

CRANFIELD UNIVERSITY

JAMES DARIUSH KARIMI

THE INFLUENCE OF LANDSCAPE STRUCTURE AND
CONNECTIVITY ON ECOSYSTEM SERVICES: TRADE-OFFS AND
SYNERGIES IN URBAN AREAS

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD

Academic Year: 2018 - 2021

Supervisor: Dr. Ron Corstanje
Associate Supervisor: Prof. Jim Harris
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This thesis is submitted in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

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ABSTRACT

Ecosystem services are the benefits that humans derive their well-being. Globally, 60 per cent of ecosystem services assessed are either being degraded or being used unsustainably. Urban ecosystem services provide a range of services such as climate regulation, erosion control, flood control, food production, urban cooling, recreation and cultural values. Ecosystem services have been found to cluster to form ecosystem service (ES) bundles. Landscape structure has been shown to affect the provision of multiple ecosystem services. However, there is limited knowledge on whether the landscape configuration and connectivity of urban green space affect the provision of ES. This research aims to understand whether ecosystem services form ES bundles at a 2 m spatial resolution in the combined built-up areas of three large towns Milton Keynes, Bedford, and Luton, UK and to analyse the trade-offs and synergies between ecosystem services. Multivariate techniques were used to identify the bundles and analyse the trade-offs and synergies between ES. This study has assessed whether landscape configuration and connectivity influence ES trade-offs and synergies. A Bayesian Belief Network (BBN) modelling approach was used to test whether landscape configuration characteristics and connectivity drive ES trade-offs and synergies. Circuit theory was used to model landscape connectivity. Overall, this study found that ES cluster to form bundles and exhibited distinct geographic patterns. There were specific spatial trade-offs and synergies between ecosystem services. BBN models proved to be suitable for predicting ES trade-offs of urban green space. Landscape configuration and connectivity influence predicted ES trade-offs and synergies. Key findings indicated clearly that landscape configuration characteristics and landscape connectivity drive ES trade-offs and synergies. Core area and connectivity were strong predictors of ES trade-offs. Evidence suggests that ES trade-offs and synergies are influenced by green space configuration characteristics, landscape connectivity and ecological processes and influence the provision of multiple ES. Low connectivity was found to be associated with high trade-off predictions. Therefore, the use of ES modelling tools, Geographical Information Systems (GIS), Bayesian Belief Networks and connectivity modelling tools provide

significant insights into understanding the influence of landscape structure and connectivity of urban green space on ES trade-offs and synergies and the underlying mechanisms for trade-offs and synergies. This study supports the conviction that enhancing green infrastructure increases ES provision and confers resilience to ES. A better understanding of the mechanisms for trade-offs and synergies can be beneficial for planning and management of ES because it can help to predict where and when trade-offs might take place, reduce the undesirable trade-offs and enhance the desirable synergies, and improve the provision of multiple ecosystem services across the landscape.

Keywords:

Landscape Configuration, Landscape Connectivity, Bayesian Belief Networks, Green Space, Circuit Theory, Synergies, Trade-offs, Landscape Metrics, Multivariate, Resilience

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisors Dr. Ron Corstanje and Prof. Jim Harris for giving me the opportunity to learn from their vast experiences and wealth of knowledge. They provided me support for getting the PhD. I would like to thank Ian Truckell for the advice and assistance with Geographical Information Systems techniques (GIS). I would like to thank my review committee members Prof. John Oakey and Dr. Jeroen Meersmans for valuable comments and suggestions. I would like to thank my family for the patience and support.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENTS.....	iii
LIST OF FIGURES.....	viii
LIST OF TABLES	x
LIST OF EQUATIONS.....	xii
LIST OF ABBREVIATIONS	xiii
1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Literature Review	8
1.2.1 Ecosystem Services	8
1.2.2 Theory and Method of Landscape Ecology	22
1.2.3 Urban and Land Planning.....	29
1.3 Aim, Research Questions, Objectives and Hypotheses.....	33
1.4 Brief Description of Approach and PhD Thesis Structure	35
1.5 Study Area	39
1.6 List of Outputs from Thesis	40
References	41
2 BUNDLING ECOSYSTEM SERVICES AT A HIGH RESOLUTION IN THE UK: TRADE-OFFS AND SYNERGIES IN URBAN LANDSCAPES	50
2.1 Introduction	51
2.2 Methods	55
2.2.1 Land Use Land Cover data	55
2.2.2 Ecosystem Services	57
2.2.2.1 Provisioning services.....	60
2.2.3 Data Analysis	66
2.3 Results.....	67
2.3.1 Correlations between Ecosystem Services	67
2.3.2 Ecosystem Service Bundles.....	69
2.4 Discussion	74
2.4.1 Correlations.....	75
2.4.2 Trade-offs and Synergies among Ecosystem Services.....	76
2.4.3 Ecosystem Service Bundles.....	77
2.4.4 Implications	80
2.4.5 Limitations and Uncertainties	82
2.5 Conclusions	82
References	84
3 UNDERSTANDING THE IMPORTANCE OF LANDSCAPE CONFIGURATION ON ECOSYSTEM SERVICE BUNDLES AT A HIGH RESOLUTION IN URBAN LANDSCAPES IN THE UK	91
3.1 Introduction	93

