these results still do not produce the re-election rates similar to the French or American countries, it is required that a successful reputation has

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**Figure 3.9:** A plot of the average re-election rates for leaders, where the unsuccessful reputation is set at $\beta_{\text{unsuc}} = 1$ having a strong negative impact on voters, while the successful reputation is having a positive impact. The colours indicate the re-election rate of a leader.
a slight negative impact on voters.

![Figure 3.10: A plot of the average re-election rates for leaders, where the successful reputation is set at $\beta_{suc} = 0$. The colours indicate the re-election rate of a leader.](image)

In Figure 3.11 the unsuccessful reputation is set to have no impact on voters, i.e. $\beta_{unsuc} = 0$, with a varying impact of the successful reputation $\beta_{suc}$ and coupling constant $J$. It is noted that the successful reputation has a negative impact on voters. Again, each square represents the value of the axis label and not the value in between. In this case it can be seen that there are no re-elected leaders for almost all values. In particular, if a successful reputation is set to have no impact are there any re-elected leaders, which in turn means that a successful reputation can not have a stronger negative impact on voters than an unsuccessful reputation.

Finally, the impact of the coupling constant $J$ on the re-election rate of a leader is tested. In Figure 3.12 on the left the coupling constant is set to $J = 0$, whereby voters are not influenced by other’s party preference, whereas in the figure on the right the coupling constant is set at $J = 1$, so that the voter is most likely to adopt their social neighbours’ party preference. Again, each square represents the value of the axis label and not the value in between. In both figures it can be seen that only if the unsuccessful reputation has a stronger impact on voters than a successful one, are there any re-elected leaders. Comparing these two figures, it can be seen that the greater the influence of social neighbours’ party preference is, the less likely it is for a leader to be re-elected. In particular, the total number of leader’s re-elected for a stronger coupling constant $J$ has declined by 1.2%.

3 Political Voting Behaviour

Figure 3.11: A plot of the average re-election rates for leaders, where the unsuccessful reputation is set at $\beta_{\text{unsuc}} = 0$. Here the x-axis represents the negative impact of a successful leader on voters.

Figure 3.12: A plot of the average re-election rates for leaders, where both the successful and unsuccessful reputations are having a negative impact on voters. In the figure on the left, the coupling constant is set at $J = 0$, so that voters are not influenced by their social neighbours. In the figure on the right, the coupling constant is set at $J = 1$, such that the voters are likely to take on their social neighbour’s party preference.
Analysing the influence of $J$, $\beta_{\text{suc}}$ and $\beta_{\text{unsuc}}$ in the real world

In the previous section a parameter of sweep of the influences $J$, $\beta_{\text{suc}}$ and $\beta_{\text{unsuc}}$ showed that for the descriptive model to reproduce the election statistics, the successful reputation has to have a slight negative impact on voters. Also, an increase in the influence of the coupling constant $J$ on voters decreases the re-election rates of a leader. This section aims to determine suitable parameter estimates for $J$, $\beta_{\text{suc}}$ and $\beta_{\text{unsuc}}$ so that the model can re-produce the election statistics for the original Commonwealth countries, France and the USA. This is done through a trial-and-error calibration. First, the coupling constant is fixed, while the successful and unsuccessful reputation are determined. Once found, the impact of the reputations are fixed, while the coupling constant is varied.

Influence of the success scores $\beta$

In this section the coupling constant is set at $J = 0.48$, such that for a system with no external influence the voters are slightly influenced by their social neighbours’ party preference.

Before analysing the impacts of the different success scores, the importance of having at least two success scores, i.e. a successful and an unsuccessful reputation are shown in Figures 3.13 and 3.14. In these figures the successful and unsuccessful reputation are set equal to each other, such that $\beta = \beta_{\text{suc}} = \beta_{\text{unsuc}}$ is the only varying influence on voters. The thick black lines indicate how often the parties have been in charge, whereas the thin blue line represents the re-election rate of a leader. In Figure 3.13, the vertical green line cuts the thin blue line at 58%, indicating how often a leader was re-elected. The percentage for the dominant party being in charge, shown by the thick black line, is around 95%. From the election statistics in §3.2 it is known that, on average, an original Commonwealth country re-elected 58% of its Prime Ministers, with the dominant party being in charge for around 57% of the time. Therefore, the use of a single success score does not lead to a match with the election results from the original Commonwealth countries. To obtain these results, at least two success scores need to influence the voters. Capelos [32] observed that voters do actually perceive the leader’s term in office in two ways, as either positive or negative. Hence, this research only considers two success scores.
Figure 3.13: A detailed overview of voting outcomes for a system with only one varying negative impact $\beta$ on voters. The black lines indicate the average amount of time the political parties were in charge, whereas the blue line indicates how often a Prime Minister was re-elected.

Figure 3.14: An overview of voting outcomes for a system with only one varying negative impact $\beta$ on voters. The black lines indicate the average amount of time the political parties were in charge, whereas the blue line indicates how often a Prime Minister was re-elected.
Success scores for the Commonwealth countries

The aim is to determine $\beta_{\text{suc}}$ and $\beta_{\text{unsuc}}$, such that the model’s results have the dominant party in charge for 60% of the time and with around 58% of Prime Ministers being re-elected. Setting $\beta_{\text{suc}} = 0.03$ and $\beta_{\text{unsuc}} = 0.4$ lets the dominant party to be in charge for approximately 54% of the elections and approximately 56% of Prime Ministers are re-elected, see Figure 3.15 for an overview of one realisation of an election history. Here the blue and red blocks describe which party is in charge and a solid line dividing the elections indicates for a new leader to be elected, whereas the dashed lines highlights for a leader to be re-elected. In the figure it can be seen that it is fairly common for a Prime Minister to be re-elected at most twice.

![Figure 3.15: An overview of one electoral history for the Commonwealth countries. The light blue and dark red fields indicate the Prime Minister’s political party. A solid line dividing the elections indicates a new Prime Minister has been elected, whereas a dotted line indicates a re-elected Prime Minister.](image)

Success scores for France and the USA

The re-election rates for France and the USA are half those of the Commonwealth countries, with an average of 26% of French and American leaders being re-elected and the dominant party being in charge for approximately 59% of the time. Setting $\beta_{\text{suc}} = 0.08$ and $\beta_{\text{unsuc}} = 0.3$ lets the dominant party be in charge for approximately 62% of the time and approximately 27% of leaders to be re-elected, see Figure 3.16 for an overview of one realisation of an election history. It can be seen that a leader can be re-elected, but this is rare and that most of the time a new leader and party is elected.

By fitting the success scores so that the model reproduces the same number of leaders to be re-elected and the dominant party is in charge for the same amount of time as observed in the data, in both cases an unsuccessful reputation has a far greater impact on voters than a successful one, which has been observed by researchers [34, 85, 134]. Comparing the two reputation scores of the original Commonwealth countries to those of France and the USA highlights that the greatest difference is in the value of the successful reputation score $\beta_{\text{suc}}$. For France and the
Election results

Figure 3.16: An overview of one electoral history for France and the USA. The light blue and dark red fields indicate the Prime Minister’s political party. A solid line dividing the elections indicates a new Prime Minister has been elected, whereas a dotted line indicates a re-elected Prime Minister.

USA the negative impact of the successful score has increased by 63% in relation to the original Commonwealth countries success score. This is a possible explanation for the differences seen in the re-election rates of the leaders.

Influence of the coupling constant $J$

Finally, the impact of the social neighbours’ party preference $J$ is analysed. The success scores of the original Commonwealth countries, $\beta_{suc} = 0.03$ and $\beta_{unsuc} = 0.4$, and France and the USA, $\beta_{suc} = 0.08$ and $\beta_{unsuc} = 0.3$, are fixed, while the coupling constant $J$ is varied. For this analysis the number of simulations of the model was increased from 50 to 100 in order to decrease the standard error of the mean.

Fixed success scores for the Commonwealth countries

The success scores for the Commonwealth countries are fixed at $\beta_{suc} = 0.03$ and $\beta_{unsuc} = 0.4$, where the coupling constant $J$ is varied, see Figure 3.17 for an overview of the impact of the coupling constant $J$ on the election rate of leaders and parties. Here the thin blue line describes the trend of the average of how often the dominant party was in charge, where the rate of the mean increases by 2% for a stronger coupling constant $J$. The blue non-filled circles around the trend line are the results of the mean party election obtained from the model, including the standard error bars, and the green dashed lines are the confidence bounds, indicating that with a 96% confidence a single re-election mean from one simulation of 100 sequential elections will lie in that corridor. The thick black line shows the trend of the average of re-election rate of leaders, where the black filled dots are the results obtained from the model including the standard error bars and the red crosses describe the confidence bounds, again indicating that with a 96% confidence a mean from 100 sequential elections will lie in that corridor. It can be seen that increasing the influence of the coupling constant $J$ on voters decreases the mean of the
re-election averages for the leaders and a drop in the confidence intervals is observed. In order to test the statistical significance that the linear relationship exists a t-test is carried out to find the p-values for the leader and party re-election rate, which are less than 0.05 (0.00058 and 0.0062 respectively). Hence, the null hypothesis that the slope is zero for both re-election averages can be rejected.

Figure 3.17: A plot of the average re-election rates of the voter model for leaders and the dominant party, where the success scores for the Commonwealth countries are kept the same, while the coupling constant $J$ steadily increases. The thin blue line shows the trend of how often the dominant party is in charge, where the non-filled dots are the mean results from the model including the standard error bars and the green dashed lines are the confidence bounds. The increase of the dominant party election is 2% over $J \in [0, 2]$. The thick black line shows the trend of how often a leader was re-elected, with the filled dots describing the results obtained from the model and the red crosses highlight the confidence bands. The average of how often a leader is re-elected decreases by 6%.
Fixed success scores for France and the USA

Finally, the success scores of a leader for France and the USA are fixed while the coupling constant $J$ increases, see Figure 3.18 for an overview of the results. Again the thick black line describes the trend on how often the average dominant party was in charge, while the thin blue line highlights the trend of the re-election rate for a leader. It can again be seen that the dominant party’s election rate increases by approximately 2.5% as the coupling constant $J$ has a stronger influence on voters, whereas the re-election rate for a leader decreases by around 14%.

![Figure 3.18: A plot of the average re-election rates of the voter model for leaders and the dominant party, where the success scores for the France and the USA are kept the same, while the coupling constant $J$ steadily increases. The thin blue line shows the trend of how often the dominant party is in charge, where the non-filled dots are the mean results from the model including the standard error bars and the green dashed lines are the confidence bounds. The increase of the dominant party election is 2.5% over $J \in [0, 2]$. The thick black line shows the trend of how often a leader was re-elected, with the filled dots describing the results obtained from the model and the red crosses highlight the confidence bands. The average of how often a leader is re-elected decreases by 14%.


In both figures the rate the dominant party is in charge for $0 \leq J \leq 0.2$ hovers between 52% and 56%. This is not surprising as in Figure 3.7 for the case when $z = 4$ such that $J < 1/4$ and $H > 0$, as shown in figure a, linear stability occurs between $\pm 1$. Therefore, random results are expected. However, for $z = 4$ such that $J > 1/4$ and $H > 0$, as shown in c in Figure 3.7, linear stability occurs at $\pm 1$. Therefore, for $J > 0.25$ there is a greater chance for a party to be re-elected, which is observed in Figures 3.17 and 3.18.

These results highlight that a stronger impact of the coupling constant $J$, i.e. the influence of social neighbours’ party preference on voters has consequently a negative influence on leader’s re-election rate, while having a slight positive influence on party re-election. This implies that for a larger coupling constant $J$, there is a greater change of a political party changeover than for a smaller coupling constant. Furthermore, this model suggests that the influence of the reputation of a leader and the impact of social neighbours’ party preference is correlated. For example, for a stronger influence of the successful reputation as given in the France and USA case, enhances the impact of the influence of social neighbours’ party preference. The model does support the theory that just the two reputation scores for a successful and unsuccessful leader are enough to understand the data. In all cases for the model to reproduce the election averages of the data, required that an unsuccessful reputation has a far greater negative impact on voters than a (negative) successful one.

3.5 Conclusion

The aim of this research was to use a KISS and KIDS model to analyse aspects of national voting behaviour.

The KISS approach used a three-state Markov chain to determine the probability of a leader and political party to be elected or re-elected. This allowed for the historic national voting behaviour for each country to be compared. From the model is was observed that there is a difference in the historic national voting behaviour for leaders and parties. Therefore, when analysing voting behaviour a distinction between electing a leader and party election needs to be made. Furthermore, it showed when analysing national voting behaviour an underlying mechanism is that there is a knowledge of who was in power prior to an election. Furthermore, the number of years a leader has been in power is not as significant to how many times the leader was elected. Finally, it was also shown that the dominant party was in charge for a similar amount of time for all countries, whereas for leadership election two different voting behaviours were observed: the original Commonwealth countries had similar voting behaviour, re-electing around 58% of their leaders, whereas France and the USA have similar voting behaviour to each other, re-electing
only around half as many leaders. It was suggested that for a Commonwealth leader being in power prior to an election has a positive impact on voters, as there is a high re-election rate of leaders, whereas, for a leader from France and the USA, being in power prior to an election has a negative influence on voters, as only a few leaders were re-elected.

To analyse how certain impacts on voters alter the national voting behaviour a KIDS model simulating the election process of a Prime Minister was created. A 2-D Ising model is used to represent an electoral district containing voters, where a voter’s choice is influenced by their social neighbours’ party preferences, the electoral district’s previous vote and the success score of the current Prime Minister. The overall vote of the electoral district determines the political complexion of the elected MP. Two political parties are formed based on the MPs’ political complexion, with each party holding a leadership battle. The leader of the party with a majority representation is selected as Prime Minister, whose success score is determined randomly, which is in turn observed by the voters. As suggested by research [32], only two success scores of the current leader are perceived by voters, where the unsuccessful reputation has a stronger influence on the voters than a successful one [34,85,134]. For the descriptive model to recreate the election statistics for the original Commonwealth countries and France and the USA, both the successful and unsuccessful reputation have a negative influence on voters. It was also determined that a larger impact of social neighbours’ party preference on individual voters decreases the re-election rate of a leader, but has a slight positive impact on party election.

Overall the KISS model suggested that the general voting mechanism of national voting behaviour is based on the knowledge of who was in power prior to an election. This is implemented in the KIDS model through the feedback of the current leader’s success score impacting the voters in the following election. Furthermore, as observed by the simplistic model, when analysing national voting behaviour, the KIDS model has to distinguish between electing leader and party election. Finally, based on the results of the KISS model it was suggested that for a Commonwealth leader being in power prior to an election has a positive impact on voters, whereas for a leader from France and the USA being in power before an election has a negative impact on voters. However, the KIDS model showed that both success scores for all countries to have a negative impact on voters. Therefore, the interpretations concluded from the models seem to disagree with each other and to understand further how the impact of a leader influences voters, further research would be needed.

While both the KISS and KIDS models are very simple, several important conclusions about various national voting behaviours and some basic voting mechanisms can be found. From the literature, several authors support the hypothesis that voters in the USA are more influenced
by their family’s party preference, whereas other countries such as the UK are more influenced by parties that present clear political alternatives [18, 92]. Furthermore, the possibility of an unsuccessful leader having a greater negative influence on voters than a successful one is also supported by several authors [34, 85, 134].

Like Campbell et al.’s model [30], this work is only a simplified version of trying to draw out selective few fundamental mechanisms for voter behaviour from specific elections and there may be other types of general behaviour of voters not investigated here. However, this work has shown that simple conceptual models are able to reproduce the gross averages from election data and support several hypotheses for the underlying rules governing electoral systems. Yet, to analyse impacts and behaviours of an individual voter a more detailed model would have to replace the Ising model.

One way to take this research further is to test the impacts of the type of election process used in a country. Chatterjee et al. [36] showed by comparing countries with an open list proportional election voting system that a similar voting behaviour across all countries is observed. The descriptive voting model could be adapted for such a system, where the hierarchy within the model would have to change. First parties would have to put forward a number of candidates to be elected as party leader, where voters in the electoral districts then list the candidates in order of their preference. Based on the overall vote a party leader would be elected and the party with the majority of elected candidates would be selected as Prime Minister. A comparison of the two different models could provide further information on impacts on voter behaviour and the influence of the type of election process used.

Alternatively, this research could be adapted further to analyse other countries’ national voting behaviour. Although countries with a short history of democratic voting were excluded, there are other countries, such as Switzerland, which have had a democratic voting system for over two centuries, yet still had to be excluded from this research. The reason of excluding Switzerland from the current research is because it is not governed by one leader, but by seven. Therefore, their overall political voting structure does not fit the model. To assess the impact of the leader’s reputation and social neighbours’ party preference on voting behaviour for more countries, the descriptive model would have to be adapted to fit a country’s specific voting system.

Finally, this research could be extended to analyse set policies proposed by parties or the influence of media on voters, which are all known to have an impact on national voting behaviour.
4 UK Phosphorus and Nitrogen Flows

To understand how policies impact a metabolic cycle, intricate interconnectedness and interdependencies need to be considered. This research analyses the short term effects of government policies on the UK phosphorus and nitrogen flows, where some of the policies aim to reduce the quantity of nutrients lost in the metabolic flows or strive for a reduction in carbon emissions.

Over the last 40 years, the global human population has risen by nearly 80%, where the amount of crops grown in the world on arable land has increased simultaneously with the population growth. This method to supply the food demand is only a short term solution as the area of arable land is finite. Another solution is to increase the use of fertilisers containing phosphorus and nitrogen in order to amplify crop yield [79]. Figure 4.1 shows an overview of the rise in global population over the decades together with the increased use of arable land. Although there are obvious benefits in using fertilisers to support crop production, there are also some negative impacts on human society [12, 46, 146].

![Graph showing population growth and arable land use](image)

Figure 4.1: Visualised is the increasing amount of global arable land used compared to the global population growth. Figure taken from James N. Galloway (1998): The global nitrogen cycle: changes and consequences.

Phosphorus is a vital element for all living organisms; plants need it as nutrition for growth, humans and animals, who can only obtain this element by consuming plants, store it in bones...
or use it for energy (ATP). Plants absorb the inorganic salt of phosphorus, which is found in the soil, or applied via fertiliser in nutrient poor soil [12, 105, 152]. The nutrients in overused or improper use of fertiliser can be leached from the soil, which gather in surface water. This excess of nutrient causes algae to bloom leading to eutrophication [105, 152]. In addition to these environmental effects, uneven spread and not all equally accessible finite phosphate rock reserves [116, 153] could potentially lead to future conflicts [42, 46].

Nitrogen is also a vital element for all living organisms [116, 118]. As with phosphorous, plants need it as nutrition to grow, and humans and animals, who can only obtain this element by consuming plants, need it to create amino acids and proteins. Plants absorb the inorganic salt of nitrogen, which is found in the soil, or in nutrient poor soil, applied via fertiliser. Not only is there the environmental effect of eutrophication [118], but also an influence on human health [10, 70, 146], as the nitrogen in the soil can react with air, creating nitrogen oxides ($NO_x$).

With the ever increasing human population, carbon emissions created by the burning of fossil fuels ($CO_2$ emissions) and from agriculture (e.g. methane emissions from livestock) have also risen [129]. In 2007 the IPCC showed that over half of the $CO_2$ being emitted originated from from fossil fuel, while deforestation contributed to the second largest emitter of methane and $CO_2$ [91]. One potential effect these emissions could have is global warming, which in turn could impact not just the climate, but also the entire carbon cycle [29, 136]. A lot of effort through research has gone into trying to reduce carbon emissions through more efficient usage of burning fossil fuels or, for example, through the encouragement from the UN to reduce carbon emissions from deforestation and degradation [147] and the encouragement of carbon sequestration [35]. Yet, some of technologies are in their infancies and require further development [35]. Other research has focused on finding alternative energy suppliers, for example non-biomass energy providers (i.e. off shore wind farms or solar panels) or biomass based energy producers (anaerobic digestion, biofuels, co-firing) [107]. Although substituting green energy for fossil fuel does reduce the net carbon emissions, using crops for its production could have an impact of the phosphorus and nitrogen flows.

In the past researchers analysed only segments of either the phosphorus or nitrogen flow, yet to understand the full cycles, there is a need for more descriptive models that allow for phenomenological scenario testing [39]. Furthermore, the metabolic flows should be analysed as a coupled system, as they depended on one another. Finally, when governmental policies for closing the phosphorus and nitrogen cycles are promoted, only a singe policy is considered, although realistically there are multiple policies in place. By demonstrating the overall accumulated positive affect of all policies combined could provided a more transparent overview of how the government
is tackling the problem at hand. Therefore, this chapter analyses the whole UK phosphorus and nitrogen flows based on the collected data. A model then simulates both flows, where various policies impact the system.

This chapter is constructed as follows:

A brief overview of the global phosphorus and nitrogen cycles is given in §4.1 to highlight the problems observed in the metabolic flows.

In §4.2 the UK phosphorus and nitrogen flows are explained from which a network model is constructed. Furthermore, the data collected for each sector of the UK phosphorus and nitrogen flows are listed. Finally, a systematic analysis of the structure of the network is then carried out, from which the key nodes within the system are determined.

Two simplistic KISS models analysing aspects of the UK phosphorus and nitrogen flows are described in §4.3. The first KISS model uses a discrete model for a system with conservation of mass to analyse the distribution of the nutrients within the network. This model shows the phosphorus and nitrogen flows to be affected by change in a similar way. Another KISS model uses an Input/Output model to analyse the amount of nutrients lost from each node. The two KISS models provide information about which policies should be considered in this research aiming to reduce the loss of nutrients and prevent emissions.

In §4.4 the policies chosen to be tested are described, which can be divided into three categories: agricultural, industrial and waste policies. The target for both the agricultural and waste policies is to reduce the quantity of nutrients lost within the flows, whereas the industrial policies analyse the side effects on the phosphorus and nitrogen flows through the production of green energy.

The descriptive model is described in §4.5, where the phosphorus and nitrogen flows are simulated with three policy types impacting the flows. By having the policies impacting the metabolic flows at various stages classifies this research as a KIDS model, see Appendix A. for more information on the classification of the KISS and KIDS models used in this thesis. The aim is to understand how the policies, first on their own and then in conjunction with each other impact the metabolic flows in the short term.

Finally, in §4.6, a conclusion and discussion of this chapter are presented.
4.1 Global Phosphorus and Nitrogen Cycles

This section presents an overview of the global phosphorus and nitrogen based on the literature.

4.1.1 Phosphorus

Phosphorus is an important element for all forms of life, and one which is also irreplaceable \[12,42,116\], i.e. it cannot be substituted or chemically recreated. The chemist Isaac Asimov once described the importance of the element as: all life will come to an inexorable halt when all the phosphorus has gone \[13\].

**Global Phosphorus Cycle**

On a global level the phosphorus cycle can be divided into three separate cycles: the inorganic, organic and societal cycle \[105,152\].

**Global Inorganic Cycle**

Phosphorus can be found in the crust of the earth (lithosphere) from where it is released into fresh water (lakes, rivers, seas) through weathering, forming calcium phosphate. This insoluble compound sinks to the bottom of the fresh water where, through geological pressure, it forms sedimentary rock. Over time, these sedimentary rocks are raised to new, dry land, from where this cycle starts again. Figure 4.2 shows an overview of the global inorganic cycle.

![Figure 4.2: An overview of the global inorganic phosphorus cycle.](image)

---

Earth crust

Fresh water bed

Fresh water
Global Organic Cycle

The second global phosphorus cycle is the organic one, which can be further divided into land- and water-based cycle.

The land-based cycle has been used as a farming method for centuries. Plants use the phosphorus from the soil to grow, which are in turn eaten by humans and animals, absorbing the phosphorus into their bodies. The phosphorus leaves the body in excrement or deterioration and re-enters the soil. The water-based cycle is similar to the land-based one, except it takes place in water. Leaching of the soil as well as the animal and human consumption of seafood creates a link between the water- and land-based cycles. Both cycles are illustrated in Figure 4.3.

![Diagram of global organic phosphorus cycle](image-url)
Global Societal Cycle

The final cycle is the societal cycle, which on a global level can be divided into four phases: phosphate rock, crop harvest, livestock and animal waste, and food consumption and human waste. This chapter on the UK phosphorus flows focuses on aspects of the UK societal cycle.

Phosphate rock

Phosphate rock, containing a high quantity of phosphates, is mined from the reserves, which can be divided into many categories [116], with the main three categories being: reserves, reserve base and additional resources [39,153]. The reserves are the known phosphate rock reserves which are accessible or can be mined with current technology. The reserve base is the known reserves that are currently not accessible either because modern technology is insufficiently developed or because there is a lack of funding, and the additional resources are the estimated reserves that have not been mapped yet. The largest phosphorus rock reserve is found in Morocco. In 2011, the second largest reserve of phosphorus was found in Iraq, making up around 9% of total reserves. There are an estimated 65 billion tonnes of phosphate rock left to mine [116], with currently around 18.9 million tonnes of phosphate rock being mined every year. Most of this rock ore consists of around 13% phosphorus. Once the rock has been mined, the rock is transported for beneficiation, where the inert material such as sludge, sand and organic compounds are removed, increasing the percentage of phosphorus in the rock to 15-33%. Unfortunately, during the mining process, around 33% of the phosphorus is lost, and another 10% lost due to transportation. After the beneficiation stage, the rock can be processed in one of three ways: 74% (14.4 million tonnes) is used for fertiliser production, 7% (1.32 million tonnes) for industrial phosphates, such as food additives and detergents and 19% (3.82 million tonnes) is lost or used in a different way. Fertiliser production, which is the major use of this rock, can again be divided into three different production categories: wet wash, thermal process or direct usage as superphosphates or nitric phosphates.

Crop harvest

Just 15-20% of the phosphorus contained in plants is supplied by fertiliser; the rest is derived from soil reserves. Research has shown that more acidic soil tends to contain more organic phosphorus, due to the reactivity of organic phosphorus with the metals in the alkaline soil. Around 1.6 times the amount of phosphorus found in the harvested crops, is applied to the soil, therefore highlighting the excess of nutrient supplied. Without any loss of phosphorus through erosion or run-offs, it is believed that globally, soil contains around 7.3 million tonnes. It has been estimated that about two-thirds of harvest phosphorus is in grains, the other third is in straw and other agricultural waste.
Livestock and animal waste

Some of the crops grown are fed to livestock, where historically, farmers used animal waste as an organic fertiliser. Nowadays, whilst 16-20 million tonnes of phosphorus in manure is produced globally per year, only 2.5 million tonnes of this phosphorus is recycled.

Food consumption and human waste

The remainder of the harvested crop, i.e. the amount not fed to livestock, is available for human consumption. The global dietary consumption is estimated to be 1,500 milligrams of phosphorus per capita for adults, with the annual global human excrement containing around 3.3 million tonnes of phosphorus. In the past, not only animal manure was used as an organic fertiliser, but human excrement as well. Nowadays, human excrement is collected in sewage, where currently around 20% of urban human waste and around 70% of rural human waste is recycled globally, which amounts to around 1.5 million tonnes of phosphorus being recycled globally per year [105].

Figure 4.4 provides an overview of the global societal cycle and the amount of phosphorus in each link, highlighting the vast phosphorus loss. Eutrophication of fresh water is evidence that the phosphorus cycle is not a closed cycle.

Given the amount of phosphorus lost and contaminating the environment, researchers raise another problem. Assuming the levels of phosphorous extraction remain approximately the same, there will be phosphorus available for about another 120 years (excluding the Iraq reserves), so there is no short term shortage. But in the long-run, phosphorus will become scarce [104,153]. Only a few countries have reasonable sized phosphorus resources, for example in Europe only Finland has a small amount of phosphate rock, with the main mining areas being located in the USA, Morocco and China [12]. This uneven distribution of phosphorus reserves could lead to conflicts in the future [42,46].

A lot of research has gone into identifying where within the cycle the phosphorus is lost and to propose policies to prevent future loss. Yet it has been argued that these policies need to be updated as they currently focus on waste disposal and storage [112]. Researchers suggest that some policies should be enforced, for example to ensure increased optimization of fertiliser usage, the reuse or prevention of industrial waste, recycling or reduction of food waste, increase knowledge to promote consumer responsibility and maybe reduce the demand for food, try to close the phosphorus cycle and encourage industrial symbiosis. These policies will have to be implemented regionally in order to optimise the maximum effect of closing the phosphorus cycle and to prevent future conflicts.
Figure 4.4: Global societal phosphorus cycle: the numbers indicate the distribution of the global amount of phosphorus, given in million tonnes, in the year 2004.
4.1.2 Nitrogen

Nitrogen, like phosphorus, is a vital element for all living organisms and cannot be replaced, i.e. there is no substitute element [41,116]. Plants, who can only pick up the inorganic salt of nitrogen, need it as nutrition to grow, where humans and animals can only obtain this element by consuming plants to create amino acids and proteins [31,69,118].

Over the past 30 years, the amount of utilized arable land for global crop production has increased proportionally to population growth. However, the amount of arable land is finite, therefore the supply of food produced will eventually reach saturation point [69]. The application of fertilisers allows the quantity of crops grown to keep pace with the increasing population and food demand (the green revolution effect). Within approximately the past 40 years, the human population increased by 78%, whereas over the same period, nitrogen use has risen by 120% [70]. Therefore, further growth in population implies a likely increased amount of fertiliser will be required as the expansion of arable land diminishes.

**Nitrogen Cycle**

There are around 5 billion tonnes of nitrogen on earth. Less than 2% of this is stored in living organisms, around 20% in sedimentary rock and about 78% in the atmosphere [69]. Although there is an abundance of nitrogen in the atmosphere, it is in the gaseous form of $N_2$, with a triple bond between the N elements, meaning a lot of energy is needed to separate them. Plants need nitrogen in an inorganic form, i.e. in the form of ammonium ($NH_4$) or nitrate ($NO_3$) [31,118]. In the global ecosystem, two vital biological processes help to convert the gaseous form of nitrogen into the organic compound, and vice versa. Nitrification consists of two steps. Firstly, *Nitrosomonas spp.*, a type of bacteria, converts ammonia ($NH_3$) and ammonium ($NH_4$) into nitrite ($NO_2$). Then *Nitrobacter spp.*, another type of bacteria, converts this nitrite ($NO_2$) into nitrate ($NO_3$). In the denitrification process, heterotrophic bacteria convert the nitrate ($NO_3$) into the gaseous form of nitrogen $N_2$ [41].

Of the 4 billion tonnes of nitrogen in the atmosphere, around 90-130 million tonnes is converted into reactive nitrogen through biological nitrogen fixation, 3-5 million tonnes is converted into reactive nitrogen through lightening and the marine ecosystem converts around 40-200 million tonnes per year. The reactive nitrogen created through biological fixation is stored in the soil and absorbed by plants, although most of it is actually lost back to the atmosphere again; around 5 million tonnes is lost as $NO_x$, 8 million tonnes of $NH_3$ through soil, plants, human and animal waste. The marine ecosystem loses around 13 million tonnes of $NH_3$ into the atmosphere, and
35 million tonnes is circulated and stored in sediments through hydraulic distribution [69].

Without any human interaction, the nitrogen cycle would be in balance, creating the same amount of reactive nitrogen in the soil as that lost to the atmosphere [31]. Through an excess application of inorganic and organic fertilisers, nitrogen is lost through leaching to the surface water creating eutrophication, and through volatilisation in the form of \( NH_3 \) [118,140]. In 1998, around 54 million tonnes of ammonia (\( NH_3 \)) were emitted globally, from which around 60% is thought to have come from human activity [14].

**Human Health Effects**

The obvious benefit from the increased use of nitrogen in agriculture is the rise in food production by allowing crops to be grown in nutrient poor soil all over the world, which in turn decreases malnutrition and starvation, and potentially leads to an increase in healthy diets. But there are some drastic negative effects too. An overuse of fertiliser causes leaching of the soil whereby nutrients from the fertiliser transfer to open and groundwater, which can then cause eutrophication. But not only does this excess have an impact on the environment, it also effects human health [10,70,146]. The nitrogen in the soil can react with air to create nitrogen oxides (\( NO_x \)) which influence the immune system. The production of nitrogen dioxide (\( NO_2 \)) is especially harmful, as this can lead to the creation of ozone (\( O_3 \)), photochemical oxidants and fine aerosol particles, each of which can cause respiratory ailments such as reactive airways disease, coughs and asthma. Also, an increase in nitrogen use can result in drinking water contamination, which in turn can lead to reproductive problems and cancer.

The increase of nitrogen both benefits human society as well as having a negative impact on human health [1,146], see Figure 4.5 for a diagram of the relationship. Here it can be seen that there is a nitrogen usage saturation point, above which the positive effects do not outweigh the negative ones.
Figure 4.5: The red line describes the air and water pollution due to an increase use of nitrogen, the blue line describes the crop production due to the use of nitrogen fertiliser and the black line describes the net public health benefit. Figure taken from Townsend et al. (2003) “Human health effects of a changing global nitrogen cycle”.
4.2 UK Metabolic Flow Networks and Data

In this section, a simplified network description of the UK phosphorus and nitrogen flows is given, with the data of the quantity of phosphorus and nitrogen in each sector listed. An analysis of the network is carried out by looking at the degree, eigenvector, betweenness and closeness centrality measures and the control nodes.

4.2.1 UK Phosphorus and Nitrogen Networks

For this research, the global phosphorus network as described in §4.1 and shown in Figure 4.6 is adapted to represent the UK phosphorus and nitrogen flows. The global phosphorus network can be further divided into four categories: agricultural, food, industry and waste. The subcategory industry is not included in the UK metabolic flows network, as the UK does not have any commercial phosphorus reserves and therefore does not go through the process of mining and handling of the element, as done in the sectors Phosphate Rock, Benefication, Wet wash and Thermal process. Furthermore, in the global societal cycle for phosphorus, only around 1 million tonne was used in the global industry. As this is only a small quantity in comparison to the rest of the flow, this sector is excluded for this research. Instead the focus is on the production and handling of food. This network can also be used to describe the nitrogen flow, as both elements are needed in the food cycle. The adapted layout for the UK phosphorus and nitrogen flows is shown in Figure 4.7, where the key sectors in the network are described below. This level of detail of the network was chosen, such that various policies can be tested on the metabolic flows while still retaining the essential dynamics.

**Agricultural sector**

In Figure 4.6, describing the global phosphorus cycle, it can be seen that this sector contains the nodes: Fertiliser, Atmospheric Decomposition, Weathering, Soil, Crops and Crop Residue.

For the UK metabolic network, the Agricultural sector has been reduced to three large stocks: Fertiliser, Soil and various forms of crops. The quantity of phosphorus and nitrogen in the UK soil are not known and are difficult to gage an estimate for the whole nation, even from soil maps. Therefore, this research assumes the nutrients contained in the node Soil to be the total amount of inorganic fertiliser applied plus the quantity supplied as manure and organic human waste. This reflects the annual additional national input of nutrients onto the Soil and does not include the constant stock quantity that is already present. It is noted that from the data there is always a larger quantity of phosphorus and nitrogen being supplied each year to the Soil, than
that is picked up by crops. Instead of having separate inputs onto Soil, this research groups all the inputs, such as inorganic fertiliser, atmospheric decomposition, biological fixation and seeds and planting material into the node Fertiliser. All inputs except for inorganic fertiliser have stayed constant over the past decade.

Unlike the global societal cycle, this research distinguishes the crops grown in the UK into five subcategories: Cereal, Industrial Crops, Oilseed, Other Crop and Pulses and Beans. By defining each crop type allows the individual need of phosphorus and nitrogen within the crop to be expressed. In particular, one policy chosen to be tested only affects one of these crops, therefore by distinguishing the crops allows the impact of the policy to be analysed.
The term *Cereal* contains wheat, barley, oats, rye, mixed corn and triticale, while *Other Crops* covers linseed, sugar beet, vegetables, potatoes and fruit, amongst others. The quantity of phosphorus and nitrogen in *Industrial Crop* is given by the Department for Environment Food and Rural Affairs (DEFRA), but what type of crop that makes up this subcategory is not known. Furthermore, it is not known how this crop is used further down in the supply chain line. As this crop only contains a small quantity of nutrients, it is assumed for this research that it is available for human consumption.

**Food sector**

As shown in the *global* phosphorus cycle in Figure 4.6, the sectors *Consumption*, *Human consumption* and *Animal consumption* are classified in the food sector. As the research focused on the global cycle, import and export are not relevant.

For the *UK* phosphorus and nitrogen flows, five areas are classified in this sector, each focusing on the nutrients in food: *Available for Human Consumption*, *Human Purchase*, *Animal Consumption*, *Import* and *Export*.

The sector *Available for Human Consumption* is the total amount of crop and animal products available for human consumption, which is a combination of UK food production as well as imports and exports, such that

\[
\text{Available for Human Consumption} = \text{Total UK food production} + \text{Import} - \text{Export} - \text{Animal consumption}.
\]

This sector is included in this research, as it highlights the amount of food available for humans to purchase and if compared to the sector *Human Purchase* the large quantity of food not being bought can be seen. The sector *Animal Consumption* is the quantity of phosphorus and nitrogen consumed by livestock, where the animal products such as milk, eggs and meat also provide food for the node *Available for Human Consumption*. It is noted that some of the data describing the quantity of phosphorus and nitrogen consumed by livestock is not known, due to no information given on the quantity of grass or straw consumed. The two additional sectors in the UK network are *Import* and *Export*, which describe the quantity of nutrients imported and exported through food.
**Waste sector**

In the global phosphorus cycle in Figure 4.6 the waste sector contains the nodes *Human Waste*, *Animal Waste* and *Loss*.

The UK metabolic network will use the same waste nodes as indicated by the global phosphorus cycle except the nodes *Human Waste* and *Animal Waste* are named *Organic Waste* and *Manure*. For both *Organic Waste* and *Manure* the nutrients are recycled back onto the *Soil* in the agricultural sector as organic fertiliser. As not all human and animal waste is recycled, there is a link between *Human Purchase* and *Animal Consumption* to the node *Loss*.

The quantity of nutrients lost is not known, but this research considers everything not actively used, i.e. is in an inert form, run-off or lost through soil volatility or stored in landfill, to be lost, which is given by

\[
\text{Loss} = (\text{Soil} - \text{Other Crops} - \text{Cereal} - \text{Beans and Pulses} - \text{Industrial Crops} - \text{Oilseed}) + (\text{Total Available for Human Consumption} - \text{Human Purchase}) + (\text{Human Purchase} - \text{Organic Waste}) + (\text{Animal Consumption} - \text{Animal Waste}).
\]

An overview of the UK phosphorus and nitrogen flows is shown in Figure 4.7.

*Figure 4.7: An overview of the UK phosphorus and nitrogen flows.*
4.2.2 Data

Tables 9 - 12 show the data used for the models, where N/A stands for data not available. Figure 4.8 shows the change in the data over time for all the nodes, where the green line describes the change in the quantity of phosphorus in the node and blue the change in the quantity of nitrogen. The red line describes the fluctuation of the total quantity of the product available in each year, where this data is only available for some nodes.

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3 See Appendix C. for the data collected on the UK phosphorus and nitrogen flows.
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<td>Cereal</td>
<td>82</td>
<td>65</td>
<td>78</td>
<td>73</td>
<td>75</td>
<td>72</td>
</tr>
<tr>
<td>Pulses and Beans</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Industrial Crop</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Oilseed</td>
<td>7</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Import</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Export</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Available for Human Purchase</td>
<td>69</td>
<td>53</td>
<td>68</td>
<td>65</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Human Consumption</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>8,188</td>
<td>8,204</td>
<td>8,251</td>
</tr>
<tr>
<td>Animal Consumption</td>
<td>389</td>
<td>377</td>
<td>352</td>
<td>324</td>
<td>303</td>
<td>292</td>
</tr>
<tr>
<td>Recycled Manure</td>
<td>201</td>
<td>191</td>
<td>185</td>
<td>187</td>
<td>188</td>
<td>185</td>
</tr>
<tr>
<td>Organic Waste</td>
<td>20</td>
<td>26</td>
<td>26</td>
<td>28</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Loss</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 9: Total quantity of phosphorus, given in tonnes, in the UK between 2000-2005.*
<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser</td>
<td>110</td>
<td>105</td>
<td>101</td>
<td>63</td>
<td>81</td>
</tr>
<tr>
<td>Soil</td>
<td>327</td>
<td>317</td>
<td>311</td>
<td>271</td>
<td>289</td>
</tr>
<tr>
<td>Other Crop</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cereal</td>
<td>71</td>
<td>65</td>
<td>83</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
<td>Pulses and Beans</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Industrial Crop</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Oilseed</td>
<td>12</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Import</td>
<td>4,805</td>
<td>4,913</td>
<td>4,780</td>
<td>4,717</td>
<td>3,657</td>
</tr>
<tr>
<td>Export</td>
<td>1,756</td>
<td>1,910</td>
<td>1,958</td>
<td>1,243</td>
<td>1,392</td>
</tr>
<tr>
<td>Available for</td>
<td>11,735</td>
<td>11,715</td>
<td>11,500</td>
<td>11,215</td>
<td>11,248</td>
</tr>
<tr>
<td>Human Consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Purchase</td>
<td>8,390</td>
<td>8,269</td>
<td>8,074</td>
<td>8,058</td>
<td>N/A</td>
</tr>
<tr>
<td>Animal Consumption</td>
<td>285</td>
<td>267</td>
<td>246</td>
<td>324</td>
<td>254</td>
</tr>
<tr>
<td>Recycled Manure</td>
<td>184</td>
<td>178</td>
<td>174</td>
<td>171</td>
<td>172</td>
</tr>
<tr>
<td>Organic Waste</td>
<td>34</td>
<td>34</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Loss</td>
<td>84,700</td>
<td>96,700</td>
<td>108,450</td>
<td>119,950</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 10: Total quantity of phosphorus, given in tonnes, in the UK between 2006-2010.
<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser</td>
<td>1,593</td>
<td>1,527</td>
<td>1,549</td>
<td>1,468</td>
<td>1,467</td>
<td>1,405</td>
</tr>
<tr>
<td>Soil</td>
<td>2,805</td>
<td>2,682</td>
<td>2,674</td>
<td>2,597</td>
<td>2,607</td>
<td>2,535</td>
</tr>
<tr>
<td>Other Crop</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Cereal</td>
<td>453</td>
<td>357</td>
<td>437</td>
<td>424</td>
<td>438</td>
<td>415</td>
</tr>
<tr>
<td>Pulses and Beans</td>
<td>29</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>Industrial Crop</td>
<td>15</td>
<td>14</td>
<td>16</td>
<td>16</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Oilseed</td>
<td>36</td>
<td>36</td>
<td>45</td>
<td>55</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Import</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Export</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Available for Human Consumption</td>
<td>403</td>
<td>313</td>
<td>406</td>
<td>408</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>78,024</td>
<td>78,033</td>
<td>78,101</td>
</tr>
<tr>
<td>Animal Consumption</td>
<td>4,160</td>
<td>4,026</td>
<td>3,758</td>
<td>3,447</td>
<td>3,237</td>
<td>3,100</td>
</tr>
<tr>
<td>Recycled Manure</td>
<td>1,180</td>
<td>1,115</td>
<td>1,084</td>
<td>1,086</td>
<td>1,092</td>
<td>1,076</td>
</tr>
<tr>
<td>Organic Waste</td>
<td>33</td>
<td>41</td>
<td>41</td>
<td>44</td>
<td>47</td>
<td>54</td>
</tr>
<tr>
<td>Loss</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 11: Total quantity of nitrogen, given in tonnes, in the UK between 2000-2005.*
<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser</td>
<td>1,342</td>
<td>1,313</td>
<td>1,311</td>
<td>1,244</td>
<td>1,332</td>
</tr>
<tr>
<td>Soil</td>
<td>2,468</td>
<td>2,407</td>
<td>2,384</td>
<td>2,302</td>
<td>2,393</td>
</tr>
<tr>
<td>Other Crop</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Cereal</td>
<td>416</td>
<td>369</td>
<td>437</td>
<td>398</td>
<td>396</td>
</tr>
<tr>
<td>Pulses and Beans</td>
<td>30</td>
<td>19</td>
<td>25</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>Industrial Crop</td>
<td>13</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Oilseed</td>
<td>58</td>
<td>64</td>
<td>60</td>
<td>61</td>
<td>70</td>
</tr>
<tr>
<td>Import</td>
<td>40,251</td>
<td>41,207</td>
<td>39,085</td>
<td>39,285</td>
<td>38,647</td>
</tr>
<tr>
<td>Export</td>
<td>12,260</td>
<td>13,725</td>
<td>15,111</td>
<td>14,246</td>
<td>15,112</td>
</tr>
<tr>
<td>Available for</td>
<td>106,581</td>
<td>106,408</td>
<td>102,648</td>
<td>101,479</td>
<td>104,586</td>
</tr>
<tr>
<td>Human Consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Purchase</td>
<td>77,787</td>
<td>76,234</td>
<td>74,567</td>
<td>74,551</td>
<td>N/A</td>
</tr>
<tr>
<td>Animal Consumption</td>
<td>3,013</td>
<td>2,805</td>
<td>2,568</td>
<td>3,431</td>
<td>2,655</td>
</tr>
<tr>
<td>Recycled Manure</td>
<td>1,071</td>
<td>1,035</td>
<td>1,013</td>
<td>994</td>
<td>997</td>
</tr>
<tr>
<td>Organic Waste</td>
<td>56</td>
<td>58</td>
<td>60</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Loss</td>
<td>777,400</td>
<td>887,400</td>
<td>993,400</td>
<td>1,099,000</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 12: Total quantity of nitrogen, given in tonnes, in the UK between 2006-2010.*
Figure 4.8: An overview of the change in the quantity of phosphorus and nitrogen in each node, and where available, the change in the product for the data collected between the years 2000 and 2011. Here the data in the year 2011 is indexed at 100 for all categories except for Human Purchase, whose index starts in 2010.
Figure 4.8 shows how the quantity of phosphorus and nitrogen in a node changed over the past decade, where the most recent data obtained is indexed at 100.

An analysis of the change in both of the elements in Fertiliser over the past decade shows a decline. This is probably due to a better understanding of optimising fertiliser practises. Furthermore, there was a price spike in the phosphorus market in 2007/08 \cite{39}, which is reflected in this node, as there was a sharp decrease in the quantity of phosphorus used in fertiliser in the year 2008.

For the change in the quantity of nutrients in various crops, two different types of behaviour are observed. The change in the quantity of phosphorus and nitrogen in Oilseed and Pulses/Beans altered simultaneously to the change in quantity of crop produced. Therefore, if the crop production increases leads there to be more nutrients in the overall crop harvest. The second behaviour shows the quantity of phosphorus and nitrogen in Cereal, Industrial Crop and Other Crops to fluctuate independently from one another. This is due to these nodes containing various types of crops, and depending on the demand of a type of crop, farmers will increase the production of a certain crop and reduce others. For example, the cereal crop consists of crops such as wheat and barley. Between 2000 and 2009 there was a 2.6 tonne decrease in wheat production, while there was a slight increase in the quantity of barley grown. As each crop type contains a different nutrient content means if the production of a crop fluctuates, so will the phosphorus and nitrogen content within the node.

This fluctuating difference in the change of nutrient behaviour is also observed in the nodes Import, Export, Available for Human Consumption and Human Purchase, as these nodes also consist of various types of food products.

An interesting observation is the change of quantity of phosphorus and nitrogen in the sector Animal Consumption. Although not all the data is known for this sector due to the unknown quantity of grass and straw consumed by livestock, the known quantity fed to animals has stayed roughly the same over the past decade, while the quantity of nutrients in their food has decreased. This reduction could have been caused by governmental restrictions on what can be fed to animals.

Furthermore, due to restrictions on the quantity and type of crop Manure allowed to be applied to the Soil, a decrease in nutrients being recycled back onto the land is observed. But an encouraging sign in aiming to reduce the quantity of nutrients lost is the steep increase in the quantity of phosphorus and nitrogen being recycled back onto land through Organic Waste. This
could be due to a change in human behaviour, or because local councils have offered food compost collection within their constituencies.

The nutrients being applied to Soil from Fertiliser, Manure and Organic Waste has decreased, which is understandable as a reduction in the quantity of phosphorus and nitrogen in Fertiliser and Manure is observed. This is probably due to more research focusing on how much nutrient applied onto crops is really needed.

Finally, there is no data available for the quantity of phosphorus and nitrogen being lost through either the leaching of soil, the non-consumption of crops and animals, or human and animal waste not being recycled. This research considers everything not accounted for in the balance of inputs and outputs as being a loss, which is given by

\[
\text{Loss} = (\text{Soil} - \text{Other Crops} - \text{Cereal} - \text{Beans and Pulses} - \text{Industrial Crops} - \text{Oilseed}) + (\text{Available for Human Consumption} - \text{Human Purchase}) + (\text{Human Purchase} - \text{Organic Waste}) + (\text{Animal Consumption} - \text{Animal Waste}).
\]

An analysis of the Loss showed over the five years of complete data (2006-2011), that there has been a slight decrease in quantity of phosphorus and nitrogen being lost.

Although the Loss sector is slightly decreasing, there is still a vast quantity not being actively available within the flows each year. For example, eutrophication is evidence of the UK leaching a lot of nutrients, which would be part of this category. Therefore, it is important that guidelines and policy come into place not only to decrease this sector, but also to reduce potential impacts on the environment and human health. This research will not consider the change of environmental impacts such as an increase in soil acidity or a change in human behaviour on the metabolic flows, but instead focuses on the influence of human imposed policies. Before analysing these impacts, a simple network analysis is constructed on the layout of the UK phosphorus and nitrogen flows, such that the interconnectedness of the nodes within the system are understood.

4.2.3 Network Analysis

A network analysis on the UK metabolic flows, shown in Figure 4.9 is carried out, describing which sectors within the network are key and/or control nodes. One type of analysis carried out uses the degree, eigenvector, closeness and betweenness centrality measures to evaluate the critical nodes within the network. Another type of analysis evaluates the control nodes for a system, describing a combination of nodes an outside factor (for example a policy) needs to
influence, in order to alter the system; see §2.1 for more information on network analysis.

Figure 4.9: An overview of the metabolic flows network, where a certain quantity of phosphorus and nitrogen is in the nodes.

4.2.4 Network Analysis Results

Table 13 lists the results of the network analysis using the degree, eigenvector, closeness and betweenness centrality measures for the UK phosphorus and nitrogen layout.

The results in Table 13 show the nodes with the most links are Available for Human Consumption, Soil and Animal Consumption, as determined by the degree centrality. Expanding the analysis to include the information of the interconnectivity of all the nodes, as done by the eigenvector centrality, demonstrates that the nodes Loss, Available for Human Consumption and Animal Consumption are well connected within the whole network. The fact that the node Loss is well connected within the entire network shows that there is a lot of opportunity for phosphorus and nitrogen to be lost from each sector, which is reflected in the data, as this node contains the most nutrients. The closeness centrality shows that the nodes Export and Loss do not have any outbound links as their closeness measure is zero. All other nodes do have outbound links, where Soil, Animal Consumption and Organic Waste will be affected by change the fastest. Finally, the betweenness centrality looks at which nodes are the most important in bridging the network. These are Soil, Available for Human Consumption and Animal Consumption, which from the data, contain the second, third and fourth largest quantity of nutrients. Therefore, the results of betweenness centrality measure highlight the nodes through which the most nutrients flow.
The final method used to analyse the network calculates the configuration of nodes that an outside influence, for example a policy, needs to control to impact the system’s behaviour. Listed in Table 14 are the number of times each node is mentioned in the 90 possible control node configurations. Each result contains a combination of six nodes, from which two different groups could be established. The first group consists of four nodes from the crops sector (Other Crops, Cereal, Pulses and Beans, Industrial Crops, Oilseed), one node from the inorganic/organic fertiliser sector (Manure, Organic Waste, Fertiliser) and a node from the loss sector (Export or Loss). The second group consists of three nodes from the crops sector (Other Crops, Cereal, Pulses and Beans, Industrial Crops, Oilseed), one node from the inorganic/organic fertiliser sector (Manure, Organic Waste, Fertiliser), a node from the loss sector (Export or Loss) and the node Import.

\[
\text{Groups} = \begin{cases} 
4 \text{ types of crop, 1 type of fertiliser, Export/Loss} \\
3 \text{ types of crop, 1 type of fertiliser, Import, Export/Loss.}
\end{cases}
\]
The results of the network analysis show that the sector \textit{Loss}, which contains the most nutrients, is well connected within the system. This highlights the opportunity for the nutrients to be lost, and is a possible explanation for the current observed side effects of eutrophication and other human health effects. From the four centrality measures the nodes \textit{Soil}, \textit{Available for Human Consumption}, \textit{Animal Consumption} and \textit{Organic Waste} seemed to be the most important. The farming method before the green revolution, i.e. no inorganic fertiliser was used and all of the food was produced and consumed locally, is based on all of the nodes evaluated to be the most important, reinstating the importance of the old farming methods.

Policy makers aiming to reduce the loss of phosphorus and nitrogen by closing the cycle usually do not consider \textit{Soil} to be an important factor, as highlighted at the All Parliamentary Group on Agroecology meeting on 6.12.2012

URL: http://agroecologygroup.org.uk/index.php/events/previous-meetings/2012-12-06/ . However, this network analysis supports the importance of including \textit{Soil} when analysing the phosphorus and nitrogen flows.
To control the system’s behaviour a combination of 3 or 4 crops, one type of input in the form of fertiliser or occasionally import, and a type of loss in the form of loss or export, need to be influenced. Furthermore, as the sectors Import and Export rely on the global financial system, a naturally preferred configuration for UK policies to impact the metabolic flows would be to use the configuration of 4 types of crops, type of fertiliser and Loss. As the import/export sectors are manly influenced through financial change, these two nodes will be from now on excluded from this research, although, they are still represented in the data in the node Available for Human Consumption. Finally, the control nodes showed that to influence the system the agricultural and waste sectors need to be altered, whereas a change in Available for Human Consumption and Human Purchase will not have an impact on the overall behaviour of the system. This may not be true, as it is known that too much food is produced for humans to consumed, therefore a lot of food bought is wasted. If the quantity of nutrients in Available for Human Consumption would equal that of the quantity in Human Purchase, this could be a way forward in trying to reduce the loss of nutrients. Yet, it is hard to control human consumption behaviour, therefore this research will not try and alter this sector, as suggested by the control node configuration.

Before any policies are tested on the metabolic flows, a data analysis and comparison of the metabolic flows is carried out by employing two KISS models.
4.3 KISS Approach

This section uses two methods based on the KISS approach, to analyse the data of the UK phosphorus and nitrogen networks in order to provide an understanding of how these metabolic flows behave. The first method fits a discrete model for a system with conservation of mass to the data, describing the flows of the nutrients from one year to another. From this the stationary distribution of the phosphorous and nitrogen flows are obtained, illustrating the distribution of these elements over the past 11 years. The second method employs an Input/Output model, see §2.4 for more information on this method, to analyse the quantity of phosphorus and nitrogen lost from each node.

4.3.1 Discrete Model for Conservation of Mass

The first method to analyse the phosphorus and nitrogen flows in the UK uses a discrete model where the system obeys the law of conservation of mass, i.e. the quantity of phosphorus and nitrogen in the whole system stays constant. A node Sink/Source is needed to avoid any import or loss of nutrients from the system such that no nutrients are lost or added within the network. Based on the Perron-Frobenius theorem this then allows for a stable solution of the nutrient’s distribution within the whole network to be found. Furthermore, it was mentioned in the data description in §4.2 that the amount of phosphorus and nitrogen consumed by animals through grass and straw is not known, and to compensate for this a link between Sink/Source and Animal Consumption is created. As Sink/Source is not a sector in the real world but is used to balance the system, this node is not represented in the results. The stationary distributions of the nutrients for all other nodes are renormalised so that the sum of the distributions is equal to one. Figure 4.11 shows a layout of the phosphorus and nitrogen flows including the node Sink/Source.

The discrete model for a system obeying the law of conservation of mass updates the distribution of the elements within the system for the following year based on its current state, which is performed separately on the phosphorus (P) and nitrogen (N) flows. Let $x_{t}^{P,N} = [\text{Soil, Other Crop, Cereal, Pulses/Beans, Industrial Crop, Oilseed Rape, Available for Human Consumption, Human Purchase, Animal Consumption, Manure, Organic Waste, Fertiliser, Import, Export, Loss, Sink/Source}]^{T}$, where $T$ is the transpose of the vector, describe the quantity of nutrients in each node at year $t$. The flow matrices $A^{P,N}$, one for the phosphorus, $A^{P}$, and the other for the nitrogen flow, $A^{N}$, describe the flow of the nutrients from each node. The model updates the distribution of phosphorus and nitrogen in the following year $x_{t+1}$ via equation

$$x_{n+1}^{P,N} = A^{P,N} x_{n}^{P,N}.$$  

(4.1)
The matrix $A_{P,N}$ is shown on the following page, where $F = (F_1, F_2, ..., F_{20})$ are the parameters describing the flow for each stock. To evaluate the parameters $F$, equation (4.1) is fitted to the data by using the model fitting method (see §2.2 for more information on fitting a model to a time series of data).

As the matrix $A_{P,N}$ is column stochastic, the standard fix point theorem guarantees there to exist a fixed point which is stable. The steady state equilibrium distribution is evaluated as the number of years tends to infinity, i.e. $t \to \infty$, as shown by the steady state relation

$$\pi_{P,N} = A_{P,N} \pi_{P,N},$$

(4.2)

where $\pi_{P,N}$ is the steady state probability vector. Solving equation (4.2) is equivalent to finding the normalised unit eigenvector of $A_{P,N}$. When presenting the results, the steady state equilibrium distribution of the flows show the distribution of the elements within the network over the past decade.
\[ A^{P,N} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & F_1 & F_2 & F_3 & 0 & 0 \\
F_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
F_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
F_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
F_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
F_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & F_9 & F_{10} & F_{11} & F_{12} & F_{13} & 0 & 0 & F_{14} & 0 & 0 & 0 & F_{15} \\
0 & 0 & 0 & 0 & 0 & 0 & F_{16} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & (1 - F_3) & (1 - F_{10}) & (1 - F_{11}) & (1 - F_{12}) & (1 - F_{13}) & 0 & 0 & 0 & 0 & 0 & 0 & F_{17} \\
0 & 0 & 0 & 0 & 0 & 0 & F_{18} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & (1 - F_1 - F_5 - F_7 - F_8) & 0 & 0 & 0 & 0 & 0 & F_{19} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(1 - F_1 - F_5 - F_7 - F_8) & 0 & 0 & 0 & 0 & 0 & 0 & (1 - F_{16}) & (1 - F_{19}) & (1 - F_{14} - F_{18}) & (1 - F_{1}) & (1 - F_2) & (1 - F_3) & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (1 - F_{15}) & 0
\end{pmatrix} \]
4.3.2 Input/Output model

The second method uses an Input/Output model to analyse the quantity of phosphorus and nitrogen lost from each sector. Although the aim is to analyse the same network as in §4.3.1, for this method the unrealistic node *Sink/Source* is removed, so as not to underestimate the quantity of nutrients lost. Furthermore, the node *Loss* is not one of the state variables, as the aim of this method is to calculate the quantity of phosphorus and nitrogen that is lost from all the others sectors; see Figure 4.11 for an overview of the system.

Let \( x_{t}^{P,N} = [\text{Soil, Other Crop, Cereal, Pulses/Beans, Industrial Crop, Oilseed Rape, Available for Human Consumption, Human Purchase, Animal Consumption, Manure, Organic Waste, Fertiliser, Import, Export}]^T \), where \( T \) is the transpose of the vector, describe the quantity of nutrients in each node in the year 2009, with \( B^{P,N}x^{P,N} \) describing the flow of the nutrients within the network, while \( \text{Loss}^{P,N} \) highlights the quantity of phosphorus and nitrogen being lost from each node, which is evaluated via equation

\[
\text{Loss}^{P,N} = (I - B^{P,N})x^{P,N}, \quad (4.3)
\]

where \( I \) is the identity matrix, and \( B^{P,N} \) are the flow matrices, i.e.

\[
B^{P,N} = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_1 & G_2 & G_3 \\
G_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
G_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
G_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
G_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
G_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & G_9 & G_{10} & G_{11} & G_{12} & G_{13} & 0 & 0 & G_{14} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & (1 - G_9) & (1 - G_{10}) & (1 - G_{11}) & (1 - G_{12}) & (1 - G_{13}) & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{16} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\]

The unknown parameters \( G \) are obtained by fitting equation (4.3) to the data using the model fitting method as described in §2.2. The results of equation (4.3) provide the quantity of nutrients, given in tonnes, being lost from each node.
4.3.3 Discrete Model for Conservation of Mass Results

This section presents the obtained stationary distributions of the discrete model for a system with conservation of mass for the phosphorus and nitrogen flows, see Figures 4.12 and 4.13 for an overview of the distributions.

An analysis of Figures 4.12 and 4.13 shows the node containing the greatest quantity of nutrients is Available for Human Consumption, which is surprising as from the data the largest container is Loss. This is probably due to the model including the node Sink/Source to obtain the distribution of the nutrients, i.e. the additional node could be taking some nutrients away from the node Loss. When the results are re-normalised without the node Sink/Source, means that the nutrients taken from the node Loss are distributed across all nodes. Even with this additional node, this model highlights the two nodes with the smallest quantity of nutrients are Organic Waste and Manure, showing that not much food and manure is recycled. Therefore, increasing the recycling of food could decrease the nutrients in the node Loss.

To investigate if there has been any change in the UK phosphorus and nitrogen distributions over the past decade, the stationary distributions are evaluated after each year. The results showed only trivial changes. It is believed though, that an increase in the time series by just 30 years would show differences in the distribution of the nutrients, as the system has evolved a lot in the past few decades.
Finally, the node *Loss* was excluded from the network and the stationary distributions were re-calculated, as shown in the striped blocks in Figures 4.14 and 4.15, where the solid blocks are the stationary distributions of the elements based on the original data collected and shown in Figures 4.12 and 4.13. Comparing the two Figures 4.14 and 4.15, where both networks are altered in the same way, shows that both flows’ distribution change. This highlights that a policy impacting one flow would also influence the other. These results also show that if there were no loss within the system, more nutrients would be stored in *Soil*. This would allow for more crops to be grown, and therefore increasing the quantity being bought. These results though suggest less nutrients are need for *Animal Consumption* and *Manure* indicating that the number of livestock held on UK farms might decrease. The quantity of nutrients in *Fertiliser* would decrease, while the quantity of *Organic Waste* recycled back onto the *Soil* would increase, such that *Organic Waste* would be the main input of nutrients for *Soil*.

*Figure 4.12: UK stationary distribution of phosphorus over the past decade.*
Figure 4.13: UK stationary distribution of nitrogen over the past decade.

Figure 4.14: The green bars are the results for the phosphorus distribution over the past decade based on the data, and the yellow striped blocks is the distribution of phosphorus for a system with no loss.
Figure 4.15: The blue bars are the results for the nitrogen distribution over the past decade based on the data, the purple striped blocks is the distribution nitrogen for a system with no loss.
4.3.4 Input/Output Model Results

The final KISS model used to analyse the UK metabolic flows computes the quantity of phosphorus and nitrogen lost from the all the sectors in the year 2009, as presented in Figures 4.16 and 4.17. It is noted that the node Sink/Source is not represented in this model.

![Figure 4.16: Quantity of phosphorus lost (given in tonnes) from all the sectors in the year 2009.](image)

Comparing the quantity lost from both networks shows that proportionally both the phosphorus and nitrogen flows lose a similar quantity from the same sectors. This is not a bad result, as by aiming to reduce the loss within one node could impact both flows. Instead of analysing the quantity lost from each sector, this section combines the nodes into agricultural (Soil and Fertiliser) and food (Available for Human Consumption and Human Purchase) sectors. These sectors are compared to the total quantity of phosphorus and nitrogen in those nodes from the data, therefore illustrating the proportion of nutrients being lost. For the food sector 66% of phosphorus and nitrogen is lost, highlighting that too much food is being produced for human consumption. The agricultural sector on the other hand loses 21% of phosphorus and 37% of nitrogen. This reinstates the importance of policies targeting to reduce the loss of the nutrients from both of these sectors.