3.2 Methods	97
3.2.1 Overall Approach	97
3.2.2 Land Use Land Cover, Land Structure and Ecosystem Services	98
3.2.3 Landscape Metrics Selection and Modelling Method	99
3.2.4 Statistical Analyses to Data Reduction.....	101
3.2.5 Model Construction	102
3.2.6 Model Performance and Sensitivity Testing	104
3.3 Results.....	105
3.3.1 Data Reduction	105
3.3.2 BBN Model Performance and Sensitivity Analysis	110
3.3.3 Probabilistic Associations between Landscape Configuration and ES Trade-offs and Synergies	112
3.4 Discussion	116
3.4.1 Selected Landscape Metrics	116
3.4.2 Predicted Ecosystem Service Trade-offs and Synergies and Landscape Configuration Influence on ES Trade-offs and Synergies	118
3.4.3 Model Performance and Landscape Configuration	120
3.4.4 Implications	121
3.4.5 Limitations	121
3.5 Conclusions	122
References	123
4 USING BAYESIAN BELIEF NETWORKS TO ASSESS THE INFLUENCE OF LANDSCAPE CONNECTIVITY ON ECOSYSTEM SERVICE TRADE- OFFS AND SYNERGIES IN URBAN LANDSCAPES IN THE UK.....	129
4.1 Introduction	130
4.2 Methods.....	135
4.2.1 Methodological framework	135
4.2.2 Land Use Land Cover	137
4.2.3 Connectivity and Circuit Theory	138
4.2.4 Landscape Resistance and Core Area Parameterisation.....	140
4.2.5 Input Data: Patch Area, Connectivity and Empirical Abundance Data	141
4.2.6 Ecosystem Service Trade-offs and Synergies Input Data	143
4.2.7 Bayesian Belief Networks.....	143
4.2.8 Model construction	144
4.3 Results.....	147
4.3.1 The Cumulative Current Maps	147
4.3.2 Model Performance and Predictor Sensitivity.....	150
4.3.3 Probabilistic Associations between Landscape Factors and ES Trade-offs and Synergies.....	151
4.4 Discussion	154

4.4.1 Predicted ES Trade-offs and Synergies and Key Drivers of ES Trade-offs and Synergies	154
4.4.2 Implications, Further Research and BBN Modelling	159
4.5 Conclusions	162
References	164
5 OVERALL DISCUSSION: IMPLEMENTATION OF THE WORK.....	169
5.1 Objective 1: To Identify and Analyse the Composition of Ecosystem Service Bundles and the Spatial Variation of all Ecosystem Services (i.e. the Bundle)	169
5.2 Objective 2: The Influence of Landscape Configuration on Ecosystem Service Trade-offs and Synergies.....	175
5.3 Objective 3: The Influence of Landscape Connectivity on Ecosystem Service Trade-offs and Synergies.....	181
5.4 Contribution to Landscape Ecology Science in Urban Ecosystems.....	185
5.5 Implications.....	186
5.5.1 Social	186
5.5.2 Urban Planning and Policies	188
5.5.3 Green Space Conservation	190
References	193
6 CONCLUSIONS AND FURTHER RESEARCH.....	197
APPENDICES	200
Appendix A Bundling Ecosystem Services at a High Resolution in the UK.	200
Appendix B The Influence of Landscape Configuration on Ecosystem Service Trade-offs and Synergies.....	207
Appendix C The Influence of Landscape Connectivity on Ecosystem Service Trade-offs and Synergies.....	217

LIST OF FIGURES

Figure 1.1 The cascade model.....	11
Figure 1.2 Thesis framework.....	38
Figure 1.3 Location map of the three towns in the UK.....	40
Figure 2.1 Study area showing land use land cover classification for Bedford, Luton, and Milton Keynes, UK	56
Figure 2.2 The maps show the spatial distribution of each ecosystem service bundle at 2 m resolution for the towns of Bedford, Luton and Milton Keynes	72
Figure 2.3 Radar charts showing Ecosystem Service Bundle types and the provision of different ESs in a cluster. K-means cluster analysis revealed four distinct ecosystem service bundle types. The charts show the average values of each service in the bundle type. (a) Cluster 1: <i>Potential Soil Erosion</i> bundle type, (b) Cluster 2: <i>Urban Trees and Woodland</i> bundle type, (c) Cluster 3: <i>Urban Grassland</i> bundle type, (d) Cluster 4: <i>Suburban Grassland</i> bundle type. Values are standardized and displayed on a scale from - 2 to 2 where 0 is the individual service mean value, not the bundle type mean.....	73
Figure 3.1 Example of Bayesian Belief Network model structure for Nutrient retention and Carbon storage trade-offs. All models used a comparable structure, with the dependent variable and the conditional probabilities changing between models. The influence diagram illustrates the relationships between the dependent variable (i.e. the ES trade-offs or synergies) and the independent variables. A similar structure was used for the class level metrics. Arrows denote the direction of probabilistic influence implemented in software rather than causal relationships between the factors	104
Figure 3.2 Heat maps that visually depict the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (i.e. core area, contiguity index and Euclidean nearest neighbour; values of bin ranges are shown in Table 3.5) and the predicted trade-offs (or synergies) of each ecosystem service trade-offs or synergies type. Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of input parameter values and predicted trade-offs (or synergies) represented by that cell in the heat map	115
Figure 4.1 Methodological framework	137
Figure 4.2 Example of Bayesian Belief Network model structure for Nutrient retention and Carbon storage trade-offs. All models used a comparable structure, with the dependent variable and the conditional probabilities changing between models. The influence diagram illustrates the	

relationships between the dependent variable (i.e. ES trade-offs or synergies) and the independent variables. Arrows denote the direction of probabilistic influence implemented in software rather than causal relationships between the factors 146

Figure 4.3 Modelled cumulative current maps (rescaled to facilitate comparison between towns) at a 2 m spatial resolution for Bedford, Luton and Milton Keynes, UK..... 149

Figure 4.4 The heat maps show the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (patch area, connectivity and bird species abundance; values of bin ranges are shown in Table 4.2) and the predicted trade-offs (or synergies). Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of input value and predicted trade-offs (or synergies) represented by that cell in the heat map 153

LIST OF TABLES

Table 2.1 Selected ecosystem services, method of estimation and indicators used in this study. Notes on interpretation of ecosystem services and indicators.	58
Table 2.2 Habitat sensitivity table showing the land cover types, habitat suitability scores and the relative sensitivity of each habitat (i.e. land cover type) to each threat.....	62
Table 2.3 Correlation matrix showing correlation coefficients between ecosystem services. The correlations were estimated with a pairwise Spearman rank correlation method. Blue shading indicates positive correlations, orange indicates negative correlations, in white no correlation. High correlation = 0.5-1, Medium correlation = 0.3-0.5, Weak correlation = 0.1-0.3, No correlation = 0-0.1. 1 (Legendre and Legendre, 1998). Level of significance: *** $P < 0.001$	68
Table 2.4 Results of the principal component factor analysis for the first three factors after Varimax rotation. Factor loadings ≥ 0.40 are shown in bold ..	70
Table 2.5 Mean values for each ecosystem service (ES) within each of the clusters	74
Table 3.1 Correlation matrix showing Spearman's rank correlation coefficients ρ (rho) illustrating the relationships between patch level landscape metrics (Significance: *** $P < 0.001$)	108
Table 3.2 Correlation matrix showing Spearman's rank correlation coefficients ρ (rho) illustrating the relationships between landscape class level metrics after data reduction and elimination of variables with $ r \geq 0.9$ based on factor loadings (Significance: * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$)	109
Table 3.3 Result of the factor analysis for the first three factors after Varimax rotation. Significant values that meet $r > 0.7$ are in bold. Highest loadings per factor are italicized.....	110
Table 3.4 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient retention and Carbon storage trade-offs (PC 1), Pollinator abundance and Habitat quality trade-offs (PC 2) and Potential soil erosion and Water supply synergies (PC 3) at a 2 m spatial resolution.....	112
Table 3.5 Bin ranges for input parameter values in Figure 3.2 heat maps of Bayesian model conditional probabilities.....	116
Table 4.1 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient retention and Carbon storage Trade-offs (PC1), Habitat quality and Pollinator abundance	

Trade-offs (PC2) and Soil erosion and Water supply Synergies (PC 3) at 2 m resolution	151
Table 4.2 Bin ranges for input parameter values in Fig. 4.4 heat maps of Bayesian model conditional probabilities.....	154

LIST OF EQUATIONS

(2-1)..... 62

(2-2)..... 63

(2-3)..... 65

(4-1)..... 139

LIST OF ABBREVIATIONS

BBNs	Bayesian Belief Networks
ES	Ecosystem Services
GIS	Geographical Information Systems
IT	Information Technology
LULC	Land Use Land Cover
PCA	Principal Component Analysis
CORE	Core Area
CONTIG	Contiguity Index
ENN	Euclidean Nearest Neighbour Distance
MESH	Effective Mesh Size
ENN_AM	Area-Weighted mean Euclidean Nearest Neighbour Distance
NDVI	Normalised Difference Vegetation Index

1 INTRODUCTION

This chapter presents the background, gaps, aims, research questions, objectives and hypotheses of the study. A review of ecosystem services and ecosystem service modelling is provided along with the aspects of landscape structure, spatial configuration and connectivity of urban green spaces, and the updated research methods. Subsequently, the theories and methods of ecosystem services and Ecosystem Services (ES) modelling, Geographical Information Systems (GIS), landscape ecology, Bayesian Belief Networks (BBNs) and connectivity modelling tools are captured. This chapter ends by outlining the thesis structure, describes the study areas and lists the outputs utilised in the thesis for publications.