Both KISS models show an insight into the network behaviour, with the first model highlighting that a lot of nutrients are lost within the system, while the recycling of Organic Waste and
Figure 4.17: Quantity of nitrogen lost (given in tonnes) from all the sectors in the year 2009.

Manure contain only a small amount of phosphorus and nitrogen. If no nutrients were lost, then the recycling of Organic Waste would increase. Furthermore, the model demonstrated that the metabolic flows behave in a similar way when the network is altered, so that policies influencing one flow will have an impact on the other. The Input/Output model highlighted that the agricultural sector loses around 21% of phosphorus and 37% of nitrogen. This reiterates the importance of not just focusing on waste policies in trying to close the phosphorus and nitrogen cycles, but agricultural policies are just as important. Furthermore, the food section also lost a lot of nutrients. As it is difficult to change human behaviour, this research will analyse the influences of policies that use the crop waste from the food sector to produce green energy. The proposed policies to be implemented though should be carefully considered, as to assure that they have a positive impact on both flows.
4.4 Policies

The KISS models in §4.3 showed that a lot of phosphorus and nitrogen is lost from the agricultural and food sector, which could be causing eutrophic water and increase human respiratory diseases [105,146,152], while the waste sector (Manure and Organic Waste) only recycled a small quantity of nutrients. Furthermore, the KISS models showed that by altering the network both the phosphorus and nitrogen flows changed. Therefore policies impacting one flow could have an impact on the other. Three policy types, each being promoted by different arms of government, have been chosen as examples to be tested for their effects on the metabolic flows. The first policy targets the agricultural sector by controlling the fertiliser application rate, while the waste policy aims to reduce the quantity of nutrients lost from the waste sector. As the food sector, which is based on human consumption behaviour, would be hard to control, the final policy tested in this research promotes the use of crop waste in industry for the production of green energy.

4.4.1 Agricultural Policy

Nitrate Vulnerable Zones

Nitrate Vulnerable Zones (NVZ) are areas where there is a high drainage of nitrogen from farmland, which in turn pollutes surface water. Water is classified as polluted if it currently contains or, if no action is taken, in the future will contain, at least $50\text{ mg l}^{-1}$ of nitrate, or water that is currently or, if no action is taken will become, eutrophic [74]. Farmers whose land is within a designated NVZ have to comply with the rules set out by the farming industry, Department for Environment, Food and Rural Affairs (DEFRA), Natural England and the Environment Agency [5,58,59,74]. Strict guidelines on the $N_{\text{max}}$ limits, describing the maximum quantity of nitrogen allowed to be applied to crops is given, as shown in Table 15.

Comparing Table 15 to the current average application rate in the UK, see Table 46 in Appendix C., shows there to be not much difference, although this policy should reduce the amount of fertiliser applied in NVZ areas to prevent unnecessary loss of nitrogen. The high allowance for NVZ farmers is probably due to the geographical location of their land, as farmers have to apply a lot more fertiliser than the average in order to compensate for the leaching.
<table>
<thead>
<tr>
<th>Crops</th>
<th>$N_{\text{max}}$ limit (N kg ha(^{-1}))</th>
<th>Standard crop yield (t ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat, autumn or early winter sown</td>
<td>220</td>
<td>8</td>
</tr>
<tr>
<td>Wheat, spring sown</td>
<td>180</td>
<td>7</td>
</tr>
<tr>
<td>Barley, winter</td>
<td>180</td>
<td>6.5</td>
</tr>
<tr>
<td>Barley, spring</td>
<td>150</td>
<td>5.5</td>
</tr>
<tr>
<td>Oilseed Rape</td>
<td>250</td>
<td>3.5</td>
</tr>
<tr>
<td>Sugar Beet</td>
<td>120</td>
<td>N/A</td>
</tr>
<tr>
<td>Potatoes</td>
<td>270</td>
<td>N/A</td>
</tr>
<tr>
<td>Forage Maize</td>
<td>150</td>
<td>N/A</td>
</tr>
<tr>
<td>Field Beans</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Peas</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Grass</td>
<td>330</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 15: DEFRA (2009). Guidance for Farmers in Nitrate Vulnerable Zones, Standard values, manure sampling protocol and glossary Leaflet 3, Table 5.

This research aims to reduce the quantity of fertiliser applied in the UK. As the figures given for NVZ areas are not applicable to the rest of the UK, this research reduces the amount of inorganic fertiliser applied to crops by 10%, 20%, 50% and 100%. This should reduce the amount of nutrients lost, but may have a knock on effect on the rest of the network. See Figure 4.18 for an overview of the NVZ policy impacting the metabolic network, where the red dotted line highlights the reduction in the inorganic fertiliser applied.
4.4.2 Industrial Policies

Three different types of industrial policies will be tested: anaerobic digestion, biodiesel and co-firing, with each policy encouraging the production of green energy from crops; see Figure 4.19 for an overview of how the three policies impact the phosphorus and nitrogen flows. The red nodes are the three new nodes created for these policies with the red lines describing the phosphorus and nitrogen flows. The green line linking Biodiesel with Soil indicates that only phosphorus is recycled back onto land, whereas the nitrogen, highlighted in blue, stays in the remains of the crop, which is used as animal feed.

Anaerobic digestion

Anaerobic digestion (AD) is a natural process for micro-organisms to break down biomass in the absence of oxygen, whilst releasing biogas. Biogas is a mixture of approximately 60% methane, 40% carbon dioxide and traces of other contaminant gases, which when combusted produces heat and/or electricity. Or the biogas can be treated further to create biomethane, which is used for mains supply in the gas grid or as road fuel. The waste of AD is high in nutrients and therefore used as an organic fertiliser [60, 76, 121]. Various government bodies such as DEFRA, Department of Energy and Climate Change (DECC) and the Department for Transport
Figure 4.19: An overview of the industrial policies impacting the UK phosphorus and nitrogen flows. The red nodes are the three new nodes created for these policies, where the red lines linking the nodes to various sectors highlight the nitrogen and phosphorus flows. The green line linking Biodiesel with Soil indicates that only the phosphorus is recycled back onto land, whereas the nitrogen, shown by the blue line is used for animal consumption.

encourage AD as the UK is legally committed to supply 15% of energy demand from renewable sources by 2020 [48,60,75].

The biomass used for AD can be food waste, non-woody crop residue, slurry and manure [121]. This research will use crop residue, excluding the woody crop Cereal, for AD, where the data obtained is the non-woody crop in the sector Available for Human Consumption minus the non-woody crop used for Human Purchase; see Table 16 for the data used for AD. The nutrients used for this policy are then recycled back onto Soil as organic fertiliser. Not only does this process reduce the amount of phosphorus and nitrogen lost from the sector Available for Human Consumption, but through less biomass going to landfill, also reduces carbon emissions.

Biodiesel

Biodiesel is a biofuel made from biomass which can be substituted or blended with diesel fuel, whereby currently, a blend up to 7% biodiesel (E7) does not need to be labelled as such. Higher
Table 16: P and N are the quantity of phosphorus and nitrogen in the crop waste used for AD. The data is obtained from the unused non-woody crops from the sector Available for Human Consumption.

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>P content (tonnes)</td>
<td>11</td>
<td>11</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>N content (tonnes)</td>
<td>76</td>
<td>69</td>
<td>80</td>
<td>73</td>
<td>65</td>
<td>73</td>
<td>85</td>
</tr>
</tbody>
</table>

or purer blends of biodiesel need to be marked as they can potentially ruin a vehicle’s engine. The Department for Transport, DEFRA and the UK Royal Commission on Environmental Pollution (RCEP) are encouraging the production of biodiesel as to reduce 60% of greenhouse gases produced in the UK by 2050 [130,148]. Producing biodiesel encourages carbon sequestration, thereby reducing the amount of carbon in the atmosphere, which is done in two ways: firstly, growing crops for biofuels reduces the carbon in the atmosphere by storing the element in the crops and, secondly, the replacement of fossil fuel with biofuel reduces the carbon emission [130,154]. Even though the use of biodiesel reduces the amount of carbon emitted, it does produce more nitrogen oxides; see Figure 4.20 for an overview of the relation of biodiesel blend mixed with fossil fuel to their emissions. There are filters for engines to catch the nitrogen emissions, but they are not widely used.

Figure 4.20: Plotted is the relation of emission created when using fossil fuel blended with biodiesel ranging from 0-100%. Figure taken from United States Environmental Protection Agency (2001) A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. Available at: http://epa.gov/otaq/models/analysis/biodsl/p02001.pdf (Accessed on 3.07.2012)
Biodiesel production in the UK started in the year 2002, with only around 137 litres being produced whilst 229 litres were consumed by the British public [2,3]. The UK relies heavily on the import of biodiesel, even though local production has increased dramatically over the decade. One crop well-suited to biodiesel production is oilseed rape, whose yield has increased steadily over the years. In 2010, 1.044 million litres of biodiesel was consumed in the UK, with around 3.33% of UK vehicles using biodiesel. Although, the UK imports a large amount of biodiesel and crops other than oilseed rape can be used for the production, this research focuses on producing biodiesel from UK oilseed rape as this crop yield has increased vastly over the past years; see Tables 17 and 18 for the amount of phosphorus and nitrogen in the oilseed required to produce the biodiesel. The phosphorus from oilseed rape used in the production of biodiesel is recycled back onto land, whereas the nitrogen stays in the crop and is used for animal feed.

<table>
<thead>
<tr>
<th>Oilseed</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>P content (tonnes)</td>
<td>0</td>
<td>0</td>
<td>41</td>
<td>140</td>
<td>140</td>
<td>639</td>
</tr>
<tr>
<td>N content (tonnes)</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>28</td>
<td>28</td>
<td>128</td>
</tr>
</tbody>
</table>

Table 17: P and N are the quantity of phosphorus and nitrogen in the oilseed used for the UK biodiesel production.

<table>
<thead>
<tr>
<th>Oilseed</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>P content (tonnes)</td>
<td>3,628</td>
<td>5,469</td>
<td>3,766</td>
<td>2,873</td>
<td>2,827</td>
</tr>
<tr>
<td>N content (tonnes)</td>
<td>715</td>
<td>11,111</td>
<td>753</td>
<td>565</td>
<td>565</td>
</tr>
</tbody>
</table>

Table 18: P and N are the quantity of phosphorus and nitrogen in the oilseed used for the UK biodiesel production.

Co-firing

Co-firing is the process of substituting between 5-30% of the fossil fuel for coal fired power stations with biomass [33,113]. There are multiple benefits associated with the use of biomass; the biomass could be domestically produced and is a robust component in the supply chain, and is carbon neutral.

In 2007, EU leaders agreed to use renewable energy to supply 20% of all energy requirements by 2020, with co-firing being the second largest sector supplying renewable energy in 2005. Currently, there are 16 major UK power plants using the co-firing technology whereby in 2005, 1.4 million tonnes of biomass and 52 million tonnes of coal were used [33].
For this research, co-firing will be a policy relying on the unused cereal crop from the sector *Available for Human Consumption*, where the data used can be seen in Table 19. Cereal is a viable crop to use as it woodier than other crops, making it burnable. As the crop is used to fuel a coal fire, the ashes of the crop have to go to landfill, therefore the nutrients within the crop are lost.

<table>
<thead>
<tr>
<th>Co-firing</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>P content (tonnes)</td>
<td>24</td>
<td>28</td>
<td>24</td>
<td>31</td>
<td>27</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>N content (tonnes)</td>
<td>141</td>
<td>162</td>
<td>139</td>
<td>180</td>
<td>152</td>
<td>217</td>
<td>176</td>
</tr>
</tbody>
</table>

*Table 19: P and N are the quantity of phosphorus and nitrogen in the cereal used for co-firing. Data used is obtained from the unused cereal from Available for Human Consumption.*

### 4.4.3 Waste policy

**Bone Meal Ash**

In 1986, Bovine Spongiform Encephalopathy (BSE) was identified in cows in the UK, which has since had a drastic impact on the treatment of animals [62]. In 1988, the first policy on controlling animal feed took effect, with the current policy being: products of high risk producers of BSE, such as bovine brain, spinal cord, dead pets and wild and experimental animals, are classified as category 1 and have to be disposed of by incineration. Category 2 products are also high risk, such as dead livestock and manure, and need to be treated to prevent disease, but can be used to produce biogas or used for composting. The final classification is category 3, which consists of products with a low risk of spreading disease. This category contains of animal products produced in slaughterhouses but not used for human consumption and waste from food factories such as butchers and supermarkets. These animal products can be treated in different ways: incinerated, rendered, sent to landfill, composted, subjected to anaerobic digestion or used in pet food production [61].

As animal by-products contain a lot of phosphorus, the Environmental Agency and DEFRA are investigating how to recover the element, including using it as a fertiliser. This would not only prevent the loss of nutrients, but potentially would also reduce the amount of waste going to landfill by about 60,000 tonnes per year [4]. This research will therefore analyse the impacts of recycling animal products back onto *Soil*, while there is no possibility for the phosphorus and
nitrogen to be lost from *Animal Consumption*; see Figure 4.21 for an overview of how this policy influences the network.

*Figure 4.21: An overview of the waste policy impacting the UK phosphorus and nitrogen flows. The red line indicates the recycling of the phosphorus and nitrogen from animal by-products, thus reducing the amount of nutrients lost.*
4.5 KIDS Approach

The KISS models in §4.3, analysing the data of the UK phosphorus and nitrogen flows, highlighted that a lot of nutrients are lost from the agricultural and food sector, while minimal is being recycled. Based on the analysis, three policy types were discussed in §4.4 and the impact of these on the metabolic flows will be tested in this section. An overview of the UK phosphorus and nitrogen flows, as determined in §4.2, is shown in Figure 4.22, where the coloured circles highlight the impacts of the three different types of policies.

![Figure 4.22: An overview of the UK phosphorus and nitrogen flows and the policies influencing the metabolic system.](image)

4.5.1 Metabolic Flows Model

The metabolic flows model analyses the impacts of policies on the UK phosphorus and nitrogen flows. The aim is to analyse the short term impacts of three policy types tested in conjunction with each other, to see whether they enhance or undermine one another. As these policies could potentially have an immediate impact on the system a descriptive continuous time model is needed.

A system dynamics model, see §2.5 for more information on this method, using ordinary differential equations (ODEs) to describe the rate of change of the quantity of phosphorus and nitrogen
in each node, i.e. the total quantity of nutrients flowing into one node minus the nutrients leaving it, is created based on the network shown in Figure 4.22. The parameters in the model, describing the proportion of the nutrients flowing from one sector to another are restricted to being positive to ensure a one way flow along a link. They are determined by fitting the equations to the data using the non-linear model fitting technique as described in §2.2. Once the parameters for the system are obtained, the ODEs are integrated, thus showing the quantity of the elements in each node at time $t$. As human behaviour is slow to adapt and this research focuses on the short term policy impacts on the metabolic flows, for all simulations the evaluated parameters are fixed for a system with no policy impacts. It is noted that for this model, the node *Loss* accumulates the phosphorus and nitrogen over the years. There are two constant inputs in this model: firstly, *Fertiliser* is a constant input, as the UK imports fertiliser. Because of this input, there is no link between *Fertiliser* and *Loss*, although it was shown in the Input/Output model in §4.3.4 that some nutrients are lost from this sector. This is compensated through an increase of nutrients lost from *Soil*. The second constant input is in *Animal Consumption*, as not the full quantity of food consumed by livestock is known. The constants chosen where based on the data.

Three types of policies are tested on the metabolic flows: agricultural, industrial and waste policies, as described in §4.4. The agricultural policy reduces the fertiliser application rate to the soil, while the industrial policy promotes the production of green energy based on crops. The final policy recycles the animal waste back onto soil. Each policy is first tested on its own, such that the impact of each policy can be observed. Finally all policies are test together to provide an insight on how they act together. When presenting the results of this model, the aim is to analyse the change of the flows after 10 years.

### 4.5.2 Metabolic Flows Model Results

This section presents the results obtained from the metabolic flows model for how the phosphorus and nitrogen flows react to various policies. First though, the model is run without any policy impacts.

**No Policy**

This section presents the results of the metabolic flows model without any policies having an impact. First a model fitting technique as shown in §2.2 was used to determine the unknown

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4See Appendix C. for all the equations used in this research.
parameters needed for the model. The standard deviation for the phosphorus fit varied between 0 and 303.4 and for nitrogen between 0.2 and 4,049.2. These are relatively small deviations compared to the data used. However, the largest deviation by far occurred in the node *Loss*, which is created through the accumulation of nutrients not used within the network. This highlights the potential need for this node to be analysed in further detail. But before this can be done, the network of metabolic flows needs to be understood further. Once the parameters are obtained the ODE’s describing the rate of change of the metabolic flows over time can be integrated so that an overview of the quantity of nutrients is each node can be obtained.

In both metabolic flows the quantity of nutrients in the nodes, except for the node *Loss* converges over time. For *Loss* the nutrients are accumulated over time, see Figure 4.23 for an overview of the UK phosphorous and nitrogen flow over 10 years.

![Figure 4.23: An overview of the UK phosphorus and nitrogen behaviour over 10 years.](image)

The flows even converge over time even if there is an external impact on the metabolic flows. In Figure 4.24 the quantity of phosphorus in *Fertiliser* has increase 60 fold, such there is an initial drastic increase of phosphorus in *Loss* and *Soil*. Therefore, over time the flows will converge irrespective of an external impact.

Finally, the quantity of phosphorus and nitrogen distributed within the network after 10 years is shown in Figures 4.25 and 4.26. There error bars in these figures depict the obtained standard deviation for each node from the model fitting. As shown by the KISS model for conversation of mass in §4.3.1, it can be seen in these figures and Figure 4.23 that the sectors *Loss*, *Available for Human Consumption* and *Human Purchase* contain the most nutrients within the whole system.

Figures 4.23, 4.25 and 4.26 highlight that over 10 years, a large quantity of phosphorus and nitrogen is lost, which is likely to cause eutrophication in open water and to have a negative
impact on human health. To prevent this, policies aiming to reduce the loss of nutrients should be encouraged. But before enforcing several types of policies, it is important to understand how these influences impact the system on their own.
Figure 4.25: An overview of the UK phosphorus distribution after 10 years with the error bars depicting the standard deviation from the model fitting.
Figure 4.26: An overview of the UK nitrogen distribution after 10 years with the error bars depicting the standard deviation from the model fitting.
Waste Policy

The first type of policy to be tested on the metabolic flows is the waste policy, where bone meal ash (BMA) from livestock is used as a fertiliser for crops. For this policy to be implemented, the model assumes no nutrients are lost from the sector Animal Consumption, as they are recycled back onto Soil. The change in the quantity of phosphorus and nitrogen for the affected sectors are shown in Figures 4.27 and 4.28, where the solid blocks are the quantity of nutrients for a system with no policy and the striped blocks are the quantity of the elements in the sectors after the system has been impacted by the waste policy after 10 years. Tables 20 and 21 describe the percentage of change between the two systems. Only four sectors are affected by this policy (and also for all other policies) over a decade, which are Soil, Human Purchase, Organic Waste and Loss.

This policy uses BMA as an additional nutritional fertiliser, so that the quantity of phosphorus and nitrogen in Soil drastically increases. This has however had a knock-on effect on the quantity of other fertilisers needed, as seen by the reduction in Organic Waste being recycled. For this policy, the quantity of phosphorus in Organic Waste is similar to the quantity being recycled in 2011. This is not the case for the nitrogen content. The waste policy still requires five times as much of nitrogen when compared to the data, even though there is a 45% reduction compared to the system with no policy impacts. This could be due to BMA being a better source of phosphorus than nitrogen so that when using BMA as a fertiliser, other phosphorus rich fertilisers are not needed, while the system is still dependent on nitrogen rich resources.

When recycling BMA back onto Soil, other fertiliser applications need to be adapted so that there is not an excessive amount of nutrients applied to Soil. This excess could be lost through run off or react with air, potentially leading to eutrophication and have a negative impact on human health. One way to combat this excessive application of nutrients applied to Soil is to apply the agricultural policy based on Nitrate Vulnerable Zones (NVZ), which restricts the amount of Fertiliser being applied to Soil.
Figure 4.27: An overview of the quantity of phosphorus in the affected sectors after 10 years. The solid green blocks are the quantity of phosphorus for the metabolic flow with no policies influencing the system and the striped yellow blocks are the quantity of phosphorus after 10 years that have been affected by the waste policy.

<table>
<thead>
<tr>
<th>Phosphorus</th>
<th>BMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+51</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-39</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-2</td>
</tr>
</tbody>
</table>

Table 20: Listed are the percent in change of the quantity of phosphorus in sectors affected by the waste policy in comparison to a system influenced by no policy.
Figure 4.28: An overview of the quantity of nitrogen in the affected sectors after 10 years. The solid blue blocks are the quantity of nitrogen for the metabolic flow with no policies influencing the system and the striped purple blocks are the quantity of nitrogen after 10 years that have been affected by the waste policy.

<table>
<thead>
<tr>
<th>Nitrogen</th>
<th>BMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+106</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-45</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 21: Listed are the percent in change of the quantity of nitrogen in sectors affected by the waste policy in comparison to a system influenced by no policy.
Agricultural Policy

The second type of policy to be tested on the metabolic flows is the agricultural policy. This policy is based on the idea of the Nitrate Vulnerable Zone (NVZ), where the quantity of nitrogen applied to Soil is limited. For this research, inorganic fertilisers containing phosphorus and nitrogen are reduced by between 10-100%, where the impacts of these rates of changes on the metabolic flows over 10 years are shown in Figures 4.29 and 4.30. Here the solid blocks are the quantity of the elements in the sectors with no policies impacting them, the striped blocks the quantity of nutrients for those nodes impacted by the waste policy and the solid line is the change in the quantity of nutrients based on a 10-100% reduction in inorganic fertiliser as given by the agricultural policy. The percentage in change for the quantity of phosphorus and nitrogen in these sectors in comparison to the system with no policy impact are listed in Tables 22 and 23.

It can be seen that a reduction in inorganic fertiliser reduces the quantity of nutrients in Soil, but relies on the recycling of organic food to drastically rise, between 5%-70%. Increasing the quantity of recycled food relies on human behaviour to change and local governments offering the resources for recycling. Although these changes have been observed, for example the increase of recycled Organic Waste from the data, these changes can take time.

Unlike the waste policy, the agricultural policy reduces the quantity of nutrients in the Soil whilst still able to produce enough food, which could have a positive effect on the environment and human health. Yet, this policy relies on the human recycling behaviour to drastically increase, which for the waste policy decreased. Therefore, combining the two policies could have beneficial effects on the environment, while human behaviour would not have to drastically change.
Figure 4.29: An overview of the quantity of phosphorus in the affected sectors after 10 years. The solid green blocks are the quantity of phosphorus for a metabolic flow with no policies influencing the system, the striped yellow blocks are the quantity of phosphorus affected by the waste policy and the solid blue lines describe the quantity of phosphorus when impacted by a 10-100% fertiliser reduction.
Figure 4.30: An overview of the quantity of nitrogen in the affected sectors after 10 years. The solid blue blocks are the quantity of nitrogen for a metabolic flow with no policies influencing the system, the striped purple blocks are the quantity of nitrogen affected by the waste policy and the solid green lines describe the quantity of nitrogen when impacted by a 10-100% fertiliser reduction.
Table 22: The percent in change of the quantity of phosphorus in the sectors affected by the agricultural policy in comparison to a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.

<table>
<thead>
<tr>
<th></th>
<th>NVZ (10%)</th>
<th>NVZ (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>-4</td>
<td>-40</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>+6</td>
<td>+72</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-0</td>
<td>-2</td>
</tr>
</tbody>
</table>

Table 23: The percent in change of the quantity of nitrogen in the sectors affected by the agricultural policy in comparison to a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.

<table>
<thead>
<tr>
<th></th>
<th>NVZ (10%)</th>
<th>NVZ (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>-6</td>
<td>-57</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>+6</td>
<td>+74</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-0</td>
<td>-1</td>
</tr>
</tbody>
</table>

Agricultural and Waste Policies Combined

Before testing the final type of policy on the metabolic flows network, both the agricultural and waste policies influencing the system at the same time are tested. Figures 4.31 and 4.32 highlights the changes on the quantity of nutrients for the affected sectors, where the solid blocks represent the results for a system with no policy influence, the shaded blocks the impact of the policy BMA, the solid lines the impact of the NVZ policy with the fertiliser application rate reducing between 10-100%, and the dashed lines are the combined impacts of BMA and NVZ. Tables 24 and 25 list the percentage in change of the quantity of phosphorus and nitrogen for the affected sectors compared to a system with no policy influence.

The results for a combined policy with only a 10% fertiliser reduction show the quantity of
nutrients in Soil is similar to that of just the BMA policy impacting the system. Furthermore, enough nutrients are being recycled back onto Soil through BMA, such that there is a 35% and 40% reduction in the quantity of phosphorus and nitrogen in Organic Waste. Once the inorganic fertiliser has reduced by 69% for the quantity of phosphorus and declined by 71% for the quantity of nitrogen, no change in human recycling behaviour is needed as the quantity of nutrients in Organic Waste is the same as if there was no policy impacting the system. When no inorganic fertiliser is applied to the Soil, i.e. a 100% reduction in fertiliser, the quantity of phosphorus and nitrogen in Organic Waste increases by 13% and 12% respectively.

Therefore, by reducing the inorganic Fertiliser by ~ 70% and recycling BMA could potential reduce the impacts on the environment and human health as there is a reduction in the quantity of nutrients being lost. Furthermore, less nutrients are stored in Soil, reducing the chance for them to be leached or to react with air, while human recycling behaviour would not have to change.

<table>
<thead>
<tr>
<th>Phosphorus</th>
<th>BMA and NVZ (10%)</th>
<th>BMA and NVZ (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+47</td>
<td>+12</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-35</td>
<td>+13</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-1</td>
<td>-5</td>
</tr>
</tbody>
</table>

Table 24: The percent in change of the quantity of phosphorus of sectors affected by a combination of agricultural and waste policies in comparison to a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.
Table 25: The percent in change of the quantity of nitrogen of sectors affected by a combination of agricultural and waste policies in comparison to a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.

<table>
<thead>
<tr>
<th>Nitrogen</th>
<th>BMA and NVZ (10%)</th>
<th>BMA and NVZ (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+100</td>
<td>+49</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-40</td>
<td>+12</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-1</td>
<td>-2</td>
</tr>
</tbody>
</table>
Figure 4.31: An overview of the quantity of phosphorus in affected sectors after 10 years. The solid green blocks are the quantity of phosphorus for a metabolic flow with no policies influencing the system, the striped yellow blocks are the quantity of phosphorus affected by the policy BMA, the solid blue lines describe the quantity of phosphorus for a 10-100% fertiliser reduction and the dashed red lines are the impact of the combined policies.
Figure 4.32: An overview of the quantity of nitrogen in affected sectors after 10 years. The solid blue blocks are the quantity of nitrogen for a metabolic flow with no policies influencing the system, the striped purple blocks are the quantity of nitrogen affected by the policy BMA, the solid green lines describe the quantity of nitrogen for a 10-100% fertiliser reduction and the dashed red lines are the impact of the combined policies.
Industrial Policies

The final type of policy to be tested on the metabolic flows is the industrial policy, which can in turn be further divided into three policies: anaerobic digestion, biodiesel and co-firing. All three policies use some form of crop for the production of green energy, whilst having a positive impact on carbon emissions. These policies are included in this research as there is a large quantity of nutrients being lost from the human consumption sector. As it is difficult to change human behaviour, one way to reduce this loss is to use the waste. By using crop waste for green energy production diverts biomass going to landfill, which further reduces the methane emitted from the sector Loss. Furthermore, these policies could potential reduces the quantity of phosphorus and nitrogen being lost, as some recycle the nutrients back onto Soil.

Anaerobic digestion uses the crop waste, excluding cereal, from the sector Available for Human Consumption to produce biogas, with the waste recycled back onto Soil. The cereal crop waste on the other hand is used by co-firing, which also produces energy. The nutrients in the end product are lost as by burning the crop it has to be sent to landfill. Finally, biodiesel uses oilseed rape to produce biofuel, which can then be used as a substitute for fossil fuels, thereby reducing the carbon emissions. Figures 4.33 and 4.34 illustrate the results of the change in the quantity of phosphorus and nitrogen from various sectors based on these three policy impacts. Tables 26 and 27 list the percentage in change of the affected sectors when compared to a system with no policy impact.

It can be seen in the Figures 4.33 and 4.34 that because anaerobic digestion recycles the crops used to produce energy back onto land, there is a slight increase in nutrients in Soil and a slight decrease in the quantity of the elements being recycled through Organic Waste. The biodiesel policy does not affect the phosphorus cycle as only a small quantity of the element is used for its production which is also recycled back onto land. The quantity of nitrogen for the production of biodiesel stays in the crop remains and is used for animal feed. Because there is more nitrogen available to be fed to animals but the quantity of the element being recycled back through Manure stays constant, the additional nutrients from this policy goes to Loss. It is not clear why the quantity of nitrogen in Organic Waste and Soil increases for this policy. The final industrial policy tested is co-firing, using cereal crop to produce green energy, where the nutrients in the node Co-firing are ultimately lost, leading to a 6% increase of the quantity of nutrients in the sector Loss.

It can be seen that all three industrial policies do have a slight impact on the phosphorus and nitrogen flows, yet at the current rate used, this influence is only minimal. However, if the use of
all three methods were to suddenly be increased, drastic impacts would be expected; anaerobic digestion would potentially increase the quantity of nutrients in the Soil, which could have an impact on the environment. Co-firing might increase the quantity of nutrients lost, and biodiesel could emit more nitrogen. Therefore, although all three industrial policies reduce the quantity of carbon being emitted or are carbon neutral, it is important to think about the other side effects they could have on other metabolic flows and the environment.

<table>
<thead>
<tr>
<th>Phosphorus</th>
<th>Anaerobic Digestion</th>
<th>Biodiesel</th>
<th>Co-firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>-0</td>
<td>0</td>
<td>-0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-3</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>+0</td>
<td>0</td>
<td>+6</td>
</tr>
</tbody>
</table>

*Table 26: The percent in change of the quantity of phosphorus of sectors affected by various industrial policies in comparison to a system influenced by no policy.*

<table>
<thead>
<tr>
<th>Nitrogen</th>
<th>Anaerobic Digestion</th>
<th>Biodiesel</th>
<th>Co-firing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+3</td>
<td>167</td>
<td>0</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+16</td>
<td>-3</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>+1</td>
<td>+120</td>
<td>+81</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>+0</td>
<td>+48</td>
<td>+6</td>
</tr>
</tbody>
</table>

*Table 27: The percent in change of the quantity of nitrogen of sectors affected by various industrial policies in comparison to a system influenced by no policy.*
Figure 4.33: An overview of the quantity of phosphorus in affected sectors after 10 years. The solid green blocks are the quantity of phosphorus for a metabolic flow with no policies influencing the system, the dotted blocks are the quantity of phosphorus for the policy anaerobic digestion, the checked blocks are the quantity of the element for biodiesel policy and the tartan blocks are the quantity of nutrient impacted by policy co-firing.
Figure 4.34: An overview of the quantity of nitrogen content in affected sectors after 10 years. The solid blue blocks are the quantity of nitrogen for a metabolic flow with no policies influencing the system, the dotted blocks are the quantity of nitrogen for the policy anaerobic digestion, the checked blocks are the quantity of the element for biodiesel policy and the tartan blocks are the quantity of nutrient impacted by policy co-firing.
Finally, all three policy types are tested on the metabolic flows at the same time. Figures 4.35 and 4.36 show the change of the quantity of phosphorus and nitrogen in the affected sectors after a decade, where the solid blocks are the content of the elements for a system with no policy and the dotted line the change of the quantity of nutrients for a system impacted by all policies combined. The percentage in change between the two systems for all affected sectors is given in Tables 28 and 29.