1.1 Background

Ecosystem services are the benefits that humans derive their well-being. Ecological functions and biodiversity support and supply ecosystem services. In land use planning and management there are often conflicting objectives in land use. Ecosystem services have been distinguished (Millennium Ecosystem Assessment, 2005) into four categories: *Supporting services* such as nutrient recycling, primary production, *Provisioning services* which include food, water, *Regulating services* such as carbon sequestration and climate regulation, *Cultural services* such as cultural, spiritual and historical, science and education. The findings of the Millennium Ecosystem Assessment (MA) showed that human use of ecosystem services is increasing and is related to the growth of human population and expansion of consumption. Integrating ecosystem services into impact assessment and the development of modelling tools makes it possible to analyse land use changes. It has been found that ecosystem services cluster to form ES bundles. Ecosystem service bundles have been defined as sets of ecosystem services that appear repeatedly together across space or time (Raudsepp-Hearne, Peterson and Bennett, 2010). The spatial distribution of bundles appears to be related to biophysical and socio-economic characteristics.

To make better decisions in land use, an evaluation of trade-offs and synergies between ES can improve ecosystem management and provide insights to land use policies required not to deteriorate ecosystem services. For example, in Ontario, Canada, municipalities have adopted varying approaches in their consideration of ecosystem services in land use plans with reference to a variety of ecosystem services. The term ecosystem services though is rarely used in land use plans (Lam and Conway, 2018). In New York City ecosystem services have been assessed in a variety of planning, policy and research contexts. An example is the 20-year economic and environmental sustainability plan PlaNYC. Both small and large-scale green infrastructure has been used to control storm water runoff. Policies have been implemented to restore wetlands to maintain high filtration efficiency and reduce flooding. A better understanding of biodiversity and an assessment of the ecosystem services provided would enable planners and managers consider how to improve ecosystem services and where trade-offs exist (McPhearson, Hamstead and Kremer, 2014).

In the UK planning guidance is provided via a range of policy documents at national, regional and local levels. In England, the *National Planning Policy Framework* (NPPF) sets out how government policies for England should be applied and must be taken into account by local councils and local people in the preparation of their own local and neighbourhood plans. It has positive policies for green infrastructure and ecosystem services. *Core Strategies* are the main local land-use plan. In England, Core Strategies form part of local authority's *Local Development Frameworks* which include *Local Plans*. Supplementary Planning Guidance (SPG) and Supplementary Planning Documents (SPDs) can be used to create Sites of Importance for Nature Conservation (SINCs). Sites of Local Importance for Nature Conservation (SLINCs), and Local Nature Reserves (LNRs). The concept of green infrastructure and ecosystem services can be used in landscape planning (Andersson et al., 2014; Hansen and Pauleit, 2014). The concept of ecosystem services can be used in Strategic Environmental Assessment (SEA) to construct more sustainable plans or programs and in Environmental Impact assessments (EIA) for individual projects for the conservation of ecosystem services. A sustainable appraisal is a systematic

process that must be carried out during the preparation of local plans and spatial development strategies. Its role is to promote sustainable development.

In the UK planning system ecological sustainability is operationalised using the notion of 'environmental capital', subdivided into 'critical capital' and 'constant capital'. Critical natural capital is the term given to important ecosystems or rare or vulnerable species that are given statutory protection. Constant capital is the term given to ecological features not given statutory protection, which, can be traded-off during the development process using different mitigation and compensation measures. This usually manifests itself spatially within the planning system at a plot scale, when the Planning Officers are making decisions on individual sites development. It is less frequently used at larger spatial scales.

Land use and management influence the system properties, processes and components that are the basis of service provision. A change in land use or management will therefore cause a change in service supply for the complete bundle of services provided by that ecosystem (de Groot et al., 2010). A comprehensive set of indicators enables the assessment of land management effects on ecosystem service provision. Indicators provide policy-makers and land managers with information on the effects of land management and interventions on ecosystem services provision (Van Oudenhoven et al., 2012). Trade-offs result in an increase of a service with a decrease of another, synergies result in multiple services being enhanced. A better knowledge of trade-offs and synergies would simplify environmental decision-making. In analysing trade-offs between services, Braat and de Groot (2012) say that spatial scale, temporal scale and reversibility should be accounted for. Scenarios can be constructed. Policies can then be developed to take into account ES trade-offs at multiple spatial and temporal scales. ES are interdependent and attempts to optimize a single service often lead to reductions or losses of other services (Rodríguez et al., 2006). In land planning and in development schemes there is the need to quantify the changes and consider the trade-offs. For example, Peña et al. (2018) analysed trade-offs and synergies of eight ecosystem services of the Bilbao Metropolitan Greenbelt (BMG) to orient management decision towards more

multifunctional landscapes. The trade-offs and synergies were identified so that managers could prioritise preservation of land use types. The most relevant areas of multiple ES were proposed as potential components of a green infrastructure. ES bundles also could help decision-makers to orient their management strategies towards sustainability in urban areas. In the urban region of Leipzig-Halle in eastern Germany, an evaluation of the spatial and temporal changes of ecosystem services between 1990 and 2006 depending on land cover change showed there were trade-offs between agricultural services (provisioning) and green space areas (cultural). The trade-offs were driven by agricultural intensification and peri-urbanisation and restoration (Haase and Schwarz, 2012). This type of analysis can determine where the changes occur and determine where it is feasible to support synergies or avoid trade-offs.

Quantifying the ecosystem responses to land use change allows to assess and evaluate the trade-offs. Examples of land use policies for the conservation ecosystem services are green infrastructure policy plans such as the regional Local Plan (GLA), e.g. Cambridgeshire Green Infrastructure Strategy and the Liverpool Green Infrastructure Strategy (Mersey Forest) (Mell et al., 2017). The assessment of ES can contribute to the conservation of ecosystem services. In a study, Haas and Ban (2018) found that land use changes between 2005 and 2015 in Beijing led to a reduction of agricultural areas (provisioning services) in the urban fringe in favour of an increase of urban built-up areas, green space and golf courses (cultural services).

Balancing the trade-offs between human needs and maintaining other ecosystem services requires quantitative knowledge about ecosystem responses to land use (Defries, Foley and Asner, 2004). Sustainable development is aimed to achieve a balance between the exploitation of natural resources for socio-economic development, and conserving ecosystem services that are critical to well-being and livelihood. A better understanding on what drives these patterns and elucidating the relationships between ecosystem processes and ecosystem services ES and human well-being (HWB) may provide insights into the

management of ecosystem services (for example regulating services) and give an indication of the resilience of social-ecological systems (Hossain et al., 2017).

In ecosystem service assessment indicators are used to describe ecological processes of an ecosystem. Most indicators were not developed for an economic assessment, so they are not always able to show clear relationships between components of biodiversity and the services or benefits they provide to people. Ecosystem service indicators are used to monitor the state or trends of ecosystems and ecosystem service delivery within a determined time interval. Indicators need to be sensitive to changes in land management, temporally and spatially explicit, scalable, and quantifiable (Van Oudenhoven et al., 2012). Furthermore, indicators should provide information about causal relationships between land management and changes in ecosystem properties and function. An indicator is considered scalable if it could be aggregated or disaggregated to different scale levels, without losing the sense of the indicator. The selection of ES indicators is closely related to the research question and the information it provides. In the EU, indicators have been proposed for the main ecosystems (i.e. agriculture, forest, freshwater and marine).

While ecosystem services have been found to cluster at a landscape scale studies of the provision of multiple ecosystem services in urban areas are limited. This study analyses how ecosystem services bundle at a 2 m spatial resolution in the combined built-up areas of three large towns and analyses the spatial variation of all ES (i.e. the entire bundle) and determines the ES gradients along which the entire bundle of ecosystem services changed across the landscape. Ecosystem service bundle analysis can provide insights for planners and decision-makers and identify areas on a landscape where ecosystem management has produced exceptionally desirable or undesirable sets of ecosystem services. In the evaluation of ecosystem services scale is important. The supply of ES depends on the functioning of ecosystems, which is driven by ecological processes at different scales (de Groot, 2010).

In a study, Rioux et al. (2019) found that at coarser spatial resolutions green space cover is underestimated and so is ES supply and flow. The effect of land

cover data spatial resolution on ES flow depended also on the spatial configuration of ES supply. The effect was found to be variable between similar landscapes, suggesting that it is very sensitive to land cover (LC) structure. The effect of decreasing spatial resolution of a LC map results in an increase in the area of dominant classes at the expense of rarer classes and a loss of information on fine-scale spatial heterogeneity. Furthermore, ES models have been found to be highly sensitive to data spatial resolution. Spatial resolution may have a significant effect on ES mapping. Often maps need to be aggregated to coarser resolution due to computational limitations or constraints on integrating them with other datasets. Map aggregation affects land cover configuration of urban green space and ES supply. Using land cover data with a spatial resolution of 5 m and higher is recommended so as to capture the small greenspaces scattered in the urban matrix and the potential supply of ecosystem services in urban areas and to accurately map the ES (Rioux et al., 2019). Raudsepp-Hearne and Peterson (2016) found that bundles are robust to changes in scale, but that large changes may result in the reconfiguration of bundles. This, as suggested, could depend on how evenly distributed the ecosystem services across the landscape were. Ecosystem services are produced at different spatial scales.