In Figures 4.35 and 4.36 it can be see that the quantity of nutrients in Soil increases, but overall there is a decrease in the quantity of nutrients being lost. For an over 70% decline in Fertiliser the quantity of phosphorus in Organic Waste increases, therefore the system relies on humans to recycle more waste. An increase in the quantity of nitrogen in Organic Waste is first observed after an 82% reduction in Fertiliser.
Figure 4.36: An overview of the quantity of nitrogen in the affected sectors after 10 years. The solid blue blocks are the quantity of nitrogen for a metabolic flow with no policies influencing the system and the light blue dashed lines are the impact of the all policies combined.
An analysis of the impacts of the policies on the metabolic flows shows that the waste policy, which uses BMA as an additional fertiliser, reduces both quantities of nutrients lost and the quantity of Organic Waste needed, yet the quantity of nutrients in Soil increased. This could potentially have an impact on the environment through nutrients being leached or the nitrogen to react with air creating nitrogen oxides. The agricultural effect from an NVZ policy could be a suitable approach for reducing the amount of phosphorus and nitrogen lost through leaching, but it relies on a drastic increase in the recycling of Organic Waste so that human behaviour need to change. A combination of these two policies suggests that, if the quantity of Fertiliser were reduced to less than ~ 70% there would be no need to change human behaviour, while the quantity of the elements in Soil has also declined. One problem with recycling BMA back onto land is that it could potentially result in a health risk, such as the outbreak of BSE in the recent past. Therefore, if BMA were to be recycled back onto land, strict regulations and controls need

<table>
<thead>
<tr>
<th></th>
<th>All Policies Combined (10%)</th>
<th>All Policies Combined (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+50</td>
<td>+15</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-19</td>
<td>+10</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-2</td>
<td>-4</td>
</tr>
</tbody>
</table>

*Table 28: The percent in change of the quantity of phosphorus of sectors affected by all policies combined in comparison the a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.*

<table>
<thead>
<tr>
<th></th>
<th>All Policies Combined (10%)</th>
<th>All Policies Combined (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (%)</td>
<td>+103</td>
<td>+52</td>
</tr>
<tr>
<td>Human Purchase (%)</td>
<td>+0</td>
<td>+0</td>
</tr>
<tr>
<td>Organic Waste (%)</td>
<td>-41</td>
<td>+11</td>
</tr>
<tr>
<td>Loss (%)</td>
<td>-1</td>
<td>-2</td>
</tr>
</tbody>
</table>

*Table 29: The percent in change of the quantity of nitrogen of sectors affected by all policies combined in comparison the a system influenced by no policy, where NVZ(10%) indicates a 10% reduction in the amount of fertiliser applied and NVZ(100%) highlights that no inorganic fertiliser is applied to the soil.*
to be enforced.

The last type of policy to be tested is industrial, which uses the food waste from human consumption sector for the production of green energy. The main impact through the recycling of nutrients used in anaerobic digestion increases the quantity of phosphorus and nitrogen in Soil, while the impact of Co-firing led to an increase in the quantity of both nutrients stored in the node Loss. There was an increase in nitrogen being lost for the policy Biodiesel. Therefore, at the current rate, these policies only have a slight impact on the UK phosphorus and nitrogen flows. Yet, if the production of green energy were to increase, a drastic impact on the metabolic flows would be expected: anaerobic digestion would potentially increase the quantity of nutrients in Soil, which could have an impact on the environment, co-firing might increase the quantity of nutrients lost, and biodiesel could emit more nitrogen and increase the quantity of nitrogen being lost.

The combination of all policies together shows a reduction in the quantity of nutrients in the sector Loss, while there is an increase of the quantity of the elements in Soil. Increasing the quantity of nitrogen in Soil raises the chance of nitrogen reacting with air creating nitrogen oxides. Furthermore, substituting biofuels for fossil fuels reduces carbon emissions, but it also increases nitrogen emissions. Therefore, although these policies do reduce the loss of nutrients and carbon emissions, if no further policies are implemented to prevent nitrogen emissions, the problem of emitting too much carbon could shift to one of too much nitrogen being released into the atmosphere.
4.6 Conclusion

The aim of this research was to use KISS and KIDS modelling approaches to analyse the UK phosphorus and nitrogen flows and to understand how various policies in the short term impact the networks.

First, a network analysis is carried out to determine the key nodes and control nodes of the system. The key nodes are Soil, Available for Human Consumption, Animal Consumption and Loss, which are the sectors farmers depended on for centuries, i.e. crops grew from soil to feed humans and animals and the waste was recycled back onto the land. Inorganic fertiliser, import and export were then not part of the cycle. Therefore, these results reconfirm the relevance of old farming methods. Furthermore, the network analysis showed that the sector Loss is well connected within the network, highlighting that a lot of nutrients can be lost from various sectors. For an outside influence to control the system, a combination of crops, a form of input (Fertiliser, Import) and a form of loss (Export, Loss) need be influenced, therefore suggesting that it is not essential to control the sectors Available for Human Consumption and Human Purchase. This is not a realistic solution as it is known that too much food is being produced for humans to consume. But impacting this sector would rely on human behaviour to change, which would take time. Therefore, this research agrees with the results from the control node configuration, that policies aiming to close the phosphorus and nitrogen cycles should not try and change this sector. From this network analysis it was also concluded that the sectors Import and Export are not vital within the metabolic network, but are mainly driven by financial considerations. These sectors could therefore be excluded for the research in the rest of the chapter.

For the KISS approach two different models were used to analyse various aspects of the metabolic flows. The first model is based on the system to obey conservation of mass, which analysed the percentage of phosphorus and nitrogen distribution within the whole network. Again, this model highlighted that a lot of nutrients are lost within the system, yet only small quantities are recycled back onto soil. The model also suggested to reduce the quantity of nutrients lost, more Organic Waste would need to be recycled back onto soil. Furthermore, this model showed both flows to be affected by an alteration in the network, which highlights the importance of having to take any secondary impacts on another flow from one policy into account. Finally, another KISS model showed the agricultural and food sectors to lose large quantities of nutrients. From this it was concluded that policies must not just aim to recycle waste, but also need to encourage controlled agricultural practices in order to reduce the loss of elements. Although it is difficult to change the human consumption behaviour in the food sector, another policy was chosen to use the food waste to produce green energy.
A KIDS model was created, simulating the UK phosphorus and nitrogen flows and to test the impacts of three different types of policies: agricultural, industrial and waste policies. The agricultural sector was based on the idea of Nitrate Vulnerable Zones (NVZ), where the application of inorganic fertiliser was reduced by levels ranging from 10-100%. This policy showed that the quantity of phosphorus and nitrogen in Soil and Loss were both reduced, while the quantity of both elements recycled back onto the Soil through Organic Waste increased. This increase in Organic Waste relies on human behaviour changing, which is feasible, but takes time. One way to compensate for this increase is to use bone meal ash (BMA) from livestock as an organic fertiliser. This waste policy showed that the quantity of nutrients in Soil vastly increased, while Loss had a slight decrease in nutrients. A combination of both policies showed that the quantity of nutrients in Loss decreased while the quantity of phosphorus and nitrogen in Organic Waste was only slightly impacted. The last type of policy to be tested was industrial, which could be further divided into three sub-policies; anaerobic digestion, biodiesel and co-firing. Anaerobic digestion and co-firing use biomass from the sector Available for Human Consumption to produce green energy, while Oilseed Rape is used to produce biodiesel. Anaerobic digestion has minor impacts on the phosphorus and nitrogen flows, with only a slight increase in the quantity of nutrients in Soil. Biodiesel has no impact on the phosphorus flow, but as the remaining crop containing the nitrogen is used for Animal Consumption and the quantity of nutrients in Manure stayed constant, there is more nitrogen being lost from Animal Consumption. The policy encouraging co-firing uses biomass, which when burnt has to go to landfill. This increases the quantity of nutrients lost within the network. Therefore, the industrial policies currently do not have a drastic impact on the UK phosphorus and nitrogen flows, but if the production of green energy increases, changes within the metabolic flows are expected. For example a surge in anaerobic digestion could increase the quantity of nutrients in the Soil, potentially impacting on the environment, while a rise in co-firing might increase the quantity of nutrients lost, whereas biodiesel could emit more nitrogen.

By combining all policies together, the network showed in general that the loss of nutrients was reduced, while the need for human behaviour to change with respect to recycling food was minimal. Although these policies combined have a positive affect on the loss of nutrients in the system, a lot of it is stored in Soil where the nitrogen could react with air to create nitrogen oxides, thus impacting human health.

There is therefore a need for more research in alternative policies, so that not to create another problem by increasing nitrogen emissions. For example, one solution could be the promotion of bioenergy systems, as described by Skenhall et al. [141]. They suggest planting perennial plants or willows in areas where the nutrients run-off from crop land. Not only would these plants
capture the leached nutrients but would allow for the elements to reenter the metabolic flows, by for example, using the plants as energy feed stock.

This research only focuses on the UK phosphorus and nitrogen cycle and ignores the other metabolic flows such as potassium. Although potassium is vital for most living entities [43] and does follow a similar cycle to the phosphorus and nitrogen flow, it was chosen not to be included in this research as when there is a singly excess of this element there seems to be no negative impact on the environment [15, 28]. In fact, potassium seems to have a positive impact on the environment by for example reducing environmental stress factor on plants. These stress factor can be caused through water deficiency or soil acidity, thus having an impact on crop yields [28]. Although there seems to be no current policy involving potassium, this research could be extended to analyse the positive impact of potassium on crops, so that the maximum potential crop yield is achieved.

As mentioned in the introduction in the past researchers analysed only segments of the phosphorus and nitrogen flows, yet to understand the full cycles, there is a need for more descriptive models that allow for phenomenological scenario testing [39]. The KIDS model in this case study aims to address this even though some data quantities were not known. Furthermore some sectors, for example industry were excluded from this research. Therefore, the whole phosphorus and nitrogen cycles were not modelled. Yet this research has allowed to draw out important behaviours of the system, for example highlighting how all policies together may impacting the environment. Based on these results the problem of emitting too much nitrogen was highlighted. Because of this knowledge preventative measure through research and enforcing policies should be encouraged. However, this KIDS model cannot take societal changes into account, for example the demand in a certain crop varying over time. This research though could be further developed to include impacts such as societal changes including human behaviour, food demand and prices/economics, which also drive the phosphorus and nitrogen flows.

Finally, this research needs some additional analysis on the KIDS model. For example, the model fitting highlighted that the node Loss needs to be examined in more detail. This could be done by separating out this node into section such as loss from soil leaching, loss to air and landfill, where some of the nutrients going to landfill could slowly reenter the network. Another issue with the KIDS model is that in the no policy case 30 variables were used to construct the model, with only a few years of data points available. By fitting this many variables to so few data points can lead to the model being overfitted, as discussed in the introduction §1. Therefore, further research is needed focusing on the build and sensitivity analysis of this KIDS model.
5 Conclusion and Outlook

This research has shown that by using two specifically chosen modelling methodologies to analyse a real world problem can yield a clearer understanding of how behaviours drive a system.

The first methodology is the “keep it simple stupid” (KISS) approach, which builds the model in a simplified way, allowing for an easier analysis and understanding of the results. However, this methodology relies on the verification of the sometimes extremely abstract model to be based on theoretical reasoning, which can make this approach harder to justify. Although these models are a simplified version of the real world, the exclusion of all intricate behaviours can provide vital information about the general mechanism of system.

The second model applies the “keep it descriptive stupid” (KIDS) methodology. The KIDS approach builds a model by including all the intricate behaviours in a system, meaning the model is a more descriptive representation of the real world, thereby enabling a straightforward verification of the model. However, the more complicated the build is, the harder it is to analyse, update and change.

This thesis shows that, by using the KISS methodology to analyse the general mechanism of the system, vital information about the build of the descriptive model, i.e. which behaviours need to be included, can be obtained. This simplifies the process for building the second model and ensures that the general behaviour of the system is included. The KIDS model is then used to analyse the intricate behaviours that drive the system and to test hypotheses.

The first case study researches how national voting behaviour in a two-party democratic system is impacted through various influences. The KISS model analyses the historic election results of seven democratic countries to determine the chance that a leader and party will be elected, re-elected once or re-elected multiple times. The results showed that the dominant party was in power for a similar amount of time for all countries. However, two different voting behaviours were observed for the probability of a leader being re-elected; one where around 58% of leaders were re-elected while other’s only had a 26% re-election rate. This suggested that for one set of countries being in power prior to an election has a beneficial affect on voters, as leaders have a high re-election rate, whereas for others it has a negative impact, as only a few leaders were re-elected. Furthermore, the KISS model highlighted that, when analysing voting behaviour a distinction has to be made between electing a leader and party election, and that the number of years a leader has been in charge is not as significant as to how many times the leader has been elected. Finally, the information about who was in power prior to an election needs to be
included in the KIDS model.

The second model uses the KIDS methodology to simulate the election process of a democratic leader, where a distinction needs to be made between party and leadership election. Furthermore, the knowledge of who was in power prior to an election must be included in the model. In this KIDS model the voters are impacted by their own and their electoral district’s previous vote, their social neighbours’ party preference and the current leader’s reputation, which can be either successful or unsuccessful. Setting the model to simulate the same number of leaders and parties to be elected and re-elected as observed in the data, showed how these intricate impacts affect national voting behaviour. One of the results suggests that both the successful and unsuccessful reputation have a negative impact on voters, for which in some countries the impact is a lot less than in others. The suggestion made from the KISS model that for some countries being in power prior to an election has a positive impact on voters was shown to be inconsistent with the interpretation made from the KIDS model. Therefore, further research would be required to understand how the voters are impacted by leader’s reputation.

As in the previous example, the second case study showed that the use of both the KISS and KIDS models provided a clearer understanding of how various policies impact the UK phosphorus and nitrogen flows. Two KISS models were fitted to the data collected concerning the UK phosphorus and nitrogen flows. The first model showed that when policies influence one element it subsequently has an impact on the other flow. Furthermore, this model highlighted that a lot of nutrients were lost and that not much phosphorus and nitrogen were recycled back onto the soil through manure and organic waste. The second KISS model analysed where the greatest loss occurred within the network. Based on these results policies aiming to reduce the quantity of phosphorus and nitrogen to be lost were determined. These policies were then included in the KIDS model.

The KIDS model simulated the UK metabolic flows where policies aim to reduce the quantity of phosphorus and nitrogen to be lost within the system. By testing the policies first on their own and then in conjunction with each other showed if these influences enhance or diminishes the aim of the policies.

Even though researchers have distinguished between the KISS and KIDS modelling methodologies, when analysing the two case studies, it was observed that there was a need for more KIDS models in those particular areas. One reason why researchers may not have used the KIDS approach is because it is more difficult to construct and to analyse the results. The over complication of the build of the KIDS model was made in the second case study, where the original
idea was to use chemical kinetics to simulate the metabolic flows, as this would guarantee the coupling of the phosphorus and nitrogen flows. This would have involved the fitting of around 100 parameters, which for the small amount of data available made for a difficult task. However, the KISS model tested the same influence on both flows independently from one another, showing that they both changed in a similar way. Had this result of the KISS model been considered more carefully, it would have avoided the efforts of trying to create a too complicated KIDS model.

Although this research has shown that the KISS model can simplify the build of the KIDS model, it should be emphasized that the build of the simplistic model needs to be carefully considered, as does the determination of which results are to be included in the KIDS model. If the KISS model does not analyse the general mechanism of the system, then the inclusion of these results in the KIDS approach could lead to a misunderstanding of how the intricate behaviours alter the system.

Finally, this research has only considered for the KISS methodology to provide information on what to include in the KIDS model. Based on this approach the build of the KIDS model was simplified, as not all behaviours in a system had to be included. An analysis of the KIDS model provided an understanding on how various intricate behaviours impacted the whole system. When forecasting the behaviour of the system into the future could lead to the change in the results to be harder to understand due to various impacts of the intricate behaviours. An alternative approach could be to build the KIDS model first so that the intricate behaviours within the system are understood. These behaviours are then represented in the KISS model in a simplistic way, i.e. the detailed impact of these behaviours within the system are not included. All the intricate behaviours within the system are separately analysed in a KIDS model so that their impacts on historic data and how they will change in the following time period can be understood. Instead of having all the detailed analysis in the KISS model only the general behaviour of intricate behaviours are included, where their strength of impact and how they will change in the future are determined from the descriptive model. This avoids an overfitting of the KISS model, i.e. the noise in the data is not represented in the results, therefore allowing for the KISS model to simulate the general behaviour of the system. This then allows for the KISS model to forecast the overall behaviour of the system. Therefore, this approach may be a more suitable method when trying to forecast the behaviour of the system.
Appendices

A. Appendix for: Introduction

This research focuses on using the KISS and KIDS methodology to analyse real world problems, where two types of models are used: uni- and multi-level models. The name “uni-” and “multi-level” are applied as the term “level” describes the organisational hierarchical structure.

The KISS methodology uses uni-level model, which focus on one level of a system, thus ignoring any hierarchical structure. Therefore, the whole system’s behaviour is analysed. There are various types of uni-level models. For example, a Markov model is a uni-level model as it investigates the probability of a system to be in a specific state at a certain point in time. Analysing this higher level behaviour of a system ignores the behaviours in the lower level, which impact the system to be in a specific state. To understand why a system changes its state and how lower level behaviours are affected by other influences, a model based on the KIDS approach is needed.

For this research the KIDS methodology uses multi-level models to analyse the micro and macro behaviour of a system. Multi-level models consist of at least two levels where entities, each with their own characteristic or behaviour, are present in the micro level and are nested within contexts (also known as groups) in a macro level. There are at least two contexts in each higher level, whereby the nesting within a specific context influences the entity’s behaviour. A classic example of a multi-level model is the analysis of a school’s performance, as the pupils are nested within a school, and schools can be clustered in different educational authorities. If the impact of a new teaching method is to be tested, which only a few schools have adapted, a multi-level model would be needed, as the exam results, highlighting the impact of the new teaching method based on the student’s progress, are measured at the pupil’s level [72]. As the micro and macro level behaviours are included in the multi-level models, therefore allowing the intricate behaviours in a system to be analyse, classifies this approach to be based on the KIDS methodology.

It is noted that different types of models could have been used for this research; for example, agent based models which are a classic example of a KIDS approach. Multi-level models were chosen as, in the past, the mathematical approach is to adapt the ordinary Least-squares regression model to include contexts, thus obtaining variances within and between contexts [6,50,99,106,142,156]. This method relies on creating the model based on data, and are commonly used for predictive purposes rather than being a more detailed descriptive model of the system trying to understand current behaviour. This research employs an alternative approach to create multi-level models,
which includes the important behaviours within and between contexts, and then to validate it against the data. The use of this approach would make it difficult, if not impossible, to describe the whole multi-level model as a mathematical equation, but does however provide a more descriptive approach.

There are some problems with the use of multi-level models. Aggregation occurs when information or behaviours on one level are grouped together and presented as an impact at another level, e.g. assuming that the behaviour of pupils represents a school’s behaviour. Disaggregation is the separation of behaviour on one level into various behaviours at a lower level. If a single behaviour is assigned to the wrong level, then it is a misspecification. An example of this is, if a company is not performing well, which is a macro level behaviour, this does not mean the workers, in the micro level, are bad workers. Aggregation bias occurs when researchers misinterpret behaviour based on an analysis of empirical data. Finally, there are ecological fallacies, which are errors arising from the interpretation of individual behaviour based on the analysis of extrapolated data. These mistakes can be divided into two categories: cross-level and contextual fallacies. Cross-level fallacies occur when individual behaviours are used to come to conclusions about macro level behaviours, whereas contextual fallacies are failures to identify the behaviours between entities at the micro level [135]. Therefore, when creating multi-level models it is important to have a clear understanding of the individual behaviours for each level.

Uni- and multi-level model in the first case study

In the first case study analysing the political voting behaviour, the KISS methodology uses a Markov model to analyse the election statistic. As mentioned earlier, Markov models are unilevel as they only consider the macroscopic behaviour of the system, in this case the re-election rate of a leader and political party. What influenced the leaders or parties to change state, i.e. voter behaviour, is not included in this model.

The KIDS model simulates the election process of a political leader, where voters are influenced by their own and their electoral district’s previous vote, their social neighbours’ party preference and the leader’s reputation. As the voters are influenced by their electoral district’s previous vote, results in electoral districts being bias towards one party. Although only the impacts of the social neighbours’ party preference and leaders’ reputation are investigated, by including the influence of electoral district’s previous vote on individual defines this model to be multi-level.
Uni- and multi-level model in the second case study

The second case study analyses the UK phosphorus and nitrogen flows. Two KISS models are created, one analysing the distribution of the elements within the system over the past decade and the other investigates from where the loss occurs within the network. As both KISS models only consider metabolic flows and ignore how influences such as policies or human behaviour can impact the system, leads to both models being uni-level.

The last model built for this case study simulates the metabolic flows and analyses how various policies impact on the system. As the policies impact the flows at various stages, i.e. either influence the agricultural, industrial or waste sector, this model is classified as being multi-level. By testing multiple policies together highlights how these impacts alter the metabolic flows.
B. Appendix for: Political Voting Behaviour

This chapter in the appendix describes the general layout of a democratic voting system and lists the election history outcomes of the seven countries analysed in Chapter 3.

This Appendix section is laid out as follows:

A basic structure of a democratic government is described in § B.1. In §B.2. - B.8. an overview of the governments and their election results are given for Australia, Canada, Republic of Ireland, New Zealand, UK, France and the USA. As this research analyses the government as a two party system, a subjective classification of the parties being left or right wing is given. The election results naming the elected leader and their affiliation with one of the parties are listed. Here “-” denotes the Prime Minister’s party being left wing, whereas “+” indicates their party affiliation to be right wing. The column “if elected” describes if the leader had been elected into power, whereas the numbers in the column “re-elected” describes how many times a leader has been re-elected. The election results were collected up until 2011, where the leader in that year was not included in the election statistics.

B.1. Democratic Government

The underlying structure of the democratic government in the seven countries analysed in this research is devised into three separate powers: the legislative, the executive and the judiciary. In Figure B.1 a basic structure of the government build is visualised, where the arrows indicate the government’s position being elected from various sectors [44,82].

The legislative can be further sub-divided, the main sectors being the upper and lower houses of parliament. Each country is divided into electoral districts; usually each district consists of approximately the same number of voters, where each electoral district elects a member for the lower house. These general elections are held at different time intervals for each country. As these electoral districts are created according to the number of voters, the larger areas such as counties, states, territories, provinces etc., consists of more electoral districts, leading to their areas to have more representatives in the lower house. The method of selecting members for the upper house differs for each country.

The executive can also be divided into different sections, the main ones being the Head of State and the Executive Council. For the Commonwealth countries, the Head of State is the Head of the Commonwealth, who currently is Queen Elizabeth II. The Executive Council consists of
the Prime Minister, Deputy Prime Minister and the Ministers. Each political party votes for
their own party leader, where the leader of the party with a majority representation in the lower
house, is selected as Prime Minister. The Prime Minister chooses the Deputy Prime Minister and
the Ministers.

The final unit of power in the government is the judiciary, which interprets the laws of the of
the country. This government power is not represented in Chapter 3, as this research does not
include any law.

*Figure B.1: An overview of the basic structure of a democratic government.*
B.2. Australia

Australia is a federal constitutional monarchy under a parliamentary democracy, which was established by the Australian constitution in 1900, and came to power on the 1 January 1901. It is a multi-party system, but there are two dominating parties: the labour and liberal party [87–90,114,119].

Legislative Power

There are 150 members of the House of Representatives (lower house), each being elected by the voters in every electorate (electoral districts). The elections are based on full preference voting, i.e. each voter ranks the candidates, and the person with the overall highest rank wins the election.

There are six states and two mainland territories, where the states can put forward 12 senators and the Northern Territory and the Australian Capital Territory have two senators each, forming the Senate (upper house) with 76 members. These members are selected based on the proportional vote from the state elections and they serve a six year term in the Senate. A general election for approximately half of the Senate is held at least every three years, but it is often within a shorter time period.

Executive Power

The Head of State is the Head of the Commonwealth, which is currently held by Queen Elizabeth II.

The Executive Council consists of the Governor General, the Prime Minister, and Ministers of State. The Prime Minister is determined by the Legislative Power. The Governor General is appointed by the Head of State on the advice of the Prime Minister. The Ministers, who are given the title “The Honourable” for life, are chosen by the Prime Minister.

Table 30 lists all of the political parties in Australia and their subjectively classification of being left or right wing. In Table 31 an overview of the past Prime Minsters of Australia, if and how often they were elected, and if they had left or right wing political views is shown.
Table 30: Listed are all of the political parties that have been elected in Australia which have subjectively been labelled to be left or right wing.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>Liberal</td>
</tr>
<tr>
<td>Green</td>
<td>National</td>
</tr>
<tr>
<td></td>
<td>Democratic Labour</td>
</tr>
<tr>
<td></td>
<td>Katter’s Australian</td>
</tr>
<tr>
<td></td>
<td>Protectionist</td>
</tr>
<tr>
<td></td>
<td>Free trade</td>
</tr>
<tr>
<td></td>
<td>Commonwealth Liberals</td>
</tr>
<tr>
<td></td>
<td>Country</td>
</tr>
<tr>
<td></td>
<td>United Australia</td>
</tr>
<tr>
<td>Number PM</td>
<td>Term of office</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>1</td>
<td>1901 - 1903</td>
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<td>2</td>
<td>1903 - 1904</td>
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<td>1904 - 1904</td>
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<td>1904 - 1905</td>
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<td>1905 - 1908</td>
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<td>1910 - 1913</td>
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<td>1913 - 1914</td>
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<td>1941 - 1941</td>
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<td>19</td>
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<td>1967 - 1968</td>
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<td>24</td>
<td>1968 - 1971</td>
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<td>25</td>
<td>1971 - 1972</td>
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<td>27</td>
<td>1975 - 1983</td>
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<td>28</td>
<td>1983 - 1991</td>
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<td>1991 - 1996</td>
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<td>30</td>
<td>1996 - 2007</td>
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<td>31</td>
<td>2007 - 2010</td>
</tr>
<tr>
<td>32</td>
<td>2010 - Present</td>
</tr>
</tbody>
</table>

Table 31: Listed are all the Prime Ministers of Australia, if and how many times they were elected, and if they were “-” left or “+” right wing.
Summary of Australia’s election results

Total number of leaders: 26, of which 16 were right wing and 10 left wing. (Billy Hughes changed his political views over the years, but for the majority he served as a right wing Prime Minister, therefore for this research he is considered to be right wing.)

Total years of independence: 109, of which 73 years were led by a right wing Prime Minister and 36 years by a left wing Prime Minister.

Total number of elections: 41

Total re-elected Prime Ministers: 21, of which 17 were right wing and 4 left wing.
B.3. Canada

Canada is a federal parliamentary democracy within a constitutional monarchy, which was based on the UK political party system. Although it is a multi-party system, there are two dominant parties: the liberal and liberal-conservative party [19, 115].

Legislative Power

Every Canadian votes for a candidate to represent their electoral district, where the candidate with the most votes becomes an MP of the House of Commons (the lower house), of which there are 308 in total.

There are 105 Senate (upper house) members who can remain there until the age 75. Each member is appointed by the Governor General, who in turn is advised by the Prime Minister.

Executive Power

The Monarch (the Head of State) is currently Queen Elizabeth II.

The Head of Government is the Prime Minister, who is elected in the Legislative Power. The Cabinet consists of around 30 Ministers, each chosen by the Prime Minister. The Governor General, who is in charge of the Cabinet, is appointed by the Monarch on the advice of the Prime Minister.

Table 32 lists all of the political parties in Canada and their subjective classification of being left or right wing. In Table 33 an overview of the past Prime Ministers of Canada, if and how often they were elected, and if they had left or right wing political views is shown.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liberal</td>
<td>Liberal-Conservative</td>
</tr>
<tr>
<td></td>
<td>Conservative (historical)</td>
</tr>
<tr>
<td></td>
<td>National Liberal and Conservative</td>
</tr>
<tr>
<td></td>
<td>Progressive Conservative</td>
</tr>
<tr>
<td></td>
<td>Conservative</td>
</tr>
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</table>

Table 32: Listed are all of the political parties that have been elected in Canada which have subjectively been labelled to be left or right wing.
<table>
<thead>
<tr>
<th>Number PM</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1867 - 1873</td>
<td>Sir John A. Macdonald</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>2</td>
<td>1873 - 1878</td>
<td>Alexander Mackenzie</td>
<td>-</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(1)</td>
<td>1878 - 1891</td>
<td>Sir John A. Macdonald</td>
<td>+</td>
<td>elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>3</td>
<td>1891 - 1892</td>
<td>Sir John Abbott</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1892 - 1894</td>
<td>Sir John Thompson</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1894 - 1896</td>
<td>Sir Mackenzie Bowell</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1896 - 1896</td>
<td>Sir Charles Tupper</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1896 - 1911</td>
<td>Sir Wilfrid Laurier</td>
<td>-</td>
<td>elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>8</td>
<td>1911 - 1920</td>
<td>Sir Robert Borden</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>9</td>
<td>1920 - 1921</td>
<td>Arthur Meighen</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1921 - 1926</td>
<td>William Lyon</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(9)</td>
<td>1926 - 1926</td>
<td>Arthur Meighen</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td>(10)</td>
<td>1926 - 1930</td>
<td>William Lyon</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Mackenzie King</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arthur Meighen</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1930 - 1935</td>
<td>Richard Bedford</td>
<td>+</td>
<td>elected</td>
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<tr>
<td></td>
<td></td>
<td>Bennett</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10)</td>
<td>1935 - 1948</td>
<td>William Lyon</td>
<td>-</td>
<td>elected</td>
<td>re-elected 2</td>
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<tr>
<td></td>
<td></td>
<td>Mackenzie King</td>
<td></td>
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<tr>
<td>12</td>
<td>1948 - 1957</td>
<td>Louis St. Laurent</td>
<td>-</td>
<td></td>
<td>re-elected 2</td>
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<tr>
<td>13</td>
<td>1957 - 1963</td>
<td>John Diefenbaker</td>
<td>+</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
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<td>1963 - 1968</td>
<td>Lester B. Pearson</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
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<td>15</td>
<td>1968 - 1979</td>
<td>Pierre Trudeau</td>
<td>-</td>
<td>re-elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>16</td>
<td>1979 - 1980</td>
<td>Joe Clark</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(15)</td>
<td>1980 - 1984</td>
<td>Pierre Trudeau</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1984 - 1984</td>
<td>John Turner</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1984 - 1993</td>
<td>Brian Mulroney</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>19</td>
<td>1993 - 1993</td>
<td>Kim Campbell</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1993 - 2003</td>
<td>Jean Chretien</td>
<td>-</td>
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</tr>
<tr>
<td>21</td>
<td>2003 - 2006</td>
<td>Paul Martin</td>
<td>-</td>
<td>re-elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>22</td>
<td>2006 - Present</td>
<td>Stephen Harper</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
</tbody>
</table>

Table 33: Listed are all the Prime Ministers of Canada, if and how many times they were elected, and if they were “-” left or “+” right wing.
Summary of Canada’s election results

Total number of leaders: 21, of which 12 were right wing and 9 left wing.

Total years of independence: 139, of which 55 years were led by a right wing Prime Minister and 84 years by a left wing leader.

Total number of elections: 38

Total re-elected Prime Ministers: 24, of which 8 were right wing, and 16 left wing.
B.4. Republic of Ireland

The Republic of Ireland is a parliamentary, representative democratic republic. Although the Republic of Ireland was an original member of the Commonwealth, it left the Commonwealth in 1949 under the Republic of Ireland act [40, 117]. The political system in the Republic of Ireland is based on that of the other original Commonwealth countries.

Legislative Power

The legislative power, also known as the Oireachtas, consists of the House of Representatives (Dail Eireann, the lower house), the Senate (Seanad Eireann, the upper house) and the President of Ireland.

The House of Representatives has 166 members, who are known as a teachna dala or in short TD. The TDs are voted into the House of Representatives by the public and have to be re-elected by the public at least once every five years. Every electoral district elects between three and five TDs.

The Senate consists of various appointed members; 11 members are appointed by the Prime Minister, 6 are elected by graduates of certain Irish universities and 43 elected by five different special panels.

A candidate for the presidency has to be nominated by at least 20 TDs. The President is then elected by a secret ballot.

Executive Power

The executive power consists of the cabinet Ministers, the Prime Minister (Taoiseach) and the Deputy Prime Minister (Tanaiste).

The cabinet, also known as the Government, has to consist of between 5 and 13 Ministers. The President elects the Ministers on the advice of the Prime Minister.

Immediately following the elections for the House of Representatives, the President appoints the leader of the political party representing the majority in the House of Representatives as Prime Minister.

Table 34 lists all of the political parties in the Republic of Ireland and their subjective classification of being left or right wing. In Table 35 an overview of the past Prime Ministers of Republic
of Ireland, if and how often they were elected, and if they had left or right wing political views is shown.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fianna Fáil</td>
<td>Cumann na nGaedheal</td>
</tr>
<tr>
<td>Labour</td>
<td>Fine Gael</td>
</tr>
<tr>
<td></td>
<td>Progressive Democrats</td>
</tr>
</tbody>
</table>

*Table 34: Listed are all of the political parties that have been elected in the Republic of Ireland which have subjectively been labelled to be left or right wing.*
Table 35: Listed are all the Prime Ministers of the Republic of Ireland, if and how many times they were elected, and if they were “-” left or “+” right wing.

<table>
<thead>
<tr>
<th>Number PM</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1922 - 1932</td>
<td>W. T. Cosgrave</td>
<td>+</td>
<td>elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>2</td>
<td>1932 - 1948</td>
<td>Eamon de Valera</td>
<td>-</td>
<td>elected</td>
<td>re-elected 5</td>
</tr>
<tr>
<td>3</td>
<td>1948 - 1951</td>
<td>John A. Costello</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>1951 - 1954</td>
<td>Eamon de Valera</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>1954 - 1957</td>
<td>John A. Costello</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>1957 - 1959</td>
<td>Eamon de Valera</td>
<td>-</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>4</td>
<td>1959 - 1966</td>
<td>Sean Lemass</td>
<td>-</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>5</td>
<td>1966 - 1973</td>
<td>Jack Lynch</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1973 - 1977</td>
<td>Liam Cosgrave</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(5)</td>
<td>1977 - 1979</td>
<td>Jack Lynch</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1979 - 1981</td>
<td>Charles Haughey</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1981 - 1982</td>
<td>Garret FitzGerald</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(7)</td>
<td>1982 - 1982</td>
<td>Charles Haughey</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(8)</td>
<td>1982 - 1987</td>
<td>Garret FitzGerald</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(7)</td>
<td>1987 - 1992</td>
<td>Charles Haughey</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>9</td>
<td>1992 - 1994</td>
<td>Albert Reynolds</td>
<td>-</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>10</td>
<td>1994 - 1997</td>
<td>John Bruton</td>
<td>+</td>
<td></td>
<td>re-elected 2</td>
</tr>
<tr>
<td>11</td>
<td>1997 - 2008</td>
<td>Bertie Ahern</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2008 - 2011</td>
<td>Brian Cowen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2011- Present</td>
<td>Enda Kenny</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
</tbody>
</table>
Summary of Ireland’s election results

Total number of leaders: 12, of which 5 were right wing and 7 left wing.

Total years of independence: 89, of which 29 years were led by a right wing Prime Minister and 60 years led by a left wing Prime Minister.

Total number of elections: 28

Total re-elected Prime Ministers: 15, of which 3 were right wing and 12 left wing.
B.5. New Zealand

New Zealand is a parliamentary representative democratic monarchy. It first formed a government in 1807 and was allowed to self-govern in 1853, although then the government consisted of no political parties. It was not until 1891 when there were two opposing parties standing for election, therefore Table 37 lists only the elections from this election forth [109,122].

Legislative power

The main body of the legislative power is the House of Representatives (lower house), which consists of 120 members elected during a general election.

The Senate (upper house) consists of 32 members, all of which are appointed by the various political party leaders. Every senator serves a three year term.

Executive power

The executive power consists of the Head of State, the Governor General, the Prime Minister and the Cabinet.

The Head of State is the Head of the Commonwealth, currently Queen Elizabeth II.

The Head of Government is the Prime Minister, who is the leader of the political party representing the majority in the House of Representatives.

The Governor General is the head of the Cabinet, who is appointed by the Head of State on the advice of the Prime Minister. The Governor General in turn appoints the members of the Cabinet on the advice of the Prime Minister.

Table 36 lists all of the political parties in New Zealand and their subjective classification of being left or right wing. In Table 37 an overview of the past Prime Ministers of New Zealand, if and how often they were elected, and if they had left or right wing political views is shown.
Table 36: Listed are all of the political parties that have been elected in New Zealand which have subjectively been labelled to be left or right wing.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labour</td>
<td>Reform</td>
</tr>
<tr>
<td></td>
<td>National</td>
</tr>
<tr>
<td></td>
<td>Liberal</td>
</tr>
<tr>
<td></td>
<td>United</td>
</tr>
</tbody>
</table>
Table 37: Listed are all the Prime Ministers of New Zealand, if and how many times they were elected, and if they were “-” left or “+” right wing.

<table>
<thead>
<tr>
<th>Number PM</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1891 - 1893</td>
<td>John Ballance</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1893 - 1906</td>
<td>Richard Seddon</td>
<td>+</td>
<td></td>
<td>re-elected 6</td>
</tr>
<tr>
<td>3</td>
<td>1906 - 1906</td>
<td>William Hall-Jones</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1906 - 1912</td>
<td>Joseph Ward</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>5</td>
<td>1912 - 1912</td>
<td>Thomas Mackenzie</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1912 - 1925</td>
<td>William Massey</td>
<td>+</td>
<td>elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>7</td>
<td>1925 - 1925</td>
<td>Francis Bell</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1925 - 1928</td>
<td>Gordon Coates</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(4)</td>
<td>1928 - 1930</td>
<td>Joseph Ward</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1930 - 1935</td>
<td>George Forbes</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>10</td>
<td>1935 - 1940</td>
<td>Michael Joseph Savage</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>11</td>
<td>1940 - 1949</td>
<td>Peter Fraser</td>
<td>-</td>
<td></td>
<td>re-elected 2</td>
</tr>
<tr>
<td>12</td>
<td>1949 - 1957</td>
<td>Sidney Holland</td>
<td>+</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>13</td>
<td>1957 - 1957</td>
<td>Keith Holyoake</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1957 - 1960</td>
<td>Walter Nash</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(13)</td>
<td>1960 - 1972</td>
<td>Keith Holyoake</td>
<td>+</td>
<td>elected</td>
<td>re-elected 3</td>
</tr>
<tr>
<td>15</td>
<td>1972 - 1972</td>
<td>Jack Marshall</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1972 - 1974</td>
<td>Norman Kirk</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>Stand in</td>
<td>Prime Minister</td>
<td>Hugh Watt</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1974 - 1975</td>
<td>Bill Rowling</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1975 - 1984</td>
<td>Robert Muldoon</td>
<td>+</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>19</td>
<td>1984 - 1989</td>
<td>David Lange</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>20</td>
<td>1989 - 1990</td>
<td>Geoffrey Palmer</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1990 - 1990</td>
<td>Mike Moore</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1990 - 1997</td>
<td>Jim Bolger</td>
<td>+</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>23</td>
<td>1997 - 1999</td>
<td>Jenny Shipley</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1999 - 2008</td>
<td>Helen Clark</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>25</td>
<td>2008 - Present</td>
<td>John Key</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
</tbody>
</table>
Summary of New Zealand’s election results

Total number of leaders: 24, of which 15 were right wing and 9 left wing.

Total years of independence: 117, of which 82 years were led by a right wing Prime Minister and 35 years led by a left wing leader.

Total number of elections: 39

Total re-elected Prime Ministers: 26, of which 21 were right wing and 5 left wing.
B.6. United Kingdom

The United Kingdom is a constitutional monarchy, meaning the Monarch is the Head of State and the Prime Minister is head of the Government [54, 96, 120, 124].

Legislative Power

The legislative power, also known as Parliament, can be further divided into three components: the Sovereign, the House of Lords (upper house), and the House of Commons (lower house).

The current Sovereign of the United Kingdom is Queen Elizabeth II.

The House of Lords consists of the Lords Spiritual and the Lords Temporal. The Lords Spiritual are the senior bishops of the Church of England whereas the Lords Temporal used to consist of hereditary and life peers and the Law Lords. The reform of the House of Lords in 1999 ensured that the majority of Lords Temporal were life peers, with only 92 hereditary peers, 90 of whom are elected by other peers. (The two exceptions are the Earl Marshal and the Lord Great Chamberlain).

The Law Lords ceased to sit in the House of Lords following the creation of the Supreme Court in 2009. The life peers are appointed by the Monarch on advice from the Prime Minister.

The House of Commons currently consists of 650 MPs, all of whom have been elected by the public. The current voting system is majority vote, i.e. the candidate with the most votes wins.

Executive Power

The executive power, also known as the Government, consists of the Prime Minister, the Cabinet, and the Government Departments and Civil Service. The Prime Minister is the leader of the political party representing the majority in the House of Commons. The Cabinet consists of MPs chosen by the Prime Minister.

The members of the Government Departments and Civil Service deal with the bureaucracy.

Table 38 lists all of the political parties in the UK and their subjective classification of being left or right wing. In Table 39 an overview of the past Prime Ministers of the UK, if and how often they were elected, and if they had left or right wing political views is shown.
Table 38: Listed are all of the political parties that have been elected in the UK which have subjectively been labelled to be left or right wing.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whig</td>
<td>Tory</td>
</tr>
<tr>
<td>Labour</td>
<td>Peelite</td>
</tr>
<tr>
<td>Liberal</td>
<td>Conservative</td>
</tr>
<tr>
<td>National Labour</td>
<td></td>
</tr>
<tr>
<td>Number PM</td>
<td>Term of office</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>1</td>
<td>1801 - 1804</td>
</tr>
<tr>
<td>2</td>
<td>1804 - 1806</td>
</tr>
<tr>
<td>3</td>
<td>1806 - 1807</td>
</tr>
<tr>
<td>4</td>
<td>1807 - 1809</td>
</tr>
<tr>
<td>5</td>
<td>1809 - 1812</td>
</tr>
<tr>
<td>6</td>
<td>1812 - 1827</td>
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<td>1828 - 1830</td>
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<td>1830 - 1834</td>
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<tr>
<td>11</td>
<td>1834 - 1834</td>
</tr>
<tr>
<td>(9)</td>
<td>1834 - 1834</td>
</tr>
<tr>
<td>12</td>
<td>1834 - 1835</td>
</tr>
<tr>
<td>(11)</td>
<td>1835 - 1841</td>
</tr>
<tr>
<td>(12)</td>
<td>1841 - 1846</td>
</tr>
<tr>
<td>13</td>
<td>1846 - 1852</td>
</tr>
<tr>
<td>14</td>
<td>1852 - 1852</td>
</tr>
<tr>
<td>15</td>
<td>1852 - 1855</td>
</tr>
<tr>
<td>16</td>
<td>1855 - 1858</td>
</tr>
<tr>
<td>(15)</td>
<td>1858 - 1859</td>
</tr>
<tr>
<td>(16)</td>
<td>1859 - 1865</td>
</tr>
<tr>
<td>(13)</td>
<td>1865 - 1866</td>
</tr>
<tr>
<td>(14)</td>
<td>1866 - 1868</td>
</tr>
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<td>17</td>
<td>1868 - 1868</td>
</tr>
<tr>
<td>18</td>
<td>1868 - 1874</td>
</tr>
<tr>
<td>(17)</td>
<td>1874 - 1880</td>
</tr>
<tr>
<td>(18)</td>
<td>1880 - 1885</td>
</tr>
<tr>
<td>19</td>
<td>1885 - 1886</td>
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<tr>
<td>(18)</td>
<td>1886 - 1886</td>
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<td>(19)</td>
<td>1886 - 1892</td>
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<td>(18)</td>
<td>1892 - 1894</td>
</tr>
<tr>
<td>20</td>
<td>1894 - 1895</td>
</tr>
</tbody>
</table>
Table 39: Listed are all the Prime Ministers of the UK, if and how many times they were elected, and if they were “-” left or “+” right wing.

<table>
<thead>
<tr>
<th>Number PM</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>(19)</td>
<td>1895 - 1902</td>
<td>3rd Marquess of Salisbury</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>21</td>
<td>1902 - 1905</td>
<td>Arthur Balfour</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1905 - 1908</td>
<td>Sir Henry Campbell-Bannerman</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>1908 - 1916</td>
<td>Herbert Henry Asquith</td>
<td>-</td>
<td></td>
<td>re-elected 2</td>
</tr>
<tr>
<td>24</td>
<td>1916 - 1922</td>
<td>David Lloyd George</td>
<td>-</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>25</td>
<td>1922 - 1923</td>
<td>Andrew Bonar Law</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>1923 - 1924</td>
<td>Stanley Baldwin</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>1924 - 1924</td>
<td>Ramsey MacDonald</td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(26)</td>
<td>1924 - 1929</td>
<td>Stanley Baldwin</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(27)</td>
<td>1929 - 1935</td>
<td>Ramsey MacDonald</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(26)</td>
<td>1935 - 1937</td>
<td>Stanley Baldwin</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>1937 - 1940</td>
<td>Neville Chamberlain</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>1940 - 1945</td>
<td>Winston Churchill</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1945 - 1951</td>
<td>Clement Attlee</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>(29)</td>
<td>1951 - 1955</td>
<td>Winston Churchill</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>1955- 1957</td>
<td>Sir Anthony Eden</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>32</td>
<td>1957 - 1963</td>
<td>Harold Macmillan</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>33</td>
<td>1963 - 1964</td>
<td>Sir Alec Douglas-Home</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>1964 - 1970</td>
<td>Harold Wilson</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>35</td>
<td>1970 - 1974</td>
<td>Edward Heath</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>(34)</td>
<td>1974 - 1976</td>
<td>Harold Wilson</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
</tr>
<tr>
<td>36</td>
<td>1976 - 1979</td>
<td>James Callaghan</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>1979 - 1990</td>
<td>Margaret Thatcher</td>
<td>+</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>38</td>
<td>1990 - 1997</td>
<td>John Major</td>
<td>+</td>
<td></td>
<td>re-elected 1</td>
</tr>
<tr>
<td>39</td>
<td>1997 - 2007</td>
<td>Tony Blair</td>
<td>-</td>
<td>elected</td>
<td>re-elected 2</td>
</tr>
<tr>
<td>40</td>
<td>2007 - 2010</td>
<td>Gordon Brown</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>2010 - Present</td>
<td>David Cameron</td>
<td>+</td>
<td>elected</td>
<td></td>
</tr>
</tbody>
</table>
Summary of UK’s election results

Total number of leaders: 40, of which 24 were right wing and 16 left wing

Total years of democracy: 209, 115 years were led by a right wing Prime Minister and 94 years led by a left wing leader

Total number of elections: 53

Total re-elected Prime Ministers: 25, of which 13 were right wing and 12 left wing.
B.7. France

After the French revolution, which begun in 1789 and was followed by a reign of terror, the first presidential election was held in 1848, electing Louise-Napoléon Bonaparte to be the first President of France. There have been four republics in the history of France, with all of them collapsing, and since 1958 the government is based on the French Fifth Republic. During the second World War France was invaded by the Germans, leading between 1940 and 1947 the Presidents being chairmen of the Provisional Government and, therefore, this period is excluded from this research [63,145].

Legislative power

The National Assembly (lower house) consists of 577 members, known as députés, are elected from their electoral district and serve a five year term. The tradition of sitting the left wing parties to the left of the President’s view and the right wing parties to his right in an assembly started in the French Revolution, which is where the terms “left” and “right” wing originated from.

The Senate (upper house) currently consists of 348 members, each serving a term of six years. Before 2011 only 321 members were elected, all serving a nine year term.

Executive power

The executive branch consists of the President, Prime Minister, Ministers, Ministers-Delicate and Secretaries.

The President, who is Head of State, is elected through the majority vote and is in power for 5 years. Before 2000 the presidency term was 7 years.

The Prime Minister is appointed by the President.

Table 40 lists all of the political parties in the UK and their subjective classification of being left or right wing. In Table 41 an overview of the past Prime Ministers of the UK, if and how often they were elected, and if they had left or right wing political views is shown.
<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radical</td>
<td>Independent</td>
</tr>
<tr>
<td>Republican (AD and predecessors)</td>
<td>Independent (moderate Republican)</td>
</tr>
<tr>
<td>Socialist (SFIO)</td>
<td>Monarchist (Legitimist)</td>
</tr>
<tr>
<td>Socialist (PS)</td>
<td>Centre-right (CNIP)</td>
</tr>
<tr>
<td>Centrist (CD)</td>
<td>Gaullist (UNR; UDR; RPR)</td>
</tr>
<tr>
<td>Republican (UDF)</td>
<td>Liberal Gaullist (UMP)</td>
</tr>
</tbody>
</table>

*Table 40: Listed are all of the political parties that have been elected in France which have subjectively been labelled to be left or right wing.*
<table>
<thead>
<tr>
<th>Number</th>
<th>President</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Louise-Napoléon</td>
<td>1848 - 1852</td>
<td>Bonaparte</td>
<td></td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Adolphe Thiers</td>
<td>1871 - 1873</td>
<td>+ elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Patrice de Mac-Mahon</td>
<td>1873 - 1879</td>
<td>+ elected</td>
<td>re-elected 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Jules Grévy</td>
<td>1879 - 1887</td>
<td>- elected</td>
<td>re-elected 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Marie François</td>
<td>1887 - 1894</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Jean Casimir-Perier</td>
<td>1894 - 1895</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Félix Faure</td>
<td>1895 - 1899</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Émile Loubet</td>
<td>1899 - 1906</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Armand Fallières</td>
<td>1906 - 1913</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Raymond Poincaré</td>
<td>1913 - 1920</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Paul Deschanel</td>
<td>1920 - 1920</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Alexandre Millerand</td>
<td>1920 - 1924</td>
<td>+ elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Gaston Doumergue</td>
<td>1924 - 1931</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Paul Doumer</td>
<td>1931 - 1932</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Albert Lebrun</td>
<td>1932 - 1940</td>
<td>+ elected</td>
<td>re-elected 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Charles de Gaulle</td>
<td>1944- 1946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Félix Gouin</td>
<td>1946 - 1946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Georges Bidault</td>
<td>1946 - 1946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vincent Auriol</td>
<td>1946 - 1946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Léon Blum</td>
<td>1946 - 1947</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Vincent Auriol</td>
<td>1947 - 1954</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>René Coty</td>
<td>1954 - 1959</td>
<td>+ elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Charles de Gaulle</td>
<td>1959 - 1969</td>
<td>+ elected</td>
<td>re-elected 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Alain Poher</td>
<td>1969 - 1969</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Georges Pompidou</td>
<td>1969 - 1974</td>
<td>- elected</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alain Poher</td>
<td>1969 - 1969</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Years</td>
<td>President</td>
<td>Side</td>
<td>Re-elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-------------</td>
<td>-------------------------</td>
<td>-------</td>
<td>------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1974 - 1981</td>
<td>Valéry Giscard d’Estaing</td>
<td>−</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1981 - 1995</td>
<td>François Mitterrand</td>
<td>−</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1995 - 2007</td>
<td>Jacques Chirac</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>2007 - Present</td>
<td>Nicolas Sarkozy</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 41: Listed are all the elected Presidents of France, if and how many times they were elected, and if they were “−” left or “+” right wing.*

**Summary of France’s election results**

Total number of leaders: 21 Presidents (excluding Louise-Napoléon Bonaparte as he was from no party), of which 14 were right wing and 13 left wing.

Total years of democracy: 136, excluding the 7 years where the Presidents were chairmen of the Provisional Government. 59 years were led by a right wing party and 77 years were led by a left wing.

Total number of elections: 27

Total re-elected leaders: 6, of which 4 were right wing and 2 left wing.
B.8. USA

The USA became an independent country in 1776, formalised the Constitution in 1788 and held the first government election in 1789, electing George Washington to be their first President. The USA is a federal state, meaning a union of self-governing states form the government [86, 151].

Legislative power

The House of Representatives (lower house) consists of 435 elected members, which are elected by their districts every two years.

The Senate (upper house) consists of 100 members, where each state can put forward two members. Each Senate is elected to serve a six year term. The leader of the Senate is the Vice President.

Executive power

The executive branch consists of the President, the Vice President and the Cabinet.

The President is Head of State, Head of Government and Commander-in-Chief of the armed forces, who is indirectly elected by the public. The public elect a member of the Electoral College, who then vote for the President. Since 1951 a President can only be re-elected once, each election being a four year term.

The Vice President is selected by the President before the presidential election.

The Cabinet deals with the daily enforcements and laws within the USA.

Table 42 lists all of the political parties in the USA and their subjective classification of being left or right wing. In Table 43 an overview of the past Presidents of the USA, if and how often they were elected, and if they had left or right wing political views is shown.

<table>
<thead>
<tr>
<th>Left wing parties (-)</th>
<th>Right wing parties (+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Democratic</td>
<td>Republican</td>
</tr>
</tbody>
</table>

Table 42: Listed are all of the political parties that have been elected in the USA, which have subjectively been labelled to be left or right wing.
<table>
<thead>
<tr>
<th>Number</th>
<th>President</th>
<th>Term of office</th>
<th>Name</th>
<th>party</th>
<th>if elected</th>
<th>re-elected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>George Washington</td>
<td>1789 - 1797</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>John Adams</td>
<td>1797 - 1801</td>
<td></td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Thomas Jefferson</td>
<td>1801 - 1809</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>James Madison</td>
<td>1809 - 1817</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>James Monroe</td>
<td>1817 - 1825</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>John Quincy Adams</td>
<td>1825 - 1829</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Andrew Jackson</td>
<td>1829 - 1837</td>
<td></td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Martin Van Buren</td>
<td>1837 - 1841</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>William Henry Harrison</td>
<td>1841 - 1841</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>John Tyler</td>
<td>1841 - 1845</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>James K. Polk</td>
<td>1845 - 1849</td>
<td></td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Zachary Taylor</td>
<td>1849 - 1850</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Millard Fillmore</td>
<td>1850 - 1853</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Franklin Pierce</td>
<td>1853 - 1857</td>
<td></td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>James Buchanan</td>
<td>1857 - 1861</td>
<td></td>
<td>-</td>
<td>elected</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Abraham Lincoln</td>
<td>1861 - 1865</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Andrew Johnson</td>
<td>1865 - 1869</td>
<td></td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Ulysses S. Grant</td>
<td>1869 - 1877</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Rutherford B. Hayes</td>
<td>1877 -1881</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>James A. Garfield</td>
<td>1881 - 1881</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Chester A. Arthur</td>
<td>1881 - 1885</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Grover Cleveland</td>
<td>1885 - 1889</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Benjamin Harrison</td>
<td>1889 - 1893</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Grover Cleveland</td>
<td>1893 - 1897</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>William McKinley</td>
<td>1897 - 1901</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Theodore Roosevelt</td>
<td>1901 - 1909</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>William Howard Taft</td>
<td>1909 - 1913</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Woodrow Wilson</td>
<td>1913 - 1921</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Warren G. Harding</td>
<td>1921 - 1923</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Calvin Coolidge</td>
<td>1923 - 1929</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Herbert Hoover</td>
<td>1929 - 1933</td>
<td>+</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Franklin D. Roosevelt</td>
<td>1933 - 1945</td>
<td>-</td>
<td>elected</td>
<td>re-elected 3</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Harry S. Truman</td>
<td>1945 - 1953</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Dwight D. Eisenhower</td>
<td>1953 - 1961</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>President</td>
<td>Term of office</td>
<td>Name</td>
<td>party</td>
<td>if elected</td>
<td>re-elected</td>
</tr>
<tr>
<td>-------</td>
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<td>----------------</td>
<td>-----------------</td>
<td>-------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>34</td>
<td>John F. Kennedy</td>
<td>1961 - 1963</td>
<td>-</td>
<td>elected</td>
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</tr>
<tr>
<td>35</td>
<td>Lyndon B. Johnson</td>
<td>1963 - 1969</td>
<td>-</td>
<td>elected</td>
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</tr>
<tr>
<td>36</td>
<td>Richard Nixon</td>
<td>1969 - 1974</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Gerald Ford</td>
<td>1974 - 1977</td>
<td>+</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>38</td>
<td>Jimmy Carter</td>
<td>1977 - 1981</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Ronald Reagan</td>
<td>1981 - 1989</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>George H. W. Bush</td>
<td>1989 - 1993</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Bill Clinton</td>
<td>1993 - 2001</td>
<td>-</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>George W. Bush</td>
<td>2001 - 2009</td>
<td>+</td>
<td>elected</td>
<td>re-elected 1</td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>Barack Obama</td>
<td>2009 - Present</td>
<td>-</td>
<td>elected</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 43: Listed are all the Presidents of the USA, if and how many times they were elected, and if they were “–” left or “+” right wing.

Summary of America’s election results

Total number of leaders: 41 Presidents (excluding George Washington as he was from no party), of which 27 were right wing and 15 left wing.

Total years of democracy: 212, of which 128 years were led by a right wing leader 84 years led by a left wing.

Total number of elections: 53

Total re-elected leaders: 16, of which 10 were right wing and 6 left wing.
Appendix C. provides a further understanding of the data used in Chapter 4 analysing the UK phosphorus and nitrogen flows.

This Appendix section is laid out as follows:

In §C.1. the data used for the UK phosphorus and nitrogen flows are explained. First, in §C.1.1., the collected data is listed. Section C.1.2. shows all the calculations needed to obtain the quantity of phosphorus and nitrogen for the sectors where they are not given from the data collection. A summary of the data used in Chapter 4 is given in §C.1.3.

Finally, the equations used for the system dynamics model in the descriptive model are given in §C.2.

C.1. Data

C.1.1. Collected Data

In this section the data collected for the phosphorus and nitrogen flows research are listed in the following tables.
### Soil Nutrient Balance: Phosphorus (tonnes)

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### Soil Nutrient Balance: Phosphorus (kg of phosphorus per hectare)

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<th>Total Harvested Crops</th>
<th>Other Inputs</th>
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### Appendix for: UK Phosphorus and Nitrogen Flows

Soil Nutrient Balance: Nitrogen (tonnes)

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## Statistics for wheat

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Land use for wheat (million hectare)

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Statistics for barley

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Land use for barley (million hectare)

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**Table 55:** UK Agriculture Crops, Maize. Available at: http://www.ukagriculture.com/crops/grain_maize.cfm (Accessed: 13.3.2013)

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<td>0.146</td>
<td>0.153</td>
<td>0.163</td>
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</table>

**Table 56:** UK Agriculture Crops, Maize. Available at: (accessed 13.3.2013) http://www.ukagriculture.com/crops/grain_maize.cfm (Accessed: 13.3.2013)

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>Maize for stock breeding (million hectare)</td>
<td>0.001</td>
<td>0.021</td>
<td>0.033</td>
<td>0.098</td>
</tr>
</tbody>
</table>

**Table 57:** UK Agriculture Crops, Oilseed Rape. Available at: http://www.ukagriculture.com/crops/oil_seed_rape.cfm (Accessed: 13.3.2013)

<table>
<thead>
<tr>
<th>Year</th>
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<th>2009</th>
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<tbody>
<tr>
<td>Area for oilseed rape (million hectare)</td>
<td>0.402</td>
<td>0.451</td>
<td>0.432</td>
<td>0.542</td>
<td>0.558</td>
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<td>0.575</td>
<td>0.681</td>
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<td>0.581</td>
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<td>Yield for oilseed rape (tonnes/hectare)</td>
<td>2.9</td>
<td>2.6</td>
<td>3.4</td>
<td>3.3</td>
<td>2.9</td>
<td>3.2</td>
<td>3.3</td>
<td>3.2</td>
<td>3.3</td>
<td>3.4</td>
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<tr>
<td>Production volume oilseed rape (million tonnes)</td>
<td>1.157</td>
<td>1.157</td>
<td>1.468</td>
<td>1.771</td>
<td>1.609</td>
<td>1.902</td>
<td>1.890</td>
<td>2.108</td>
<td>1.973</td>
<td>1.912</td>
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</table>
Land use for oilseed rape (million hectare)

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<tr>
<td>Oilseed rape</td>
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<td>0.004</td>
<td>0.343</td>
<td>0.294</td>
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Table 58: UK Agriculture Crops, Oilseed Rape. Available at: http://www.ukagriculture.com/crops/oil_seed_rape.cfm (Accessed: 13.3.2013)

Statistics for sugar beet

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<tr>
<td>Area for sugar beet (million hectare)</td>
<td>0.173</td>
<td>0.177</td>
<td>0.169</td>
<td>0.162</td>
<td>0.154</td>
<td>0.148</td>
<td>0.130</td>
<td>0.125</td>
<td>0.120</td>
<td>0.114</td>
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<tr>
<td>Yield for sugar beet (tonnes/hectare)</td>
<td>52.5</td>
<td>47.0</td>
<td>56.5</td>
<td>57.3</td>
<td>57.5</td>
<td>58.5</td>
<td>56.6</td>
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Land use for sugar beet (million hectare)

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<td>Sugar beet</td>
<td>0.140</td>
<td>0.130</td>
<td>0.168</td>
<td>0.170</td>
<td>0.182</td>
<td>0.212</td>
<td>0.194</td>
<td>0.173</td>
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### Statistics for beans

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<tbody>
<tr>
<td>Area for beans and peas (million hectares)</td>
<td>0.208</td>
<td>0.276</td>
<td>0.249</td>
<td>0.235</td>
<td>0.242</td>
<td>0.239</td>
<td>0.231</td>
<td>0.161</td>
<td>0.148</td>
<td>0.228</td>
</tr>
<tr>
<td>Area for beans (million hectares)</td>
<td>0.124</td>
<td>0.173</td>
<td>0.164</td>
<td>0.171</td>
<td>0.178</td>
<td>0.184</td>
<td>0.184</td>
<td>0.123</td>
<td>0.118</td>
<td>0.186</td>
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<td>Yield - beans (tonnes/hectare)</td>
<td>3.9</td>
<td>3.5</td>
<td>3.9</td>
<td>3.8</td>
<td>3.7</td>
<td>3.8</td>
<td>3.4</td>
<td>3.0</td>
<td>4.5</td>
<td>3.7</td>
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<tr>
<td>Production volume beans (million tonnes)</td>
<td>0.485</td>
<td>0.606</td>
<td>0.632</td>
<td>0.646</td>
<td>0.661</td>
<td>0.675</td>
<td>0.613</td>
<td>0.526</td>
<td>0.638</td>
<td>0.588</td>
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### Land use for beans (million hectare)

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<tbody>
<tr>
<td>Beans</td>
<td>0.101</td>
<td>0.105</td>
<td>0.103</td>
<td>0.071</td>
<td>0.034</td>
<td>0.043</td>
<td>0.033</td>
<td>0.076</td>
<td>0.048</td>
<td>0.139</td>
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### Statistics for peas

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<tbody>
<tr>
<td>Area for beans and peas (million hectare)</td>
<td>0.208</td>
<td>0.276</td>
<td>0.249</td>
<td>0.235</td>
<td>0.242</td>
<td>0.239</td>
<td>0.231</td>
<td>0.161</td>
<td>0.148</td>
<td>0.228</td>
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<tr>
<td>Area for peas</td>
<td>0.071</td>
<td>0.081</td>
<td>0.074</td>
<td>0.066</td>
<td>0.051</td>
<td>0.041</td>
<td>0.037</td>
<td>0.026</td>
<td>0.021</td>
<td>0.027</td>
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<tr>
<td>Yield - peas (tonnes/hectare)</td>
<td>3.7</td>
<td>3.5</td>
<td>3.4</td>
<td>3.9</td>
<td>3.5</td>
<td>3.8</td>
<td>3.3</td>
<td>3.1</td>
<td>4.0</td>
<td>3.6</td>
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<tr>
<td>Production volume peas (million tonnes)</td>
<td>0.260</td>
<td>0.285</td>
<td>0.254</td>
<td>0.259</td>
<td>0.176</td>
<td>0.156</td>
<td>0.122</td>
<td>0.080</td>
<td>0.085</td>
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### Land use for peas (million hectare)