Landscape structure, composition and configuration, is believed to affect the provision of ES bundles. While landscape composition has been shown to affect the provision of ES bundles (Lamy et al., 2016) less is known whether landscape configuration characteristics affect ES provision. These gaps need to be addressed by means of the integration of multiple approaches such as landscape ecology methods and ecological modelling tools. Chen et al. (2020) found synergies between carbon storage and habitat quality in Beijing and its surrounding areas. Trade-offs were found between water yield and carbon storage and habitat quality. Chen et al. (2020) also found trade-offs between soil retention and water yield. In Rotterdam, in an area that covers 326 km² mostly synergies were found between ecosystem services (Derkzen, van Teeffelen and Verburg, 2015). In the city of Bilbao, in an area that covers 413 km² trade-offs were found between aesthetic value and timber production. Synergies were

found among regulating ecosystem services (i.e. habitat maintenance, air purification and water flow regulation) (Peña et al., 2018).

Bayesian Belief Networks (BBNs) are semi-quantitative, probabilistic models, and are useful tools for modelling ecological predictions. BBNs can be used to make predictions of the provision of ecosystem services and model multiple ecosystem services (Landuyt et al., 2012). BBNs are well suited to account for uncertainties in ES research. Its potential use to combine empirical data and expert knowledge make it suitable to model ecological systems (Van der Biest et al., 2013). This approach allows to assess the influence of mapped predictors to model output with the advantage for the model to generate its own conditional probabilities based on the available data. A BBN modelling approach allows to test the sensitivity of ES trade-offs and synergies to landscape configuration characteristics thus providing ecological understanding that is relevant to planning decisions and urban planning. It allows to test a method for predicting the spatial variation of ES trade-offs and synergies. This enables relationships to be drawn between ES provision and urban habitat structure that could inform sustainable urban planning.

As some ES are influenced by the movement of organisms and materials across landscapes, connectivity is assumed to play an important role in the provision of multiple ecosystem services (Mitchell, Bennett and Gonzalez, 2013). Landscape connectivity includes structural connectivity, corresponding to spatial relationships (continuity and adjacencies) between structural elements of the landscape, and functional connectivity, which refers to species behaviour in response to landscape pattern. Connectivity is expected to affect the provision of ES (Mitchell, Bennett and Gonzalez, 2013). Studies suggest that biotic and abiotic connectivity affect the provision of multiple ES. Structural and functional connectivity are assumed to affect biodiversity and the provision of ES. However, few studies have been conducted on the effects of connectivity on multiple ES at a 2 m resolution. Therefore, this study uses combined approaches of (i) BBN modelling, (ii) GIS, (iii) landscape ecological analytics and (iv) connectivity modelling to assess the sensitivity of ES trade-offs and synergies to the variation

in landscape connectivity of urban green space and analyses the relationships between landscape connectivity and predicted ES trade-offs and synergies. This modelling approach allows to test whether landscape connectivity affects ES trade-offs and synergies, and thereby relevant to planning decision and landscape scale research. This research highlights a BBN modelling approach to test whether urban habitat configuration and connectivity drive predicted ES trade-offs and synergies and consecutively, affect ES provision.

1.2 Literature Review

1.2.1 Ecosystem Services

Since its ecological conception the term ecosystem services has evolved where ES are the benefits humans derive their well-being and linked, directly or indirectly, to ecosystem functions. Ecosystems and society are connected within a socio-ecological system. Ecological functions and biodiversity support and supply ecosystem services. ES demand is societies influence on the ecosystem generated by drivers and governance. The term 'ecosystem services' was first introduced in the late 1970s and builds on previous studies and continues in the 1980s with sustainable development debate and in the 1990s with the mainstreaming of ecosystem services with more specialised literature. It appeared for the first time in 1981 in a book by Ehrlich and Ehrlich as an evolution of the term 'environmental services' (Ehrlich and Ehrlich, 1981). Different definitions of ecosystem services have been proposed. The Economics of Ecosystems and Biodiversity (TEEB, 2010) definition is that they are the direct and indirect contributions of ecosystems to human well-being. Its ecological roots can be traced as far back as Marsh's book *Man and Nature* (1864). The term ecosystem function was originally used in ecological sense but then extended to include the potential that ecosystems have to deliver a service. Nature's benefits economic roots can be traced throughout economic history from the classical economics period to the consolidation of neoclassical economics and economic sub-disciplines specialized in environmental issues. Some of the classical economists explicitly recognised the contribution of the services. However, they

recognised only their value in use, and on the whole denied nature's services role in exchange value, because they were considered as free, non-appropriable gifts of nature. Recently, environmental problems have been framed in economic terms and been approached with cost-benefit analysis. The Millennium Ecosystem Assessment (2005) was a large study of the state and relevance of ecological systems for society. The TEEB study has brought ecosystem services in the policy arena with a clear economic connotation. Ecosystem services have been posed on the left and human, social and economic on the right (Braat and de Groot, 2012).