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<tr>
<td>Beans</td>
<td>0.062</td>
<td>0.068</td>
<td>0.067</td>
<td>0.054</td>
<td>0.015</td>
<td>0.015</td>
<td>0.005</td>
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<td>0.072</td>
<td>0.082</td>
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### Statistics for potatoes

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<th>2006</th>
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<th>2009</th>
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<tbody>
<tr>
<td>Area for potatoes</td>
<td>0.166</td>
<td>0.165</td>
<td>0.158</td>
<td>0.145</td>
<td>0.149</td>
<td>0.137</td>
<td>0.140</td>
<td>0.140</td>
<td>0.144</td>
<td>0.144</td>
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<tr>
<td>(million hectare)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield for early potatoes (tonnes/hectare)</td>
<td>22.6</td>
<td>12.4</td>
<td>16.4</td>
<td>18.2</td>
<td>16.8</td>
<td>14.3</td>
<td>15.7</td>
<td>12.5</td>
<td>13.3</td>
<td>15.0</td>
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<tr>
<td>Yield for main crop potatoes (tonnes/hectare)</td>
<td>41.4</td>
<td>42.8</td>
<td>46.7</td>
<td>42.9</td>
<td>45.2</td>
<td>46.4</td>
<td>43.0</td>
<td>43.1</td>
<td>46.7</td>
<td>48.0</td>
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<td>Production volume early potatoes (million tonnes)</td>
<td>0.276</td>
<td>0.172</td>
<td>0.235</td>
<td>0.247</td>
<td>0.248</td>
<td>0.179</td>
<td>0.177</td>
<td>0.198</td>
<td>0.224</td>
<td>0.236</td>
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### Land use for potatoes (million hectare)

<table>
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<tr>
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<tbody>
<tr>
<td>Potatoes</td>
<td>0.161</td>
<td>0.153</td>
<td>0.209</td>
<td>0.164</td>
<td>0.208</td>
<td>0.330</td>
<td>0.229</td>
<td>0.200</td>
<td>0.148</td>
<td>0.135</td>
<td>0.127</td>
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### Harvest, Import and Export (million tonnes)

<table>
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<th>2007</th>
<th>2008</th>
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<tbody>
<tr>
<td><strong>Cereal</strong></td>
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<tr>
<td>Harvest area (million hectares)</td>
<td>2.859</td>
<td>2.884</td>
<td>3.274</td>
<td>3.075</td>
<td>3.013</td>
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<tr>
<td>Harvested (Volume)</td>
<td>20.838</td>
<td>19.130</td>
<td>24.283</td>
<td>21.018</td>
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<td>Import from EU (Volume)</td>
<td>1.861</td>
<td>1.662</td>
<td>1.537</td>
<td>1.677</td>
<td>1.547</td>
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<td>Import rest of the world (Volume)</td>
<td>0.655</td>
<td>1.103</td>
<td>1.057</td>
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<td>Total Import</td>
<td>2.516</td>
<td>2.765</td>
<td>2.594</td>
<td>2.491</td>
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<td>Export to EU (Volume)</td>
<td>2.680</td>
<td>2.362</td>
<td>3.016</td>
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<td>3.920</td>
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<td>Export to rest of the world (Volume)</td>
<td>0.065</td>
<td>0.078</td>
<td>0.446</td>
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<td>Total export</td>
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<td>2.440</td>
<td>3.462</td>
<td>3.450</td>
<td>4.438</td>
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<td><strong>Wheat</strong></td>
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<td>Harvest area (million hectares)</td>
<td>1.836</td>
<td>1.830</td>
<td>2.080</td>
<td>1.775</td>
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<td>Yiel (tonnes per hectare)</td>
<td>8</td>
<td>7.2</td>
<td>8.3</td>
<td>7.9</td>
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<td>Import from EU (Volume)</td>
<td>0.569</td>
<td>0.625</td>
<td>0.645</td>
<td>0.780</td>
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<td>Import rest of the world (Volume)</td>
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<td>2.765</td>
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<td><strong>Barley</strong></td>
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<td>Harvest area (million hectares)</td>
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<td>0.898</td>
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<td>Yiel (tonnes per hectare)</td>
<td>5.9</td>
<td>5.7</td>
<td>6</td>
<td>5.8</td>
<td>5.7</td>
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<td>Harvested (Volume)</td>
<td>5.239</td>
<td>5.079</td>
<td>6.144</td>
<td>6.668</td>
<td>5.252</td>
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<td>0.095</td>
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<td>Import rest of the world (Volume)</td>
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<td>Total Import</td>
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<td>0.118</td>
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<td>0.471</td>
<td>0.559</td>
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<td><strong>Oats</strong></td>
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<td>Harvest area (million hectares)</td>
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<td>5.5</td>
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<td>5.8</td>
<td>5.5</td>
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<tr>
<td>Harvested (Volume)</td>
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<td>0.712</td>
<td>0.784</td>
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<td>-</td>
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| Total export   | 0.038       | 0.038       | 0.119       | 0.033       | 0.076       

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<th>2008</th>
<th>2009</th>
<th>2010</th>
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<tbody>
<tr>
<td><strong>Oilseed rape</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.575</td>
<td>0.681</td>
<td>0.598</td>
<td>0.570</td>
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<td>Yield (tonnes per hectare)</td>
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<td>Harvested (Volume)</td>
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<td>1.912</td>
<td>2.230</td>
</tr>
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<td>Import from EU (Volume)</td>
<td>0.132</td>
<td>0.063</td>
<td>0.175</td>
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<td>0.159</td>
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<tr>
<td>Import rest of the world (Volume)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>0.264</td>
<td>0.219</td>
<td>-</td>
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<td><strong>Linseed</strong></td>
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</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.036</td>
<td>0.013</td>
<td>0.016</td>
<td>0.028</td>
<td>0.044</td>
</tr>
<tr>
<td>Yield (tonnes per hectare)</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
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<td>0.030</td>
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<td>0.002</td>
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<td>0.010</td>
<td>0.008</td>
<td>0.012</td>
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<td>Export to EU (Volume)</td>
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<td>0.020</td>
<td>0.013</td>
<td>0.036</td>
<td>0.047</td>
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<tr>
<td>Export to rest of the world (Volume)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Total export</td>
<td>0.022</td>
<td>0.020</td>
<td>0.013</td>
<td>0.036</td>
<td>0.047</td>
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<tr>
<td><strong>Sugar beet and sugar</strong></td>
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<tr>
<td>Harvest area (million hectares)</td>
<td>0.131</td>
<td>0.125</td>
<td>0.120</td>
<td>0.114</td>
<td>0.119</td>
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<tr>
<td>Yield (tonnes per hectare)</td>
<td>56.6</td>
<td>53.8</td>
<td>63.8</td>
<td>74.0</td>
<td>54</td>
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<td>Harvested (Volume)</td>
<td>7.400</td>
<td>6.733</td>
<td>7.641</td>
<td>8.457</td>
<td>6.484</td>
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<td>0.234</td>
<td>0.197</td>
<td>0.220</td>
<td>0.246</td>
<td>0.404</td>
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<td>Import rest of the world (Volume)</td>
<td>1.099</td>
<td>1.109</td>
<td>1.186</td>
<td>1.091</td>
<td>0.926</td>
</tr>
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<td>Total Import</td>
<td>1.333</td>
<td>1.306</td>
<td>1.347</td>
<td>1.337</td>
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<td>0.462</td>
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<td>0.536</td>
<td>0.519</td>
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<tr>
<td><strong>Peas</strong></td>
<td></td>
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<td></td>
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<td>Harvest area (million hectares)</td>
<td>0.037</td>
<td>0.026</td>
<td>0.021</td>
<td>0.027</td>
<td>0.023</td>
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<tr>
<td>Yield (tonnes per hectare)</td>
<td>3.3</td>
<td>3.1</td>
<td>4</td>
<td>3.6</td>
<td>3.5</td>
</tr>
<tr>
<td>Harvested (Volume)</td>
<td>0.122</td>
<td>0.080</td>
<td>0.085</td>
<td>0.098</td>
<td>0.081</td>
</tr>
<tr>
<td><strong>Beans</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.184</td>
<td>0.123</td>
<td>0.118</td>
<td>0.186</td>
<td>0.168</td>
</tr>
<tr>
<td>Yield (tonnes per hectare)</td>
<td>3.4</td>
<td>3</td>
<td>4.5</td>
<td>3.7</td>
<td>3</td>
</tr>
<tr>
<td>Harvested (Volume)</td>
<td>0.617</td>
<td>0.375</td>
<td>0.526</td>
<td>0.688</td>
<td>0.579</td>
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*Table 68: DEFRA (2011) Agriculture in the United Kingdom 2010 (pages 38-40)*

### Harvest, Import and Export (million tonnes)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fresh vegetables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.120</td>
<td>0.119</td>
<td>0.117</td>
<td>0.125</td>
<td>0.122</td>
</tr>
<tr>
<td>Harvested</td>
<td>2.632</td>
<td>2.481</td>
<td>2.588</td>
<td>2.657</td>
<td>2.712</td>
</tr>
<tr>
<td>Import from EU (Volume)</td>
<td>1.682</td>
<td>1.685</td>
<td>1.698</td>
<td>1.577</td>
<td>1.642</td>
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<td>Import rest of the world (Volume)</td>
<td>0.210</td>
<td>0.263</td>
<td>0.258</td>
<td>0.246</td>
<td>0.252</td>
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<tr>
<td>Total Import</td>
<td>1.892</td>
<td>1.948</td>
<td>1.956</td>
<td>1.823</td>
<td>1.894</td>
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<tr>
<td>Export to EU (Volume)</td>
<td>0.071</td>
<td>0.069</td>
<td>0.062</td>
<td>0.072</td>
<td>0.087</td>
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<td>Export to rest of the world (Volume)</td>
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<td>0.019</td>
<td>0.018</td>
<td>0.006</td>
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<tr>
<td>Total export</td>
<td>0.083</td>
<td>0.088</td>
<td>0.080</td>
<td>0.078</td>
<td>0.093</td>
</tr>
<tr>
<td><strong>Potatoes</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.140</td>
<td>0.140</td>
<td>0.144</td>
<td>0.144</td>
<td>0.138</td>
</tr>
<tr>
<td>Yield (tonnes per hectare)</td>
<td>40.8</td>
<td>39.7</td>
<td>42.8</td>
<td>44.3</td>
<td>44</td>
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<tr>
<td>Harvested</td>
<td>5.727</td>
<td>5.564</td>
<td>6.145</td>
<td>6.396</td>
<td>6.045</td>
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<tr>
<td>Total Import</td>
<td>1.494</td>
<td>1.544</td>
<td>1.705</td>
<td>1.606</td>
<td>1.560</td>
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<td>Total export</td>
<td>1.626</td>
<td>1.680</td>
<td>1.738</td>
<td>1.624</td>
<td>1.505</td>
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<tr>
<td><strong>Fresh fruit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harvest area (million hectares)</td>
<td>0.028</td>
<td>0.027</td>
<td>0.028</td>
<td>0.028</td>
<td>0.029</td>
</tr>
<tr>
<td>Harvested</td>
<td>0.392</td>
<td>0.406</td>
<td>0.408</td>
<td>0.413</td>
<td>0.421</td>
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<td>Import from EU (Volume)</td>
<td>1.361</td>
<td>1.264</td>
<td>1.175</td>
<td>1.055</td>
<td>1.148</td>
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<tr>
<td>Import rest of the world (Volume)</td>
<td>2.128</td>
<td>2.268</td>
<td>2.169</td>
<td>2.137</td>
<td>2.090</td>
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<td>3.532</td>
<td>3.344</td>
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<td>Export to EU (Volume)</td>
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<td>0.128</td>
<td>0.154</td>
<td>0.141</td>
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<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
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<td>Total export</td>
<td>0.178</td>
<td>0.148</td>
<td>0.129</td>
<td>0.154</td>
<td>0.143</td>
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</table>

### Livestock (million tonnes)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cattle and calves</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cattle and calves (million head)</td>
<td>10.579</td>
<td>10.304</td>
<td>10.107</td>
<td>10.025</td>
<td>10.112</td>
</tr>
<tr>
<td>Dairy cows (million head)</td>
<td>1.979</td>
<td>1.954</td>
<td>1.909</td>
<td>1.857</td>
<td>1.847</td>
</tr>
<tr>
<td>Beef cows (million head)</td>
<td>1.737</td>
<td>1.698</td>
<td>1.670</td>
<td>1.626</td>
<td>1.657</td>
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<tr>
<td><strong>Average carcase weight (kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steers, heifers and young bulls (kg)</td>
<td>330</td>
<td>342</td>
<td>349</td>
<td>342</td>
<td>346</td>
</tr>
<tr>
<td>Calves (kg)</td>
<td>29</td>
<td>32</td>
<td>31</td>
<td>33</td>
<td>32</td>
</tr>
<tr>
<td>Cows and adult bulls (kg)</td>
<td>311</td>
<td>317</td>
<td>314</td>
<td>315</td>
<td>320</td>
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<tr>
<td><strong>Production (dressed carcase weight)</strong></td>
<td>0.852</td>
<td>0.888</td>
<td>0.866</td>
<td>0.824</td>
<td>0.898</td>
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<td>Import from EU (dressed carcase weight)</td>
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<td>0.204</td>
<td>0.216</td>
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<td>0.203</td>
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<tr>
<td>Import rest of the world (dressed carcase weight)</td>
<td>0.072</td>
<td>0.075</td>
<td>0.079</td>
<td>0.076</td>
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<tr>
<td>Total Import (dressed carcase weight)</td>
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<td>0.279</td>
<td>0.295</td>
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<td>0.277</td>
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<tr>
<td>Export to EU (dressed carcase weight)</td>
<td>0.052</td>
<td>0.076</td>
<td>0.099</td>
<td>0.096</td>
<td>0.120</td>
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<tr>
<td>Export to rest of the world (dressed carcase weight)</td>
<td>-</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
<td>0.004</td>
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<tr>
<td>Total export (dressed carcase weight)</td>
<td>0.052</td>
<td>0.077</td>
<td>0.100</td>
<td>0.099</td>
<td>0.124</td>
</tr>
<tr>
<td><strong>Pigs and pigmeat</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Total pigs (million head)</td>
<td>4.933</td>
<td>4.834</td>
<td>4.714</td>
<td>4.540</td>
<td>4.460</td>
</tr>
<tr>
<td>Sows in pig and other sows for breeding (million head)</td>
<td>0.401</td>
<td>0.398</td>
<td>0.365</td>
<td>0.379</td>
<td>0.360</td>
</tr>
<tr>
<td>Gilts in pig (million head)</td>
<td>0.067</td>
<td>0.057</td>
<td>0.055</td>
<td>0.048</td>
<td>0.067</td>
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<tr>
<td><strong>Average carcase weight (kg)</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean pigs (kg)</td>
<td>75</td>
<td>76</td>
<td>76</td>
<td>78</td>
<td>78</td>
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<tr>
<td>Sows and boars (kg)</td>
<td>153</td>
<td>151</td>
<td>151</td>
<td>152</td>
<td>155</td>
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<tr>
<td><strong>Production (dressed carcase weight)</strong></td>
<td>0.667</td>
<td>0.707</td>
<td>0.706</td>
<td>0.681</td>
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<td>0.864</td>
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<td>0.012</td>
<td>0.012</td>
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<td>0.869</td>
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<td>Export to EU (carcase weight)</td>
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<td>0.113</td>
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<td>0.012</td>
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<td>0.026</td>
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<td>0.125</td>
<td>0.155</td>
<td>0.135</td>
<td>0.171</td>
</tr>
<tr>
<td><strong>Sheep and lambs</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Total sheep and lambs (million head)</td>
<td>34.722</td>
<td>33.946</td>
<td>33.131</td>
<td>31.445</td>
<td>31.084</td>
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<tr>
<td>Lambs under one year old (million head)</td>
<td>17.058</td>
<td>16.855</td>
<td>16.574</td>
<td>15.892</td>
<td>15.431</td>
</tr>
<tr>
<td><strong>Average carcase weight (kg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean sheep and lambs (kg)</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Ewes and rams (kg)</td>
<td>28</td>
<td>27</td>
<td>24</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>Production (dressed carcase weight)</strong></td>
<td>0.334</td>
<td>0.329</td>
<td>0.332</td>
<td>0.313</td>
<td>0.287</td>
</tr>
<tr>
<td>Import from EU (dressed carcase weight)</td>
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<td>0.021</td>
<td>0.020</td>
<td>0.021</td>
<td>0.019</td>
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<tr>
<td>Import rest of the world (dressed carcase weight)</td>
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<td>0.116</td>
<td>0.115</td>
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<tr>
<td>Total Import (dressed carcase weight)</td>
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<td>0.137</td>
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<td>0.143</td>
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<td>0.076</td>
<td>0.094</td>
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<td>0.001</td>
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<tr>
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<td>0.077</td>
<td>0.095</td>
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</table>

Livestock (million tonnes)

<table>
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<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Poultry</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Total fowls (million head in June)</td>
<td>173.081</td>
<td>167.667</td>
<td>166.200</td>
<td>152.753</td>
<td>163.867</td>
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<td>Table fowls (million head in June)</td>
<td>110.672</td>
<td>109.794</td>
<td>109.859</td>
<td>98.754</td>
<td>105.309</td>
</tr>
<tr>
<td>Laying and breeding fowls (million head in June)</td>
<td>47.530</td>
<td>47.719</td>
<td>44.321</td>
<td>42.663</td>
<td>47.107</td>
</tr>
<tr>
<td>Turkey, ducks, goose and all other poultry (million head in June)</td>
<td>14.879</td>
<td>10.154</td>
<td>12.019</td>
<td>11.335</td>
<td>11.451</td>
</tr>
<tr>
<td>Slaughters</td>
<td>886</td>
<td>874</td>
<td>862</td>
<td>868</td>
<td>933</td>
</tr>
<tr>
<td>Fowls</td>
<td>849</td>
<td>842</td>
<td>831</td>
<td>839</td>
<td>904</td>
</tr>
<tr>
<td>Turkey</td>
<td>18</td>
<td>16</td>
<td>16</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>Ducks and goose</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td><strong>Production carcass weight</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chickens and other table fowls</td>
<td>1.237</td>
<td>1.212</td>
<td>1.214</td>
<td>1.221</td>
<td>1.327</td>
</tr>
<tr>
<td>Boiling fowls</td>
<td>51</td>
<td>49</td>
<td>53</td>
<td>48</td>
<td>53</td>
</tr>
<tr>
<td>Turkey</td>
<td>178</td>
<td>165</td>
<td>160</td>
<td>157</td>
<td>162</td>
</tr>
<tr>
<td>Ducks and goose</td>
<td>44</td>
<td>38</td>
<td>35</td>
<td>32</td>
<td>31</td>
</tr>
<tr>
<td><strong>Import from EU (carcass weight)</strong></td>
<td>0.411</td>
<td>0.430</td>
<td>0.377</td>
<td>0.388</td>
<td>0.441</td>
</tr>
<tr>
<td>Import rest of the world (carcass weight)</td>
<td>0.040</td>
<td>0.034</td>
<td>0.029</td>
<td>0.032</td>
<td>0.033</td>
</tr>
<tr>
<td>Total Import (carcass weight)</td>
<td>0.451</td>
<td>0.461</td>
<td>0.406</td>
<td>0.420</td>
<td>0.474</td>
</tr>
<tr>
<td><strong>Export to EU (carcass weight)</strong></td>
<td>0.163</td>
<td>0.268</td>
<td>0.255</td>
<td>0.218</td>
<td>0.203</td>
</tr>
<tr>
<td>Export to rest of the world (carcass weight)</td>
<td>0.070</td>
<td>0.025</td>
<td>0.024</td>
<td>0.035</td>
<td>0.062</td>
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<tr>
<td>Total export (carcass weight)</td>
<td>0.233</td>
<td>0.293</td>
<td>0.279</td>
<td>0.253</td>
<td>0.265</td>
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</table>

## Statistics for poultry (million head)

<table>
<thead>
<tr>
<th></th>
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<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slaughtering fowls</td>
<td>816</td>
<td>798</td>
<td>819</td>
<td>807</td>
<td>843</td>
<td>864</td>
<td>844</td>
<td>836</td>
<td>831</td>
<td>839</td>
</tr>
<tr>
<td>Slaughtering turkeys</td>
<td>29</td>
<td>27</td>
<td>26</td>
<td>23</td>
<td>21</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Slaughtering ducks and geese</td>
<td>19</td>
<td>19</td>
<td>22</td>
<td>20</td>
<td>18</td>
<td>19</td>
<td>16</td>
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</table>


## Statistics for beef (million head)

<table>
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<tr>
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<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy cows</td>
<td>2.336</td>
<td>2.251</td>
<td>2.227</td>
<td>2.192</td>
<td>2.129</td>
<td>2.063</td>
<td>2.066</td>
<td>1.954</td>
<td>1.909</td>
<td>1.857</td>
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</table>

### Statistics for beef (million head)

|------|------|------|------|------|------|------|------|------|------|------|------|


### Statistics for sheep (million head)

<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sheep and lambs</td>
<td>42.264</td>
<td>36.716</td>
<td>35.834</td>
<td>35.846</td>
<td>35.817</td>
<td>35.416</td>
<td>34.722</td>
<td>33.946</td>
<td>33.131</td>
<td>31.445</td>
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</table>


### Statistics for sheep (million head)

|------|------|------|------|------|------|------|------|------|------|------|------|
Statistics for pigs (million head)

<table>
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<tr>
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<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
</table>


Statistics for pigs (million head)

|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|


Statistics for fisheries (million tonnes)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>0.892</td>
<td>0.891</td>
<td>0.924</td>
<td>0.836</td>
<td>0.748</td>
<td>0.738</td>
<td>0.686</td>
<td>0.640</td>
<td>0.654</td>
<td>0.708</td>
<td>0.614</td>
<td>0.610</td>
<td>0.588</td>
<td>0.581</td>
<td>0.606</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Export</td>
<td>0.310</td>
<td>0.300</td>
<td>0.377</td>
<td>0.351</td>
<td>0.365</td>
<td>0.391</td>
<td>0.389</td>
<td>0.479</td>
<td>0.478</td>
<td>0.461</td>
<td>0.461</td>
<td>0.467</td>
<td>0.416</td>
<td>0.479</td>
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</tr>
<tr>
<td>Import</td>
<td>0.533</td>
<td>0.503</td>
<td>0.533</td>
<td>0.552</td>
<td>0.550</td>
<td>0.627</td>
<td>0.621</td>
<td>0.631</td>
<td>0.672</td>
<td>0.720</td>
<td>0.754</td>
<td>0.748</td>
<td>0.782</td>
<td>0.720</td>
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</tbody>
</table>

### Milk production (million litres)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy herd (million head)</td>
<td>1.992</td>
<td>1.970</td>
<td>1.918</td>
<td>1.867</td>
<td>1.850</td>
</tr>
<tr>
<td>Average yield per dairy cow (thousand litres per year)</td>
<td>6.997</td>
<td>6.913</td>
<td>6.943</td>
<td>7.068</td>
<td>7.315</td>
</tr>
<tr>
<td>Total production</td>
<td>13.099</td>
<td>13.626</td>
<td>13.326</td>
<td>13.204</td>
<td>13.504</td>
</tr>
<tr>
<td>Import</td>
<td>0.033</td>
<td>0.057</td>
<td>0.049</td>
<td>0.075</td>
<td>0.067</td>
</tr>
<tr>
<td>Export</td>
<td>0.617</td>
<td>0.538</td>
<td>0.559</td>
<td>0.433</td>
<td>0.433</td>
</tr>
</tbody>
</table>


### Eggs (million dozens)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of laying fowl and breeding fowls (millions)</td>
<td>47,530</td>
<td>47,719</td>
<td>44,321</td>
<td>42,663</td>
<td>47,107</td>
</tr>
<tr>
<td>Volume of production of eggs</td>
<td>852</td>
<td>831</td>
<td>867</td>
<td>869</td>
<td>950</td>
</tr>
<tr>
<td>For human consumption</td>
<td>742</td>
<td>720</td>
<td>754</td>
<td>751</td>
<td>826</td>
</tr>
<tr>
<td>For hatching</td>
<td>97</td>
<td>99</td>
<td>98</td>
<td>101</td>
<td>105</td>
</tr>
<tr>
<td>Hatching for export</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Waste</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Import from EU</td>
<td>168</td>
<td>203</td>
<td>219</td>
<td>224</td>
<td>201</td>
</tr>
<tr>
<td>Import from rest of world</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total Import</td>
<td>170</td>
<td>205</td>
<td>220</td>
<td>225</td>
<td>204</td>
</tr>
<tr>
<td>Export from EU</td>
<td>18</td>
<td>17</td>
<td>24</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Export from rest of world</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total export</td>
<td>18</td>
<td>17</td>
<td>24</td>
<td>19</td>
<td>21</td>
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</table>

## Food purchases (grams per person per week in UK)

<table>
<thead>
<tr>
<th>Food Item</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread</td>
<td>692</td>
<td>677</td>
<td>659</td>
<td>656</td>
</tr>
<tr>
<td>Vegetables</td>
<td>1,142</td>
<td>1,140</td>
<td>1,118</td>
<td>1,103</td>
</tr>
<tr>
<td>Potatoes</td>
<td>810</td>
<td>781</td>
<td>776</td>
<td>761</td>
</tr>
<tr>
<td>Fruit</td>
<td>1,313</td>
<td>1,281</td>
<td>1,199</td>
<td>1,143</td>
</tr>
<tr>
<td>Flour</td>
<td>54</td>
<td>54</td>
<td>63</td>
<td>58</td>
</tr>
<tr>
<td>Other cereals</td>
<td>530</td>
<td>536</td>
<td>535</td>
<td>548</td>
</tr>
<tr>
<td>Milk and cream (million litres)</td>
<td>2,022</td>
<td>1,984</td>
<td>1,957</td>
<td>2,003</td>
</tr>
<tr>
<td>Cheese</td>
<td>116</td>
<td>119</td>
<td>111</td>
<td>116</td>
</tr>
<tr>
<td>Carcase meat</td>
<td>238</td>
<td>235</td>
<td>211</td>
<td>212</td>
</tr>
<tr>
<td>Non-carcase meat and meat products</td>
<td>804</td>
<td>795</td>
<td>787</td>
<td>787</td>
</tr>
<tr>
<td>Fish</td>
<td>170</td>
<td>165</td>
<td>161</td>
<td>158</td>
</tr>
<tr>
<td>Eggs (number)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fats</td>
<td>184</td>
<td>181</td>
<td>184</td>
<td>181</td>
</tr>
<tr>
<td>Sugar and preserves</td>
<td>126</td>
<td>125</td>
<td>127</td>
<td>125</td>
</tr>
<tr>
<td>Cakes, buns and pastries</td>
<td>165</td>
<td>159</td>
<td>153</td>
<td>158</td>
</tr>
<tr>
<td>Biscuits and crispbreads</td>
<td>165</td>
<td>163</td>
<td>170</td>
<td>169</td>
</tr>
<tr>
<td>Beverages</td>
<td>55</td>
<td>56</td>
<td>55</td>
<td>54</td>
</tr>
<tr>
<td>Soft drinks (litres)</td>
<td>1,807</td>
<td>1,686</td>
<td>1,682</td>
<td>1,678</td>
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<tr>
<td>Confectionery</td>
<td>123</td>
<td>129</td>
<td>131</td>
<td>134</td>
</tr>
<tr>
<td>Alcoholic drinks (litres)</td>
<td>760</td>
<td>772</td>
<td>706</td>
<td>744</td>
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</table>

### Food purchases (per person per week in UK (grams per person))

<table>
<thead>
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<th></th>
<th>2002-03</th>
<th>2004-05</th>
<th>2005-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk and cream (ml)</td>
<td>2.006</td>
<td>1.996</td>
<td>2.027</td>
</tr>
<tr>
<td>Liquid whole milk (ml)</td>
<td>572</td>
<td>497</td>
<td>475</td>
</tr>
<tr>
<td>Cheese (g)</td>
<td>112</td>
<td>110</td>
<td>116</td>
</tr>
<tr>
<td>Carcass meat (g)</td>
<td>230</td>
<td>229</td>
<td>226</td>
</tr>
<tr>
<td>Other meat and other meat products</td>
<td>820</td>
<td>820</td>
<td>821</td>
</tr>
<tr>
<td>Fish (g)</td>
<td>155</td>
<td>158</td>
<td>167</td>
</tr>
<tr>
<td>Eggs (no)</td>
<td>1.66</td>
<td>1.56</td>
<td>1.61</td>
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<tr>
<td>Fats</td>
<td>190</td>
<td>182</td>
<td>183</td>
</tr>
<tr>
<td>Butter</td>
<td>37</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>Sugar and preserves</td>
<td>146</td>
<td>134</td>
<td>129</td>
</tr>
<tr>
<td>Fresh and processed potatoes</td>
<td>873</td>
<td>822</td>
<td>842</td>
</tr>
<tr>
<td>Fruit and vegetables excluding potatoes</td>
<td>2,307</td>
<td>2,274</td>
<td>2,448</td>
</tr>
<tr>
<td>Vegetables excluding potatoes</td>
<td>1,101</td>
<td>1,106</td>
<td>1,156</td>
</tr>
<tr>
<td>Fruit</td>
<td>1,206</td>
<td>1,168</td>
<td>1,292</td>
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<tr>
<td>Cereals</td>
<td>1,671</td>
<td>1,577</td>
<td>1,626</td>
</tr>
<tr>
<td>Bread</td>
<td>757</td>
<td>695</td>
<td>701</td>
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<table>
<thead>
<tr>
<th>Food purchases and waste (million tonnes)</th>
<th>Purchase</th>
<th>Waste</th>
</tr>
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<tbody>
<tr>
<td>Bread</td>
<td>2.1</td>
<td>0.75</td>
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<tr>
<td>Vegetables</td>
<td>3.5</td>
<td>1.24</td>
</tr>
<tr>
<td>Potatoes</td>
<td>2.3</td>
<td>1.01</td>
</tr>
<tr>
<td>Fruit</td>
<td>3.7</td>
<td>1.23</td>
</tr>
<tr>
<td>Cereal products</td>
<td>2.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Other minority products</td>
<td>1.6</td>
<td>0.33</td>
</tr>
<tr>
<td>Meat and fish</td>
<td>3.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Deserts, cakes and sweets</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>Eggs</td>
<td>0.3</td>
<td>0.078</td>
</tr>
<tr>
<td>Dairy products</td>
<td>6.6</td>
<td>0.56</td>
</tr>
<tr>
<td>Soft drinks</td>
<td>6.2</td>
<td>0.44</td>
</tr>
<tr>
<td>Alcoholic drinks</td>
<td>2.2</td>
<td>0.14</td>
</tr>
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<td>Not linked to purchases</td>
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<td>0.35</td>
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### Food waste (million tonnes)

<table>
<thead>
<tr>
<th>Category</th>
<th>Total</th>
<th>%</th>
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</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>Bakery</td>
<td>0.8</td>
<td>9%</td>
</tr>
<tr>
<td>Fresh vegetables and salad</td>
<td>1.9</td>
<td>11%</td>
</tr>
<tr>
<td>Processed vegetables and salad</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Condiments, sauces, herbs, and spices</td>
<td>0.21</td>
<td>6%</td>
</tr>
<tr>
<td>Fresh fruit</td>
<td>1.1</td>
<td>8%</td>
</tr>
<tr>
<td>Processed fruit</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Staple foods</td>
<td>0.2</td>
<td>4%</td>
</tr>
<tr>
<td>Other</td>
<td>0.3</td>
<td>7%</td>
</tr>
<tr>
<td>Meat and fish</td>
<td>0.61</td>
<td>13%</td>
</tr>
<tr>
<td>Deserts and cakes</td>
<td>0.19</td>
<td>4%</td>
</tr>
<tr>
<td>Meals (homemade and pre-prepared)</td>
<td>0.69</td>
<td>18%</td>
</tr>
<tr>
<td>Dairy products and eggs</td>
<td>0.58</td>
<td>7%</td>
</tr>
<tr>
<td>Drink</td>
<td>1.3</td>
<td>13%</td>
</tr>
<tr>
<td>Oil and fat</td>
<td>0.09</td>
<td></td>
</tr>
</tbody>
</table>