According to Costanza (2000) in the valuation of ecosystem services, a wide-ranging set of goals that include ecological sustainability and social fairness, as well as traditional economic goal of efficiency are needed. The TEEB study (2008-2010) defined ecosystem services as the direct and indirect contributions of ecosystems to human well-being (Burkhard and Maes, 2017). An integration of ecosystem services in decision-making (Daily et al., 2009) would result in better actions to the use of land, water and other elements of the natural capital. The social-ecological system is sustainable when there is an environmental, social, based on equity and equal opportunities for all citizens, and economic sustainability (the costs are lower than the benefits).

The ecosystem service approach involves the science of identifying, measuring, mapping or modelling the stocks and flows of different ecosystem services and the synergies and trade-offs that may occur among them as a result of different decisions. Indicators can help to assess the influence of land management on ecosystem services and to map and assess ecosystem services. Indicators provide information to policymakers on the conditions, trends and rate of change of ES. It aims to conserve ecosystem services and restore natural resources while, at the same time, meeting socio-economic and cultural targets (Burkhard and Maes, 2017). Often it complements conservation approaches, since the aim is not to protect vulnerable species but rather to ensure human well-being by enhancing ecosystem services. Indicators can measure the stock and flow of ES.

In 2013, an EU initiative on Mapping and Assessment of Ecosystems and their Services (MAES) was launched (Burkhard and Maes, 2017) which saw the development of a coherent analytical framework to ensure consistent approaches to be applied in the EU. A second report proposed indicators to map and to assess ecosystem services. However, Maes et al. (2012) note that more primary data is needed to map ecosystem services. Fisher, Turner and Morling (2009) argue that any attempt to classify ecosystem services should consider both the characteristics of the ecosystem of interest and the decision context. Ecosystem services include ecosystem organization or structure as well as process and/or functions if they are consumed or utilized by humanity. Natural capital is a synonym for structure and the term function for process. The functions or processes become services if there are humans that benefit from them.

Biophysical processes tell us about the supply side of the ecosystem service provision. However, it is equally important to include the demand side, and understanding the balance between them is crucial to understanding of the way people and nature are linked (Tallis and Polasky, 2009). Wolff, Schulp and Verburg (2015) have categorised four demand types as expressed in terms of risk reduction (regulating services), preferences and values (cultural services), direct use (provisioning services) or consumption of goods and services. They have distinguished five groups of methods for mapping ES demand: empirical methods, participatory approaches, expert-based approaches, process-based models and monetary valuation. And suggest that studies should focus on the spatial variation of drivers such as demography, poverty, education, socio-political and cultural forces.

A conceptual framework (Haines-Young and Potschin, 2010) termed the ecosystem service cascade was developed to show that there is a production chain relating ecological and biophysical structures and processes to human well-being (Figure 1.1). Ecological structures and processes generate services and then benefits are provided. It appears there is a relationship between ecosystem function and biodiversity.