Meat waste (million tonnes)

<table>
<thead>
<tr>
<th></th>
<th>Total waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poultry</td>
<td>0.3</td>
</tr>
<tr>
<td>Pork/ham/bacon</td>
<td>0.12</td>
</tr>
<tr>
<td>Fish and shellfish</td>
<td>0.043</td>
</tr>
<tr>
<td>Lamb</td>
<td>0.032</td>
</tr>
<tr>
<td>All other meat and fish</td>
<td>0.120</td>
</tr>
</tbody>
</table>

### Food waste and its disposal route (million tonnes)

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Total Local Authorities collected</th>
<th>Sewer</th>
<th>Home composting and fed to animals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakery</td>
<td>0.8</td>
<td>0.66</td>
<td>0.12</td>
</tr>
<tr>
<td>Fresh vegetables and salad</td>
<td>1.9</td>
<td>1.6</td>
<td>0.031</td>
</tr>
<tr>
<td>Processed vegetables and salad</td>
<td>0.21</td>
<td>0.16</td>
<td>0.033</td>
</tr>
<tr>
<td>Condiments, sauces, herbs, and spices</td>
<td>0.21</td>
<td>0.12</td>
<td>0.085</td>
</tr>
<tr>
<td>Fresh fruit</td>
<td>1.1</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Processed fruit</td>
<td>0.03</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Staple foods</td>
<td>0.2</td>
<td>0.16</td>
<td>0.013</td>
</tr>
<tr>
<td>Other</td>
<td>0.3</td>
<td>0.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Meat and fish</td>
<td>0.61</td>
<td>0.5</td>
<td>0.053</td>
</tr>
<tr>
<td>Deserts and cakes</td>
<td>0.19</td>
<td>0.13</td>
<td>0.012</td>
</tr>
<tr>
<td>Meals (homemade and pre-prepared)</td>
<td>0.69</td>
<td>0.56</td>
<td>0.37</td>
</tr>
<tr>
<td>Dairy products and eggs</td>
<td>0.58</td>
<td>0.11</td>
<td>0.37</td>
</tr>
<tr>
<td>Drink</td>
<td>1.3</td>
<td>0.18</td>
<td>0.73</td>
</tr>
<tr>
<td>Oil and fat</td>
<td>0.09</td>
<td>0.026</td>
<td>0.064</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Animal feed (million tonnes)</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>2.780</td>
<td>2.869</td>
<td>2.758</td>
<td>2.783</td>
<td>2.661</td>
<td>2.847</td>
<td>2.915</td>
<td>2.662</td>
<td>2.818</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>0.503</td>
<td>0.654</td>
<td>0.729</td>
<td>0.566</td>
<td>0.709</td>
<td>0.521</td>
<td>0.635</td>
<td>0.656</td>
<td>0.726</td>
<td>0.921</td>
<td></td>
</tr>
<tr>
<td>Oats</td>
<td>0.030</td>
<td>0.024</td>
<td>0.023</td>
<td>0.028</td>
<td>0.045</td>
<td>0.032</td>
<td>0.047</td>
<td>0.065</td>
<td>0.067</td>
<td>0.107</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>0.084</td>
<td>0.075</td>
<td>0.079</td>
<td>0.096</td>
<td>0.112</td>
<td>0.083</td>
<td>0.086</td>
<td>0.123</td>
<td>0.224</td>
<td>0.108</td>
<td>0.110</td>
</tr>
<tr>
<td>Rice bran</td>
<td>0.036</td>
<td>0.030</td>
<td>0.026</td>
<td>0.029</td>
<td>0.028</td>
<td>0.027</td>
<td>0.026</td>
<td>0.020</td>
<td>0.016</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Wheat gluten free</td>
<td>0.472</td>
<td>0.471</td>
<td>0.475</td>
<td>0.435</td>
<td>0.427</td>
<td>0.304</td>
<td>0.277</td>
<td>0.095</td>
<td>0.042</td>
<td>0.033</td>
<td>0.116</td>
</tr>
<tr>
<td>Wheat feed</td>
<td>0.861</td>
<td>0.860</td>
<td>0.886</td>
<td>0.869</td>
<td>0.841</td>
<td>0.824</td>
<td>0.823</td>
<td>0.862</td>
<td>0.903</td>
<td>0.791</td>
<td>0.852</td>
</tr>
<tr>
<td>Other cereal by-products</td>
<td>0.158</td>
<td>0.168</td>
<td>0.162</td>
<td>0.188</td>
<td>0.189</td>
<td>0.174</td>
<td>0.215</td>
<td>0.219</td>
<td>0.211</td>
<td>0.172</td>
<td>0.167</td>
</tr>
<tr>
<td>Distillery by-products</td>
<td>0.149</td>
<td>0.151</td>
<td>0.205</td>
<td>0.257</td>
<td>0.257</td>
<td>0.243</td>
<td>0.242</td>
<td>0.221</td>
<td>0.189</td>
<td>0.210</td>
<td>0.316</td>
</tr>
<tr>
<td>Cereal by-products</td>
<td>1.168</td>
<td>1.179</td>
<td>1.253</td>
<td>1.314</td>
<td>1.287</td>
<td>1.241</td>
<td>1.270</td>
<td>1.303</td>
<td>1.303</td>
<td>1.172</td>
<td>1.335</td>
</tr>
<tr>
<td>Whole Oilseeds</td>
<td>0.069</td>
<td>0.057</td>
<td>0.060</td>
<td>0.037</td>
<td>0.049</td>
<td>0.051</td>
<td>0.058</td>
<td>0.040</td>
<td>0.058</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td>Oiled rape cake and meal</td>
<td>0.586</td>
<td>0.562</td>
<td>0.521</td>
<td>0.505</td>
<td>0.515</td>
<td>0.615</td>
<td>0.665</td>
<td>0.719</td>
<td>0.768</td>
<td>0.719</td>
<td>0.771</td>
</tr>
<tr>
<td>Soya cake and meal</td>
<td>0.934</td>
<td>1.015</td>
<td>1.010</td>
<td>1.029</td>
<td>0.943</td>
<td>0.888</td>
<td>0.982</td>
<td>1.161</td>
<td>1.197</td>
<td>1.070</td>
<td>1.152</td>
</tr>
<tr>
<td>Sunflower cake and meal</td>
<td>0.433</td>
<td>0.412</td>
<td>0.272</td>
<td>0.347</td>
<td>0.374</td>
<td>0.265</td>
<td>0.286</td>
<td>0.255</td>
<td>0.204</td>
<td>0.325</td>
<td>0.252</td>
</tr>
<tr>
<td>Other oilseeds</td>
<td>0.470</td>
<td>0.550</td>
<td>0.453</td>
<td>0.404</td>
<td>0.435</td>
<td>0.399</td>
<td>0.453</td>
<td>0.421</td>
<td>0.434</td>
<td>0.457</td>
<td>0.438</td>
</tr>
<tr>
<td>Field Beans</td>
<td>0.041</td>
<td>0.064</td>
<td>0.102</td>
<td>0.123</td>
<td>0.089</td>
<td>0.083</td>
<td>0.120</td>
<td>0.074</td>
<td>0.041</td>
<td>0.094</td>
<td>0.103</td>
</tr>
<tr>
<td>Field Peas</td>
<td>0.099</td>
<td>0.076</td>
<td>0.062</td>
<td>0.042</td>
<td>0.038</td>
<td>0.035</td>
<td>0.037</td>
<td>0.035</td>
<td>0.027</td>
<td>0.025</td>
<td>0.032</td>
</tr>
<tr>
<td>Dried Sugar Beet Pulp</td>
<td>0.231</td>
<td>0.195</td>
<td>0.182</td>
<td>0.224</td>
<td>0.193</td>
<td>0.209</td>
<td>0.252</td>
<td>0.225</td>
<td>0.200</td>
<td>0.200</td>
<td>0.274</td>
</tr>
<tr>
<td>Molasses</td>
<td>0.327</td>
<td>0.318</td>
<td>0.285</td>
<td>0.302</td>
<td>0.320</td>
<td>0.276</td>
<td>0.278</td>
<td>0.309</td>
<td>0.327</td>
<td>0.256</td>
<td>0.263</td>
</tr>
<tr>
<td>Citrus and other fruit pulp</td>
<td>0.076</td>
<td>0.076</td>
<td>0.063</td>
<td>0.048</td>
<td>0.111</td>
<td>0.080</td>
<td>0.066</td>
<td>0.095</td>
<td>0.094</td>
<td>0.086</td>
<td>0.066</td>
</tr>
<tr>
<td>All meal</td>
<td>0.177</td>
<td>0.171</td>
<td>0.159</td>
<td>0.145</td>
<td>0.135</td>
<td>0.130</td>
<td>0.126</td>
<td>0.117</td>
<td>0.107</td>
<td>0.145</td>
<td>0.110</td>
</tr>
<tr>
<td>Minerals</td>
<td>0.399</td>
<td>0.412</td>
<td>0.405</td>
<td>0.393</td>
<td>0.402</td>
<td>0.401</td>
<td>0.417</td>
<td>0.435</td>
<td>0.434</td>
<td>0.406</td>
<td>0.438</td>
</tr>
<tr>
<td>Oil and fat</td>
<td>0.217</td>
<td>0.222</td>
<td>0.228</td>
<td>0.224</td>
<td>0.207</td>
<td>0.183</td>
<td>0.187</td>
<td>0.191</td>
<td>0.183</td>
<td>0.179</td>
<td>0.184</td>
</tr>
<tr>
<td>Protein concentrates</td>
<td>0.021</td>
<td>0.022</td>
<td>0.20</td>
<td>0.021</td>
<td>0.020</td>
<td>0.021</td>
<td>0.028</td>
<td>0.020</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>Other materials</td>
<td>0.326</td>
<td>0.306</td>
<td>0.276</td>
<td>0.256</td>
<td>0.253</td>
<td>0.224</td>
<td>0.229</td>
<td>0.266</td>
<td>0.370</td>
<td>0.244</td>
<td>0.251</td>
</tr>
<tr>
<td>Confectionery by-products</td>
<td>0.120</td>
<td>0.115</td>
<td>0.125</td>
<td>0.124</td>
<td>0.121</td>
<td>0.132</td>
<td>0.143</td>
<td>0.165</td>
<td>0.163</td>
<td>0.172</td>
<td>0.188</td>
</tr>
</tbody>
</table>

## Household waste (kg per person per year)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total waste</th>
<th>Recycled/composted waste</th>
<th>Not recycled waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983/4</td>
<td>397</td>
<td>3</td>
<td>394</td>
</tr>
<tr>
<td>1991/2</td>
<td>428</td>
<td>11</td>
<td>417</td>
</tr>
<tr>
<td>1995/6</td>
<td>450</td>
<td>27</td>
<td>423</td>
</tr>
<tr>
<td>2000/1</td>
<td>507</td>
<td>52</td>
<td>455</td>
</tr>
<tr>
<td>2002/3</td>
<td>521</td>
<td>71</td>
<td>449</td>
</tr>
<tr>
<td>2004/5</td>
<td>517</td>
<td>113</td>
<td>404</td>
</tr>
<tr>
<td>2005/6</td>
<td>511</td>
<td>135</td>
<td>376</td>
</tr>
<tr>
<td>2006/7</td>
<td>516</td>
<td>157</td>
<td>359</td>
</tr>
<tr>
<td>2007/8</td>
<td>507</td>
<td>173</td>
<td>334</td>
</tr>
</tbody>
</table>


## Biofuel production UK (thousand tonnes)

<table>
<thead>
<tr>
<th>Year</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>9</td>
<td>9</td>
<td>51</td>
<td>192</td>
<td>150</td>
<td>192</td>
<td>137</td>
<td>145</td>
</tr>
</tbody>
</table>

Biodiesel production and consumption UK

<table>
<thead>
<tr>
<th></th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production (Barrels a day)</td>
<td>60</td>
<td>200</td>
<td>200</td>
<td>900</td>
<td>5,000</td>
<td>8,000</td>
<td>5,500</td>
<td>4,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Consumption (Barrels a day)</td>
<td>100</td>
<td>300</td>
<td>400</td>
<td>2,100</td>
<td>4,500</td>
<td>8,600</td>
<td>18,800</td>
<td>23,500</td>
<td>29,000</td>
</tr>
</tbody>
</table>


C.1.2. Manipulated Data

In the previous section the data gathered for the UK phosphorus and nitrogen flows chapter was listed. But the data does not provide information on the quantity of phosphorus and nitrogen for all of the sectors needed for Chapter 4. Therefore, this sections shows the calculations and assumptions made to obtain the quantity of phosphorus and nitrogen in various sectors.

The amount of phosphorus and nitrogen in certain foods was determined and published on wholefoodcatalog website. The quantity of phosphorus and nitrogen in fish, meat, eggs and milk was averaged as shown in the Table 92. It is assumed 1 litre of milk and cream weighs 1 kilogram, and 1 egg weighs 50 grams.

<table>
<thead>
<tr>
<th></th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish</td>
<td>1.528</td>
<td>1.8452</td>
</tr>
<tr>
<td>Meat</td>
<td>2.045</td>
<td>22.6497</td>
</tr>
<tr>
<td>Eggs</td>
<td>1.522</td>
<td>1.7234</td>
</tr>
<tr>
<td>Milk</td>
<td>2.265</td>
<td>3.88</td>
</tr>
</tbody>
</table>

Table 92: Phosphorus Content of Foods, Nitrogen Content of Foods (given in the milligram of phosphorus or nitrogen per one gram of the product). Available at: http://wholefoodcatalog.info/nutrient/phosphorus/foods/ (Accessed: 13.3.2013)

From the previous section, in Tables 44 and 46 the quantity of phosphorus and nitrogen applied to soil through fertiliser and other inputs and the crop uptake of the elements is given.
Tables 50, 57, 59, 61, 63 and 65 give the quantity of a particular crop harvested from 2000 - 2009, where Tables 67 - 69 also provide the amount of crop harvested in 2010 and the amount imported and exported from 2006 - 2010. The category Other Crops usually consists of the crops potato, sugar beet, fruit, vegetables and linseed, but from 2000 - 2005 only the quantity of potato and sugar beet harvested is known. This does not alter the data much, as the UK category Other Crops harvest mainly consists of potato and sugar beet.

With this information the quantity of phosphorus and nitrogen in the crops grown in the UK, imported and exported can be calculated, as shown in Tables 93 and 94. The total amount of food available for UK consumption is obtained

\[
\text{UK crop availability} = \text{UK harvest} + \text{import} - \text{export}. \tag{C.1}
\]

Applying

\[
E_{\text{content}} = \frac{E_{\text{grown}}}{C_{\text{grown}}} \cdot C_{\text{imp/resp}}, \tag{C.2}
\]

provides the quantity of phosphorus and nitrogen for a crop imported or exported.

Here \(E_{\text{content}}\) is the content of one of the two elements in a certain crop quantity, \(E_{\text{grown}}\) the quantity of phosphorus or nitrogen found in the harvested crop in the UK, \(C_{\text{grown}}\) the amount of the crop harvested in the UK, and finally \(C_{\text{imp/resp}}\) is the amount of the crop that was imported or exported.

For example, the UK cereal production in 2006 used 71 tonnes of phosphorus to harvest 20.816 million tonnes of the crop, of which 2.745 million tonnes was exported. Applying equation (C.2) gives the amount of phosphorus exported through this crop in 2006 to be

\[
P_{\text{content}} = \frac{P_{\text{grown}}}{C_{\text{rgrown}}} \cdot C_{\text{exp}} = \frac{71}{20.816 \cdot 10^6} \cdot 2.745 \cdot 10^6 = 9.353 t.
\]

For beans and peas the amount of this crop imported and exported is not known, therefore the amount of elements lost or gained through this process is not given.
Table 93: Statistics for crops harvested in the UK, and the quantity imported and exported, given in tonnes, where $P$ and $N$ are the quantity of phosphorus and nitrogen in the crop, and “-” is data no available for that year.
<table>
<thead>
<tr>
<th>Year</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK other crop production (10^6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>36</td>
<td>36</td>
<td>45</td>
<td>55</td>
<td>50</td>
<td>60</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Other crop import (10^6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>7.824</td>
<td>8.337</td>
<td>8.421</td>
<td>7.966</td>
<td>8.034</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1.932</td>
<td>2.193</td>
<td>2.094</td>
<td>1.772</td>
<td>2.042</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other crop export (10^6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>1.773</td>
<td>1.193</td>
<td>1.21</td>
<td>1.228</td>
<td>1.301</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>N</td>
<td>2.627</td>
<td>1.805</td>
<td>1.799</td>
<td>1.776</td>
<td>2.15</td>
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<tr>
<td>Total UK availability (10^6)</td>
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<td></td>
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</tr>
<tr>
<td>P</td>
<td>22.25</td>
<td>22.34</td>
<td>24.023</td>
<td>24.715</td>
<td>22.467</td>
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<td></td>
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</tr>
<tr>
<td>N</td>
<td>32.965</td>
<td>33.795</td>
<td>35.723</td>
<td>35.745</td>
<td>37.126</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>UK beans and peas production (10^6)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.745</td>
<td>0.891</td>
<td>0.886</td>
<td>0.905</td>
<td>0.837</td>
<td>0.861</td>
<td>0.739</td>
<td>0.455</td>
<td>0.611</td>
<td>0.786</td>
<td>0.66</td>
</tr>
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<td>N</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 94: Statistics for crops harvested in the UK, and the quantity imported and exported, given in tonnes, where P and N are the quantity of phosphorus and nitrogen in the crop, and “-” is data no available for that year.
Similar method was used to calculate the amount of phosphorus and nitrogen in animal products reared in the UK, imported, exported and total amount available for UK consumption, see Table 95 for the results.

Table 92 lists the quantity of the elements in certain animal product, which by multiplying this by the production quantities given in Tables 70 - 73, 75, 77, 79 - 81 allows for the quantity of the elements in the products to be obtained, i.e.

\[
E_{\text{content}} = A_{\text{product}} \cdot E_{\text{content for 1g}} \cdot 10^{-3}. \quad \text{(C.3)}
\]

Here \(E_{\text{content}}\) is the quantity of either phosphorus or nitrogen in a certain animal product, \(A_{\text{product}}\) is the quantity of an animal product, and \(E_{\text{content for 1g}}\) is the amount of 1 milligram of the element in 1 gram of the chosen animal product, as given in Table 92.

For example the amount of nitrogen imported in meat in 2006 is obtained by adding the various types of meat imported from Tables 70 and 71, giving 1.705 million tonnes of meat being imported. Given in Table 92, on average 22.6497 mg of nitrogen is in 1 g of meat. Applying equation (C.3) gives the amount of nitrogen in meat imported into the UK in 2006 to be

\[
N_{\text{content}} = \text{Meat import} \cdot N_{\text{meat content}} = 1.705 \cdot 10^6 \cdot 22.647 \cdot 10^{-3} = 38,613.13t.
\]

Table 96 shows an overview of quantity and phosphorus and nitrogen produced in the UK through animal products and crops. By combining both products together provides an insight into the UK food production grown or reared in the UK. Tables 97 and 98 summarise the amount of food and the quantity of phosphorus and nitrogen in crops, animal products and a combination of both imported and exported respectively. Finally, Table 99 summarises the total amount of phosphorus and nitrogen available for human and animal consumption in the UK, which was obtained by applying equation (C.1) to the data.
### UK meat production (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>3.364</td>
<td>76,193.59</td>
</tr>
<tr>
<td>2007</td>
<td>3.388</td>
<td>6,928.46</td>
</tr>
<tr>
<td>2008</td>
<td>3.366</td>
<td>6,883.47</td>
</tr>
<tr>
<td>2009</td>
<td>3.274</td>
<td>6,695.33</td>
</tr>
<tr>
<td>2010</td>
<td>3.47</td>
<td>7,096.15</td>
</tr>
</tbody>
</table>

### UK meat import (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>1.705</td>
<td>3,486.72</td>
</tr>
<tr>
<td>2007</td>
<td>1.746</td>
<td>3,570.57</td>
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<tr>
<td>2008</td>
<td>1.649</td>
<td>3,372.20</td>
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<tr>
<td>2009</td>
<td>1.663</td>
<td>3,400.83</td>
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<tr>
<td>2010</td>
<td>1.692</td>
<td>3,460.14</td>
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### UK meat export (10^6)

<table>
<thead>
<tr>
<th>Year</th>
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<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.5</td>
<td>9,343.60</td>
</tr>
<tr>
<td>2007</td>
<td>0.572</td>
<td>103,486.58</td>
</tr>
<tr>
<td>2008</td>
<td>0.629</td>
<td>9,883.48</td>
</tr>
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<td>2009</td>
<td>0.593</td>
<td>9,202.5</td>
</tr>
<tr>
<td>2010</td>
<td>0.662</td>
<td>101,923.65</td>
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</tbody>
</table>

### UK meat total (10^6)

<table>
<thead>
<tr>
<th>Year</th>
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<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>4.569</td>
<td>3,469.78</td>
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<tr>
<td>2007</td>
<td>4.562</td>
<td>3,567.11</td>
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<tr>
<td>2008</td>
<td>4.386</td>
<td>3,386.37</td>
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<tr>
<td>2009</td>
<td>4.344</td>
<td>3,444.89</td>
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<td>2010</td>
<td>4.5</td>
<td>3,459.65</td>
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### UK fish production (10^6)

<table>
<thead>
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<th>Year</th>
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<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.614</td>
<td>938.192</td>
</tr>
<tr>
<td>2007</td>
<td>0.64</td>
<td>932.08</td>
</tr>
<tr>
<td>2008</td>
<td>0.588</td>
<td>898.46</td>
</tr>
<tr>
<td>2009</td>
<td>0.581</td>
<td>887.77</td>
</tr>
<tr>
<td>2010</td>
<td>0.606</td>
<td>925.97</td>
</tr>
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</table>

### UK fish import (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.754</td>
<td>1,152.11</td>
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<tr>
<td>2007</td>
<td>0.748</td>
<td>1,142.94</td>
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<td>2008</td>
<td>0.782</td>
<td>1,194.90</td>
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<td>2009</td>
<td>0.720</td>
<td>1,100.16</td>
</tr>
<tr>
<td>2010</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### UK fish export (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.461</td>
<td>704.41</td>
</tr>
<tr>
<td>2007</td>
<td>0.467</td>
<td>713.58</td>
</tr>
<tr>
<td>2008</td>
<td>0.416</td>
<td>635.65</td>
</tr>
<tr>
<td>2009</td>
<td>0.479</td>
<td>731.91</td>
</tr>
<tr>
<td>2010</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### UK fish total (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.907</td>
<td>1,385.90</td>
</tr>
<tr>
<td>2007</td>
<td>0.891</td>
<td>1,361.45</td>
</tr>
<tr>
<td>2008</td>
<td>0.954</td>
<td>1,457.71</td>
</tr>
<tr>
<td>2009</td>
<td>0.822</td>
<td>1,256.02</td>
</tr>
<tr>
<td>2010</td>
<td>0.606</td>
<td>925.97</td>
</tr>
</tbody>
</table>

### UK milk production (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>13.099</td>
<td>29.669</td>
</tr>
<tr>
<td>2007</td>
<td>13.626</td>
<td>30.863</td>
</tr>
<tr>
<td>2008</td>
<td>13.326</td>
<td>30.183</td>
</tr>
<tr>
<td>2009</td>
<td>13.204</td>
<td>29.907</td>
</tr>
<tr>
<td>2010</td>
<td>13.048</td>
<td>30.587</td>
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### UK milk import (10^6 litres)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.033</td>
<td>0.075</td>
</tr>
<tr>
<td>2007</td>
<td>0.057</td>
<td>0.129</td>
</tr>
<tr>
<td>2008</td>
<td>0.049</td>
<td>0.111</td>
</tr>
<tr>
<td>2009</td>
<td>0.075</td>
<td>0.170</td>
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<tr>
<td>2010</td>
<td>0.067</td>
<td>0.152</td>
</tr>
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</table>

### UK milk export (10^6 litres)

<table>
<thead>
<tr>
<th>Year</th>
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<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.617</td>
<td>5.088</td>
</tr>
<tr>
<td>2007</td>
<td>0.538</td>
<td>5.550</td>
</tr>
<tr>
<td>2008</td>
<td>0.599</td>
<td>5.033</td>
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<tr>
<td>2009</td>
<td>0.510</td>
<td>4.833</td>
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<tr>
<td>2010</td>
<td>0.581</td>
<td>4.833</td>
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</table>

### UK milk total (10^6 litres)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>12.515</td>
<td>28.346</td>
</tr>
<tr>
<td>2007</td>
<td>12.528</td>
<td>28.376</td>
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<tr>
<td>2008</td>
<td>12.816</td>
<td>29.028</td>
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<tr>
<td>2009</td>
<td>12.846</td>
<td>29.096</td>
</tr>
<tr>
<td>2010</td>
<td>13.138</td>
<td>29.758</td>
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### UK egg production (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.51</td>
<td>776.22</td>
</tr>
<tr>
<td>2007</td>
<td>0.50</td>
<td>761.76</td>
</tr>
<tr>
<td>2008</td>
<td>0.52</td>
<td>791.44</td>
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<tr>
<td>2009</td>
<td>0.52</td>
<td>791.44</td>
</tr>
<tr>
<td>2010</td>
<td>0.57</td>
<td>867.54</td>
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</table>

### UK egg import (10^6)

<table>
<thead>
<tr>
<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.102</td>
<td>155.24</td>
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<tr>
<td>2007</td>
<td>0.123</td>
<td>187.21</td>
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<td>2008</td>
<td>0.132</td>
<td>200.90</td>
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<td>2009</td>
<td>0.135</td>
<td>205.47</td>
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<tr>
<td>2010</td>
<td>0.122</td>
<td>185.68</td>
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</table>

### UK egg export (10^6)

<table>
<thead>
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<th>Year</th>
<th>Phosphorus</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>175.79</td>
<td>157.99</td>
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<tr>
<td>2007</td>
<td>211.93</td>
<td>217.24</td>
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<td>2008</td>
<td>227.49</td>
<td>232.66</td>
</tr>
<tr>
<td>2009</td>
<td>232.66</td>
<td>239.26</td>
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<tr>
<td>2010</td>
<td>210.25</td>
<td>210.25</td>
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### UK egg import (10^6)

<table>
<thead>
<tr>
<th>Year</th>
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<tr>
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<td>18.96</td>
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<td>17.23</td>
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<td>2010</td>
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### UK egg export (10^6)

<table>
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<th>Year</th>
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<td>391.72</td>
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<td>2008</td>
<td>971.04</td>
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<td>2009</td>
<td>980.17</td>
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<tr>
<td>2010</td>
<td>1,033.44</td>
<td>1,170.19</td>
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</table>

Table 95: Statistics for animal products reared in the UK, imported and exported, given in tonnes.
### Table 96: Statistics for crops grown and animal products reared in the UK, given in tonnes, where P and N are the quantity of phosphorus and nitrogen in the product.

<table>
<thead>
<tr>
<th></th>
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<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
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<th>2008</th>
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<th>2010</th>
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</thead>
<tbody>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>17.59</td>
<td>18.12</td>
<td>17.8</td>
<td>17.58</td>
<td>18.15</td>
</tr>
<tr>
<td>products</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>P</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>8,922.25</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>78,777.32</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>P</td>
<td>96</td>
<td>80</td>
<td>95</td>
<td>92</td>
<td>93</td>
<td>92</td>
<td>84</td>
<td>102</td>
<td>95</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>N</td>
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<td>465</td>
<td>563</td>
<td>570</td>
<td>572</td>
<td>570</td>
<td>528</td>
<td>487</td>
<td>547</td>
<td>521</td>
<td>519</td>
</tr>
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<td></td>
</tr>
<tr>
<td>P</td>
<td>96</td>
<td>80</td>
<td>95</td>
<td>92</td>
<td>93</td>
<td>92</td>
<td>8,713.46</td>
<td>8,736.40</td>
<td>8,705.56</td>
<td>8,499.45</td>
<td>9,014.25</td>
</tr>
<tr>
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<td>544</td>
<td>465</td>
<td>563</td>
<td>570</td>
<td>572</td>
<td>570</td>
<td>78,784.29</td>
<td>79,264.32</td>
<td>78,818.74</td>
<td>76,695.58</td>
<td>81,266.38</td>
</tr>
</tbody>
</table>

|            |       |       |       |       |       |       |       |       |       |       |       |

Table 96: Statistics for crops grown and animal products reared in the UK, given in tonnes, where P and N are the quantity of phosphorus and nitrogen in the product.
<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal products (10^6)</td>
<td>2.59</td>
<td>2.67</td>
<td>2.612</td>
<td>2.59</td>
<td>1.88</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>4,794.14</td>
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<td>4,768.11</td>
<td>4,706.63</td>
<td>3,645.97</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>40,184.93</td>
<td>41,138.74</td>
<td>39,019.98</td>
<td>39,227.94</td>
<td>38,585.93</td>
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<tr>
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<td>10.47</td>
<td>11.16</td>
<td>11.19</td>
<td>10.46</td>
<td>10.43</td>
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<td>11.93</td>
<td>11.93</td>
<td>10.41</td>
<td>10.64</td>
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<td>65.93</td>
<td>67.86</td>
<td>64.53</td>
<td>57.38</td>
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<tr>
<td>Total (10^6)</td>
<td>13.07</td>
<td>13.84</td>
<td>13.80</td>
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<td>4,780.04</td>
<td>4,717.04</td>
<td>3,656.61</td>
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<td>39,084.51</td>
<td>39,285.32</td>
<td>38,646.56</td>
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</table>

Table 97: Statistics for crops and animal products import into the UK, given in tonnes. Here Phosphorus and Nitrogen are the quantity of phosphorus and nitrogen in the product.
<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal products (10^6)</td>
<td>1.59</td>
<td>1.59</td>
<td>2.64</td>
<td>1.516</td>
<td>1.77</td>
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<td>Phosphorus</td>
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<td>12,196.84</td>
<td>13,685.65</td>
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<td>3.90</td>
<td>4.89</td>
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<td>10.23</td>
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<td>Nitrogen</td>
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<td>56.88</td>
<td>70.76</td>
<td>65.29</td>
<td>94.21</td>
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<td>Total (10^6)</td>
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<td>5.48</td>
<td>7.529</td>
<td>6.19</td>
<td>7.77</td>
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<td>1,909.99</td>
<td>1,957.98</td>
<td>1,243.12</td>
<td>1,391.56</td>
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<td>13,742.53</td>
<td>15,111.32</td>
<td>14,246.19</td>
<td>15,112.39</td>
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</table>

Table 98: Statistics for crops and animal products export from the UK, given in tonnes. Here Phosphorus and Nitrogen are the quantity of phosphorus and nitrogen in the product.

<table>
<thead>
<tr>
<th></th>
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<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Animal products (10^6)</td>
<td>18.59</td>
<td>18.59</td>
<td>18.79</td>
<td>18.66</td>
<td>18.92</td>
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<tr>
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<td>11,672.57</td>
<td>11,656.67</td>
<td>11,427.15</td>
<td>11,148.77</td>
<td>11,191.67</td>
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<tr>
<td>Nitrogen</td>
<td>106,209.78</td>
<td>106,077.05</td>
<td>102,251.16</td>
<td>101,111.78</td>
<td>104,263.00</td>
</tr>
<tr>
<td>Crops (10^6)</td>
<td>45.43</td>
<td>44.16</td>
<td>49.98</td>
<td>48.07</td>
<td>44.00</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>90.33</td>
<td>85.74</td>
<td>100.6</td>
<td>93.17</td>
<td>85.54</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>530.55</td>
<td>485.96</td>
<td>541.39</td>
<td>513.09</td>
<td>485.42</td>
</tr>
<tr>
<td>Total (10^6)</td>
<td>64.022</td>
<td>62.75</td>
<td>68.77</td>
<td>66.73</td>
<td>62.92</td>
</tr>
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<td>Phosphorus</td>
<td>11,762.90</td>
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<td>11,527.75</td>
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<tr>
<td>Nitrogen</td>
<td>106,740.33</td>
<td>106,563.01</td>
<td>102,792.546</td>
<td>101,624.87</td>
<td>104,748.42</td>
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</table>

Table 99: Statistics for total quantity of food available in the UK for human and animal consumption, given in tonnes. Here Phosphorus and Nitrogen are the quantity of phosphorus and nitrogen in the product.
Next, the quantity of phosphorus and nitrogen for animal consumption, available for human consumption and the amount purchased by humans are computed.

From Table 88 the amount of food fed to animals from 2000 - 2010 is known, from which the quantity of food, phosphorus and nitrogen fed to livestock can be calculated. Tables 100 and 101 show the results of the quantity of food, the quantity of phosphorus and nitrogen it contains, which has been summarised into the categories: cereal, oilseed, other, beans and peas and all meal. All meal is animal remainders, for which the quantity of phosphorus and nitrogen in it is obtained by using the quantity of the nutrients in meat, as given in Table 92. It is assumed there is more phosphorus and nitrogen in this category, as there are more nutrients in bones.

The quantity of nutrients in the category available for human consumption is defined as

\[ \text{Available for human consumption} = \text{UK food production} - \text{import} - \text{export} - \text{animal consumption}. \]  

(C.4)

For 2000 - 2005 the crop availability is based on the UK crop production as the amount of crop imported and exported is not known. The quantity of food available for human consumption for the years 2000 - 2010 are listed in Tables 102 and 103.

From Tables 82 and 83 the quantity of food purchased per person per week is given. The quantity of food purchased in total per year in the whole UK is obtained by

\[ F_{\text{year}} = F_{\text{PPW}} \cdot 10^{-6} \cdot 52 \cdot 61.8 \cdot 10^6, \]  

(C.5)

where it is assumed that there are 61.8 million people in the UK and there are 52 weeks in a year.

Here \( F_{\text{year}} \) is the type of food purchased in a year, \( F_{\text{PPW}} \) the type of food purchased per week per person as given in Tables 82 and 83. Tables 104 and 105 show the quantity of food purchased over the whole year in the UK.

Tables 104 and 105 need to be adapted such that the food purchased by humans fits into one of the following categories: cereal, oilseed, beans and peas, other, meat, fish, eggs, milk and cheese, as these are the general categories the crop and animal products obtained from earlier are grouped in. The category cereal contains bread, flour, other cereals and cereal products, cakes, buns and pastries, and biscuits and crispbread. There is no oilseed used in the human
consumption except for in oils, which do not contain any phosphorus and the quantity of nitrogen in oil is not known. The category other contains vegetables, potatoes and fruit. Cheese, milk and cream are combined into the dairy category, where the amount of phosphorus and nitrogen in this category is determined through the milk content given in Table 92. From Tables 44 and 46 the amount of phosphorus and nitrogen in the UK crop harvest is given and by using equation (C.2) the amount of element in the food can be calculated. As no data on animal products pre-2006 is available, the same data for 2006 is used for the time series 2000-2006. Table 106 shows the results of the food quantity purchased and the quantity of phosphorus and nitrogen in it.
<table>
<thead>
<tr>
<th></th>
<th>2000</th>
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<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>118.972</td>
<td>122.891</td>
<td>125.602</td>
<td>129.461</td>
<td>130.514</td>
<td>124.291</td>
</tr>
<tr>
<td>Oilseed ((\times 10^6))</td>
<td>0.655</td>
<td>0.619</td>
<td>0.581</td>
<td>0.542</td>
<td>0.552</td>
<td>0.521</td>
</tr>
<tr>
<td>Other ((\times 10^6))</td>
<td>2.491</td>
<td>2.894</td>
<td>2.561</td>
<td>2.632</td>
<td>2.649</td>
<td>2.362</td>
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<tr>
<td>Phosphorus</td>
<td>0.645</td>
<td>0.781</td>
<td>0.629</td>
<td>0.697</td>
<td>0.714</td>
<td>0.652</td>
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<tr>
<td>Nitrogen</td>
<td>5.809</td>
<td>7.027</td>
<td>7.075</td>
<td>9.582</td>
<td>8.921</td>
<td>9.782</td>
</tr>
<tr>
<td>Field Beans &amp; Peas ((\times 10^6))</td>
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<td>0.139</td>
<td>0.164</td>
<td>0.165</td>
<td>0.127</td>
<td>0.118</td>
</tr>
<tr>
<td>Phosphorus</td>
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<td>0.624</td>
<td>0.740</td>
<td>0.729</td>
<td>0.607</td>
<td>0.548</td>
</tr>
<tr>
<td>Nitrogen</td>
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<td>5.626</td>
<td>6.664</td>
<td>6.563</td>
<td>5.159</td>
<td>4.793</td>
</tr>
<tr>
<td>All meal ((\times 10^6))</td>
<td>0.177</td>
<td>0.171</td>
<td>0.159</td>
<td>0.145</td>
<td>0.135</td>
<td>0.130</td>
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<tr>
<td>Phosphorus</td>
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<td>349.695</td>
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<td>276.075</td>
<td>265.85</td>
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<tr>
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<td>376.79</td>
<td>352.496</td>
<td>323.606</td>
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<td>3,237.457</td>
<td>3,099.765</td>
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</table>

<table>
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<tr>
<th></th>
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<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>128.781</td>
<td>124.627</td>
<td>113.214</td>
<td>112.212</td>
<td>127.803</td>
</tr>
<tr>
<td>Oilseed ($10^6$)</td>
<td>0.664</td>
<td>0.717</td>
<td>0.808</td>
<td>0.777</td>
<td>0.831</td>
</tr>
<tr>
<td>Phosphorus</td>
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<td>4.422</td>
<td>4.914</td>
<td>4.876</td>
<td>5.217</td>
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<tr>
<td>Other ($10^6$)</td>
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<td>2.753</td>
<td>2.840</td>
<td>2.651</td>
<td>2.710</td>
</tr>
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<td>Phosphorus</td>
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<td>0.724</td>
<td>0.676</td>
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<td>0.6889</td>
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<td>4.478</td>
</tr>
<tr>
<td>Field Beans &amp; Peas ($10^6$)</td>
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<td>0.109</td>
<td>0.068</td>
<td>0.119</td>
<td>0.135</td>
</tr>
<tr>
<td>Phosphorus</td>
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<td>0.479</td>
<td>0.334</td>
<td>0.605</td>
<td>0.614</td>
</tr>
<tr>
<td>Nitrogen</td>
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<td>4.552</td>
<td>2.782</td>
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<td>5.523</td>
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<tr>
<td>All meal ($10^6$)</td>
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<td>0.117</td>
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<td>0.110</td>
</tr>
<tr>
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<td>218.815</td>
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<td>3,430.504</td>
<td>2,655.359</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
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<td>55.59</td>
<td>50.71</td>
<td>52.65</td>
<td>50.04</td>
<td>48.26</td>
<td>44.25</td>
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<td>236.47</td>
<td>311.45</td>
<td>294.54</td>
<td>307.49</td>
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<td>1.17</td>
<td>1.19</td>
</tr>
<tr>
<td>P</td>
<td>3.04</td>
<td>3.25</td>
<td>5.43</td>
<td>7.63</td>
<td>6.57</td>
<td>8.71</td>
<td>7.37</td>
<td>7.34</td>
</tr>
<tr>
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<td>32.85</td>
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<td>12.20</td>
<td>12.48</td>
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<td>19.59</td>
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<td>UK beans and peas production (10^6)</td>
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<td>P</td>
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<td>3.38</td>
<td>3.26</td>
<td>3.27</td>
<td>3.39</td>
<td>3.45</td>
<td>2.36</td>
<td>1.52</td>
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<td>29.34</td>
<td>29.44</td>
<td>28.84</td>
<td>30.20</td>
<td>23.63</td>
<td>14.45</td>
</tr>
<tr>
<td>Crops (10^6)</td>
<td>31.74</td>
<td>25.78</td>
<td>31.71</td>
<td>29.38</td>
<td>29.42</td>
<td>29.14</td>
<td>35.6</td>
<td>34.12</td>
</tr>
<tr>
<td>P</td>
<td>69.29</td>
<td>52.9</td>
<td>67.05</td>
<td>64.91</td>
<td>65.9</td>
<td>65.55</td>
<td>62.88</td>
<td>58.26</td>
</tr>
<tr>
<td>N</td>
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<td>312.56</td>
<td>405.9</td>
<td>407.57</td>
<td>410.26</td>
<td>410.33</td>
<td>371.36</td>
<td>330.85</td>
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<tr>
<td>Animal products (10^6)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>18.59</td>
<td>18.59</td>
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<tr>
<td>P</td>
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<td>11,656.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>106,209.78</td>
<td>106,077.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (10^6)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>54.19</td>
<td>52.71</td>
</tr>
<tr>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11,735.45</td>
<td>11,714.83</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>106,581.14</td>
<td>106,407.9</td>
</tr>
</tbody>
</table>

Table 102: Food available for human consumption, given in tonnes. Here P and N are the quantity of phosphorus and nitrogen in the product.
<table>
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<tr>
<th></th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cereal (10^6)</td>
<td>17.12</td>
<td>14.56</td>
<td>11.97</td>
</tr>
<tr>
<td></td>
<td>58.53</td>
<td>50.53</td>
<td>40.59</td>
</tr>
<tr>
<td></td>
<td>308.79</td>
<td>268.13</td>
<td>226.38</td>
</tr>
<tr>
<td>Oilseed (10^6)</td>
<td>1.12</td>
<td>1.13</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>6.82</td>
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<td>34.09</td>
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<td>41.03</td>
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<tr>
<td>Other crop (10^6)</td>
<td>21.18</td>
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<td>19.76</td>
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<td>5.04</td>
<td>4.91</td>
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<td>31.5</td>
<td>31.91</td>
<td>32.65</td>
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<tr>
<td>UK beans and peas</td>
<td>0.54</td>
<td>0.67</td>
<td>0.52</td>
</tr>
<tr>
<td>production (10^6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.52</td>
<td>2.67</td>
<td>3.39</td>
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<tr>
<td></td>
<td>22.22</td>
<td>30.55</td>
<td>21.477</td>
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<td>Crops (10^6)</td>
<td>39.96</td>
<td>39.42</td>
<td>316.56</td>
</tr>
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<td></td>
<td>73.06</td>
<td>65.95</td>
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<td></td>
<td>396.6</td>
<td>366.79</td>
<td>322.54</td>
</tr>
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<td>Animal products (10^6)</td>
<td>18.79</td>
<td>18.66</td>
<td>18.92</td>
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<td>11,148.77</td>
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<td></td>
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<td>104,263.00</td>
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<td>Total (10^6)</td>
<td>58.75</td>
<td>58.08</td>
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<td>11,214.72</td>
<td>11,247.87</td>
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<td></td>
<td>102,647.76</td>
<td>101,478.57</td>
<td>104,585.54</td>
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*Table 103: Food available for human consumption, given in tonnes. Here P and N are the quantity of phosphorus and nitrogen in the product.*
<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread</td>
<td>2.22</td>
<td>2.18</td>
<td>2.12</td>
<td>2.11</td>
</tr>
<tr>
<td>Vegetables</td>
<td>3.67</td>
<td>3.66</td>
<td>3.59</td>
<td>3.45</td>
</tr>
<tr>
<td>Potatoes</td>
<td>2.60</td>
<td>2.50</td>
<td>2.49</td>
<td>2.45</td>
</tr>
<tr>
<td>Fruit</td>
<td>4.22</td>
<td>4.12</td>
<td>3.85</td>
<td>3.67</td>
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<tr>
<td>Flour</td>
<td>0.170</td>
<td>0.170</td>
<td>0.202</td>
<td>0.182</td>
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<tr>
<td>Other cereals</td>
<td>1.703</td>
<td>1.722</td>
<td>1.719</td>
<td>1.761</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>and cereal products</td>
<td></td>
</tr>
<tr>
<td>Milk and cream (ml)</td>
<td>6.498</td>
<td>6.376</td>
<td>6.289</td>
<td>6.437</td>
</tr>
<tr>
<td>Cheese</td>
<td>0.373</td>
<td>0.382</td>
<td>0.357</td>
<td>0.373</td>
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<tr>
<td>Carcase meat</td>
<td>0.765</td>
<td>0.755</td>
<td>0.678</td>
<td>0.681</td>
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<tr>
<td>Non-carcase meat</td>
<td>2.584</td>
<td>2.555</td>
<td>2.529</td>
<td>2.529</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>and meat products</td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td>0.546</td>
<td>0.530</td>
<td>0.517</td>
<td>0.508</td>
</tr>
<tr>
<td>Eggs *</td>
<td>0.445</td>
<td>0.432</td>
<td>0.452</td>
<td>0.451</td>
</tr>
<tr>
<td>Fats</td>
<td>0.591</td>
<td>0.582</td>
<td>0.591</td>
<td>0.582</td>
</tr>
<tr>
<td>Sugar and preserves</td>
<td>0.405</td>
<td>0.402</td>
<td>0.591</td>
<td>0.582</td>
</tr>
<tr>
<td>Cakes, buns and pastries</td>
<td>0.530</td>
<td>0.511</td>
<td>0.492</td>
<td>0.508</td>
</tr>
<tr>
<td>Biscuits and crispbreads</td>
<td>0.530</td>
<td>0.524</td>
<td>0.546</td>
<td>0.543</td>
</tr>
<tr>
<td>Beverages</td>
<td>0.177</td>
<td>0.180</td>
<td>0.177</td>
<td>0.173</td>
</tr>
<tr>
<td>Soft drinks (ml)</td>
<td>5.807</td>
<td>5.418</td>
<td>5.405</td>
<td>5.392</td>
</tr>
<tr>
<td>Confectionery</td>
<td>0.395</td>
<td>0.414</td>
<td>0.421</td>
<td>0.430</td>
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<tr>
<td>Alcoholic drinks (ml)</td>
<td>2.442</td>
<td>2.481</td>
<td>2.269</td>
<td>2.391</td>
</tr>
</tbody>
</table>

Table 104: Quantity of food purchased, given in million tonnes.
Table 105: Quantity of food purchased in the UK, given in million tonnes.

<table>
<thead>
<tr>
<th>Item</th>
<th>2002-03</th>
<th>2004-05</th>
<th>2005-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk and cream (mil l)</td>
<td>6.45</td>
<td>6.41</td>
<td>6.51</td>
</tr>
<tr>
<td>Liquid whole milk (mil l)</td>
<td>1.84</td>
<td>1.60</td>
<td>1.53</td>
</tr>
<tr>
<td>Cheese</td>
<td>0.36</td>
<td>0.35</td>
<td>0.33</td>
</tr>
<tr>
<td>Carcass meat</td>
<td>0.74</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>Other meat and other meat products</td>
<td>2.63</td>
<td>2.63</td>
<td>2.64</td>
</tr>
<tr>
<td>Fish</td>
<td>0.498</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>Eggs *</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Fats</td>
<td>0.61</td>
<td>0.58</td>
<td>0.59</td>
</tr>
<tr>
<td>Butter</td>
<td>0.12</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Sugar and preserves</td>
<td>0.47</td>
<td>0.43</td>
<td>0.41</td>
</tr>
<tr>
<td>Fresh and processed potatoes</td>
<td>2.80</td>
<td>2.64</td>
<td>2.71</td>
</tr>
<tr>
<td>Fruit and vegetables excluding potatoes</td>
<td>7.41</td>
<td>7.31</td>
<td>7.87</td>
</tr>
<tr>
<td>Vegetables excluding potatoes</td>
<td>3.54</td>
<td>3.55</td>
<td>3.71</td>
</tr>
<tr>
<td>Fruit</td>
<td>3.88</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>Cereals</td>
<td>5.37</td>
<td>5.07</td>
<td>5.22</td>
</tr>
<tr>
<td>Bread</td>
<td>2.43</td>
<td>2.23</td>
<td>2.25</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td><strong>Cereal purchase (10^6)</strong></td>
<td>7.8</td>
<td>7.3</td>
<td>7.47</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>26.47</td>
<td>24.88</td>
<td>25.6</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>153.74</td>
<td>145.3</td>
<td>147.54</td>
</tr>
<tr>
<td><strong>Other purchase (10^6)</strong></td>
<td>10.21</td>
<td>9.95</td>
<td>10.58</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>2.7</td>
<td>2.68</td>
<td>2.92</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>37.17</td>
<td>33.51</td>
<td>43.82</td>
</tr>
<tr>
<td><strong>Dairy purchase (10^6)</strong></td>
<td>8.65</td>
<td>8.36</td>
<td>8.37</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>19.59</td>
<td>18.93</td>
<td>18.96</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>33.56</td>
<td>32.44</td>
<td>32.48</td>
</tr>
<tr>
<td><strong>Eggs purchase (10^6)</strong></td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>487.04</td>
<td>487.04</td>
<td>487.04</td>
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<tr>
<td>Nitrogen</td>
<td>551.488</td>
<td>551.488</td>
<td>551.488</td>
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<tr>
<td><strong>Meat purchase (10^6)</strong></td>
<td>3.37</td>
<td>3.37</td>
<td>3.37</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>6,891.65</td>
<td>6,891.65</td>
<td>6,891.65</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>76,329.489</td>
<td>76,329.489</td>
<td>76,329.489</td>
</tr>
<tr>
<td><strong>Fish purchase (10^6)</strong></td>
<td>0.498</td>
<td>0.51</td>
<td>0.54</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>760.944</td>
<td>779.28</td>
<td>825.12</td>
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<tr>
<td>Nitrogen</td>
<td>918.910</td>
<td>941.052</td>
<td>996.408</td>
</tr>
<tr>
<td><strong>Total purchase (10^6)</strong></td>
<td>30.85</td>
<td>29.81</td>
<td>30.65</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>8,188.39</td>
<td>8,204.46</td>
<td>8,251.29</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>78,024.36</td>
<td>78,033.28</td>
<td>78,101.22</td>
</tr>
</tbody>
</table>

*Table 106: Quantity of food purchased, given in tonnes.*
In Table 91 the quantity of UK biodiesel production and consumption is given in barrels a day, from which the quantity of biodiesel produced and consumed per year given in litres as shown in Table 107. Here 1 Barrel = 158.9873 litres and there are 365 days in a year.
Table 107: Biodiesel production and consumption in the UK.
Only 40% of oil is gathered from oilseed crop, of which 97% is converted into biodiesel [149]. Therefore

\[ \text{Oilseed (tonnes)} = 0.4 \cdot 0.97 \cdot \text{Biodiesel (litres)}, \]  

(C.6)

calculates the amount of oilseed needed to produce a certain quantity of biodiesel.

Not all biodiesel is produced from the oilseed, as tallow and used cooking oil are also good substances. In Table 108 the UK biodiesel production and consumption is given, the quantity of oilseed rape used to produce the UK biodiesel production as given by DEFRA: Area of Crops Grown For Bioenergy in England and the UK: 2008-2011 (Table 4). From this, the amount of phosphorus and nitrogen in the oilseed needed to produce the biodiesel can be estimated.
<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong> (10^6 litres)</td>
<td>0</td>
<td>0</td>
<td>3.481</td>
<td>11.606</td>
<td>11.606</td>
<td>52.23</td>
<td>290.15</td>
<td>464.24</td>
<td>319.16</td>
<td>232.12</td>
<td>232.12</td>
</tr>
<tr>
<td><strong>Oilseed (tonnes)</strong> (10^3 litres)</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>50</td>
<td>60</td>
<td>14.5</td>
</tr>
<tr>
<td><strong>Phosphorus (tonnes)</strong></td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.304</td>
<td>0.376</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>Nitrogen (tonnes)</strong></td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>1.52</td>
<td>1.91</td>
<td>0.455</td>
</tr>
<tr>
<td><strong>Consumption</strong> (10^6 litres)</td>
<td>0</td>
<td>0</td>
<td>0.006</td>
<td>0.017</td>
<td>0.023</td>
<td>0.035</td>
<td>0.168</td>
<td>0.348</td>
<td>0.89</td>
<td>1.044</td>
<td>1.044</td>
</tr>
</tbody>
</table>

Table 108: Biodiesel production and consumption in the UK, and where known, the quantity of oilseed rape used for production.
C.1.3. Data Used

This last section on data provides the tables as used in Chapter 4.
Table 109: Phosphorus (tonnes)

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
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<td>Fertiliser</td>
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<td>129</td>
<td>131</td>
<td>130</td>
<td>128</td>
<td>120</td>
</tr>
<tr>
<td>Soil</td>
<td>366</td>
<td>345</td>
<td>341</td>
<td>344</td>
<td>345</td>
<td>339</td>
</tr>
<tr>
<td>Other Crop</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>73</td>
<td>75</td>
<td>72</td>
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<td>Pulses</td>
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<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>and Beans</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>67.65</td>
<td>64.91</td>
<td>65.9</td>
<td>65.55</td>
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<td>Human Consumption</td>
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<td>0</td>
<td>8,188.39</td>
<td>8,204.46</td>
<td>8,251.29</td>
</tr>
<tr>
<td>Animal</td>
<td>388.67</td>
<td>376.79</td>
<td>352.50</td>
<td>323.61</td>
<td>303.17</td>
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<tr>
<td>Organic Waste</td>
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<td>26</td>
<td>28</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Loss</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 110: Phosphorus (tonnes)

<table>
<thead>
<tr>
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<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser</td>
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<td>105</td>
<td>101</td>
<td>63</td>
<td>81</td>
</tr>
<tr>
<td>Soil</td>
<td>327</td>
<td>317</td>
<td>311</td>
<td>271</td>
<td>289</td>
</tr>
<tr>
<td>Other Crop</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Cereal</td>
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<td>65</td>
<td>83</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
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<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Industrial Crop</td>
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<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
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<td>12</td>
<td>12</td>
<td>14</td>
</tr>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Import</td>
<td>4,805.49</td>
<td>4,912.78</td>
<td>4,780.04</td>
<td>4,717.04</td>
<td>3,656.61</td>
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<td>1,957.98</td>
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<td>1,391.56</td>
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<tr>
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<td>11,735.45</td>
<td>11,714.83</td>
<td>11,500.21</td>
<td>11,214.72</td>
<td>11,247.87</td>
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</table>

Human Consumption

<table>
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<tr>
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<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
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<tbody>
<tr>
<td>Human Purchase</td>
<td>8,390.43</td>
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<td>184</td>
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<td>174</td>
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<td>172</td>
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<td>Organic Waste</td>
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<td>34</td>
<td>36</td>
<td>36</td>
<td>36</td>
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<tr>
<td>Loss</td>
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<td>108,450</td>
<td>110,950</td>
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### Table 111: Nitrogen (tonnes)

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<td>2,597</td>
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<td>27</td>
<td>27</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<td>357</td>
<td>437</td>
<td>424</td>
<td>438</td>
<td>415</td>
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<td>Pulses and Beans</td>
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<td>36</td>
<td>36</td>
<td>34</td>
<td>35</td>
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<td>14</td>
<td>16</td>
<td>16</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Oilseed</td>
<td>36</td>
<td>36</td>
<td>45</td>
<td>55</td>
<td>50</td>
<td>60</td>
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<td>0</td>
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<td>0</td>
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<td>0.04</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<td>405.9</td>
<td>407.57</td>
<td>410.26</td>
<td>410.33</td>
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<td>Human Consumption</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Purchase</td>
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<td>N/A</td>
<td>N/A</td>
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<td>78,033.28</td>
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<td>4,159.61</td>
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<td>3,758.402</td>
<td>3,446.648</td>
<td>3,237.45</td>
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<td>1,115</td>
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<td>1,086</td>
<td>1,092</td>
<td>1,076</td>
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<tr>
<td>Organic Waste</td>
<td>33</td>
<td>41</td>
<td>41</td>
<td>44</td>
<td>47</td>
<td>54</td>
</tr>
<tr>
<td>Loss</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 112: Nitrogen (tonnes)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser</td>
<td>1,342</td>
<td>1,313</td>
<td>1,311</td>
<td>1,244</td>
<td>1,332</td>
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<tr>
<td>Soil</td>
<td>2,468</td>
<td>2,407</td>
<td>2,384</td>
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<td>2,393</td>
</tr>
<tr>
<td>Other Crop</td>
<td>24</td>
<td>23</td>
<td>25</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Cereal</td>
<td>416</td>
<td>369</td>
<td>437</td>
<td>398</td>
<td>396</td>
</tr>
<tr>
<td>Pulses and Beans</td>
<td>30</td>
<td>19</td>
<td>25</td>
<td>36</td>
<td>27</td>
</tr>
<tr>
<td>Industrial Crop</td>
<td>13</td>
<td>11</td>
<td>13</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Oilseed</td>
<td>58</td>
<td>64</td>
<td>60</td>
<td>61</td>
<td>70</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
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</tr>
<tr>
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<td>40,250.86</td>
<td>41,206.60</td>
<td>39,084.51</td>
<td>39,285.32</td>
<td>38,646.56</td>
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<td>12,260.20</td>
<td>13,724.535</td>
<td>15,111.32</td>
<td>14,246.193</td>
<td>15,112.39</td>
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<tr>
<td>Total Available</td>
<td>106,581.14</td>
<td>106,407.90</td>
<td>102,647.76</td>
<td>101,478.57</td>
<td>104,585.54</td>
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<tr>
<td>for Human Consumption</td>
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</tr>
<tr>
<td>Human Purchase</td>
<td>77,787.34</td>
<td>76,234.02</td>
<td>74,567.00</td>
<td>74,551.00</td>
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</tr>
<tr>
<td>Animal Consumption</td>
<td>3,012.957</td>
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</tr>
<tr>
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<td>1,035</td>
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<td>997</td>
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<tr>
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<td>56</td>
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<td>60</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Loss</td>
<td>777,400</td>
<td>887,400</td>
<td>993,400</td>
<td>1,099,000</td>
<td>N/A</td>
</tr>
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</table>
C.2. Metabolic Flows Model Equations

This section provides the equations used for the KIDS model in Chapter 4.

Flows

Listed below are the phosphorus and nitrogen flows, where the square brackets [ ] define the quantity of phosphorus and nitrogen for each node. These quantities are given in tonnes of nutrients per year as obtained from the data collection.

\[ \alpha_1[\text{Manure}] + \alpha_2[\text{Organic Waste}] + \alpha_3[\text{Fertiliser}] \to [\text{Soil}] \]

\[ \alpha_4[\text{Soil}] \to [\text{Other Crops}] \]

\[ \alpha_5[\text{Soil}] \to [\text{Cereal}] \]

\[ \alpha_6[\text{Soil}] \to [\text{Pulses and Beans}] \]

\[ \alpha_7[\text{Soil}] \to [\text{Industrial Crop}] \]

\[ \alpha_8[\text{Soil}] \to [\text{Oilseed}] \]

\[ \alpha_9[\text{Other Crops}] + \alpha_{10}[\text{Cereal}] + \alpha_{11}[\text{Pulses and Beans}] + \alpha_{12}[\text{Industrial Crop}] + \alpha_{13}[\text{Oilseed}] + \alpha_{14}[\text{Animal Consumption}] \to [\text{Available for Human Consumption}] \]

\[ \alpha_{15}[\text{Available for Human Consumption}] \to [\text{Human Purchase}] \]

\[ \alpha_{16}[\text{Other Crops}] + \alpha_{17}[\text{Cereal}] + \alpha_{18}[\text{Pulses and Beans}] + \alpha_{19}[\text{Industrial Crop}] + \alpha_{20}[\text{Oilseed}] \to [\text{Animal Consumption}] \]

\[ \alpha_{22}[\text{Animal Consumption}] \to [\text{Manure}] \]

\[ \alpha_{23}[\text{Human Purchase}] \to [\text{Organic Waste}] \]

Constant Input \to [\text{Fertiliser}] \]

\[ \alpha_{24}[\text{Soil}] + \alpha_{25}[\text{Available for Human Consumption}] + \alpha_{26}[\text{Human Purchase}] + \alpha_{27}[\text{Animal Consumption}] + \alpha_{28}[\text{Fertiliser}] + \alpha_{29}[\text{Manure}] + \alpha_{30}[\text{Organic Waste}] \to \text{[Loss]} \]

Ordinary Differential Equations
From the flows the ODEs describing the instantaneous rate in change in the quantity of phosphorus and nitrogen in each node over time can be obtained.

\[
\frac{d\text{Soil}}{dt} = \alpha_1\text{[Manure]} + \alpha_2\text{[Organic Waste]} + \alpha_3\text{[Fertiliser]} - \alpha_4\text{[Other crops]} - \alpha_5\text{[Cereal]} - \alpha_6\text{[Pulses and Beans]} - \alpha_7\text{[Industrial Crop]} - \alpha_8\text{[Oilseed]} - \alpha_9\text{[Loss]}
\]

\[
\frac{d\text{Other Crops}}{dt} = \alpha_4\text{[Soil]} - \alpha_9\text{[Available for Human Consumption]} - \alpha_{10}\text{[Animal Consumption]}
\]

\[
\frac{d\text{Cereal}}{dt} = \alpha_5\text{[Soil]} - \alpha_{10}\text{[Available for Human Consumption]} - \alpha_{17}\text{[Animal Consumption]}
\]

\[
\frac{d\text{Pulses and Beans}}{dt} = \alpha_6\text{[Soil]} - \alpha_{11}\text{[Available for Human Consumption]} - \alpha_{18}\text{[Animal Consumption]}
\]

\[
\frac{d\text{Industrial Crop}}{dt} = \alpha_7\text{[Soil]} - \alpha_{12}\text{[Available for Human Consumption]} - \alpha_{19}\text{[Animal Consumption]}
\]

\[
\frac{d\text{Oilseed}}{dt} = \alpha_8\text{[Soil]} - \alpha_{13}\text{[Available for Human Consumption]} - \alpha_{20}\text{[Animal Consumption]}
\]

\[
\frac{d\text{Available for Human Consumption}}{dt} = \alpha_9\text{[Other Crops]} + \alpha_{10}\text{[Cereal]} + \alpha_{11}\text{[Pulses and Beans]} + \alpha_{12}\text{[Industrial Crop]} + \alpha_{13}\text{[Oilseed]} + \alpha_{14}\text{[Animal Consumption]} - \alpha_{15}\text{[Human Consumption]} - \alpha_{25}\text{[Loss]}
\]

\[
\frac{d\text{Human Consumption}}{dt} = \alpha_{15}\text{[Available for human consumption]} - \alpha_{23}\text{[Organic Waste]} - \alpha_{26}\text{[Loss]}
\]

\[
\frac{d\text{Animal Consumption}}{dt} = \alpha_{16}\text{[Other Crops]} + \alpha_{17}\text{[Cereal]} + \alpha_{18}\text{[Pulses and Beans]} + \alpha_{19}\text{[Industrial Crop]} + \alpha_{20}\text{[Oilseed]} - \alpha_{14}\text{[Available for Human Consumption]} - \alpha_{22}\text{[Manure]} - \alpha_{27}\text{[Loss]}
\]

\[
\frac{d\text{Manure}}{dt} = \alpha_{22}\text{[Animal Consumption]} - \alpha_{1}\text{[Soil]} - \alpha_{29}\text{[Loss]}
\]

\[
\frac{d\text{Organic Waste}}{dt} = \alpha_{23}\text{[Human Consumption]} - \alpha_{2}\text{[Soil]} - \alpha_{30}\text{[Loss]}
\]

\[
\frac{d\text{Fertiliser}}{dt} = \text{Constant Input} - \alpha_{3}\text{[Soil]} - \alpha_{28}\text{[Loss]}
\]
\[
\frac{d[\text{Loss}]}{dt} = \alpha_{24}[\text{Soil}] + \alpha_{25}[\text{Available for Human Consumption}] + \alpha_{26}[\text{Human Purchase}] + \\
\alpha_{27}[\text{Animal Consumption}] + \alpha_{28}[\text{Fertiliser}] + \alpha_{29}[\text{Manure}] + \alpha_{30}[\text{Oranic Waste}]
\]
References


Scientific Contribution

Prizes and awards

None

List of publications


List of invited presentations


Poster presentation held at the University of Surrey for the visit of EPSRC (14.9.2012)