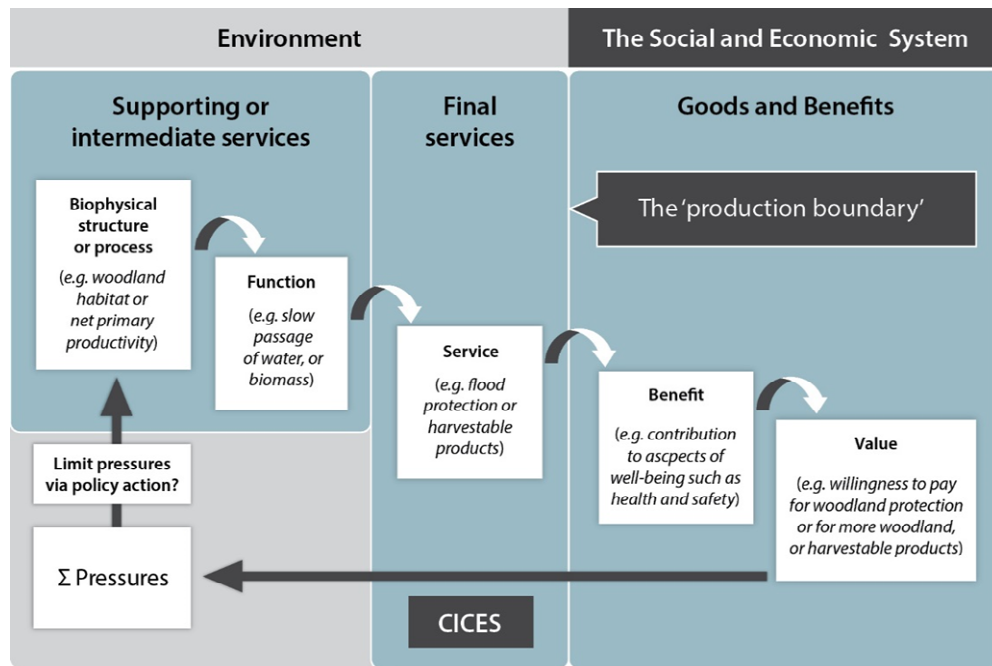


Figure 1.1 The cascade model

These characteristics distinguish supporting services. Services are the outputs of ecological processes and benefits are things that people assign value to. The cascade includes both ecological and social aspects and, as such, it might be described as a 'socio-ecological system' (Burkhard and Maes, 2017). In an attempt to classify ecosystem services, the Common International Classification of Ecosystem Services (CICES) was proposed in 2009 and revised in 2013. Similar to the TEEB classification, CICES does not include the Millennium Ecosystem Assessment (2005) 'supporting services', but combines the TEEB (2010) 'habitat services' with regulating services, in a category called 'regulating and maintenance services' (La Notte et al., 2017). CICES was developed to provide a hierarchically consistent and science-based classification. There are similarities with the DPSIR (Driver, Pressure, State, Impact and Response) model. While the MA provides a classification that is globally recognised and used in sub global assessments, TEEB is used for TEEB national assessments. CICES provides a hierarchical system used for accounting.

The importance or value of ecosystems and their services can be evaluated in different ways. Basically, there are three value domains ecological, socio-cultural and economic. The ecological value encompasses the health state

of a system, measured with indicators such as diversity and integrity, while socio-cultural values include the importance people give to, for example, the cultural identity and the degree to which that is related to ecosystem services. In economics, there are two types of values; use values and non-use values. Use values encompass direct consumptive use values such as the value of timber, fish or other resources that ecosystems provide, and direct, non-consumptive use values such as those related to recreation and aesthetic appreciation. Indirect use values relate to the services provided by nature such as air- and water-purification, erosion prevention and pollination of crops. Non-use value is the importance attributed to an aspect of the environment in addition to, or irrespective of its use values. In essence, it can be understood as the value attributed to its existence value sometimes referred to as 'insurance value' or 'glue' value. A type of value in between use and non-use is the notion of option value i.e. the value we place on keeping the option open to use ecosystem services in the future, either within our own life time, or for future generations (in the latter case this is called bequest value) (de Groot et al., 2010). The Total Economic Value (TEV) is the sum of use and non-use values associated with a resource or an aspect of the environment.

There are methods to translate economic and some socio-cultural of ecosystem services into monetary values. Market prices (marginal values) exist for many ecosystem services, especially the provisioning services such as timber and non-timber forest products. Values of other services are often also expressed through the market but in an indirect way which can be measured through, for example, (avoided) damage cost methods (for regulating services), and hedonic pricing and travel cost methods for some cultural services such as aesthetically pleasing landscapes. Contingent valuation and benefit transfer provide yet other alternatives. Furthermore, in the evaluating plan alternatives about trade-offs between ecosystem services in land use change, all costs and benefits should be taken into account. There are instruments available to analyse the implications of land use and management changes, including mapping and visualizing ecosystem services, modelling changes in ecosystem services and integrated

cost-benefit analysis. For proper valuation, and trade-off analysis, all scales, and associated stakeholders, should be taken into account (de Groot et al., 2010).

In the quantification of biophysical stocks and flows of ecosystem services there are three methods which can be considered: direct measurements, indirect measurement and modelling. In this way indicators can be measured. Direct measurements are also referred to as primary data. Direct measurements of an ecosystem service indicator are the actual measurement of a state, a quantity or a process from observations, monitoring, surveys or questionnaires which cover the entire study area. Direct measurements of ES deliver a biophysical value of ES in physical units which correspond to the units of the indicator. Direct measurements quantify or measure a stock or a flow value and are also referred to as primary data. Indirect measurements of ecosystem services deliver a biophysical value in physical units, but this value needs further interpretation, certain assumptions or data processing, or it needs to be combined in a model with other sources of environmental information before it can be used to measure an ecosystem service. Ecosystem services modelling can be used to quantify ES if no direct or indirect measurements are available. This is usually the case in any ecosystem assessment. With ES modelling, we understand the simulation of supply, use and demand of ES based on ecological and socio-economic input data or knowledge (Burkhard and Maes, 2017). Models can be used for spatial and temporal gap filling of direct and indirect measurements, extrapolation of direct and indirect measurements, modelling ES for which there are no measurements available or for scenario analysis.

As Rodríguez et al. (2005) pointed out, ecosystem services interact with each other and in the provision of ecosystem services there can be synergisms or trade-offs. Ecosystem services emerge from the interactions of diverse ecological structures and processes, and interact creating trade-offs and synergies between services and form bundles. Raudsepp-Hearne, Peterson and Bennett (2010) suggest that they are 'sets of ecosystem services that repeatedly appear together across space or time'. Decisions relating to natural resource management often concern ecosystem service trade-offs and involve services

that interact synergistically. A better knowledge of trade-offs and synergisms would simplify environmental decision-making and be of support to land use planning. The findings of the MA showed that human use of ecosystem services is increasing and is related to the growth of human population and expansion of consumption. The decline of regulating services is of special concern because it could affect other ecosystem services (Carpenter et al., 2009). Thus, in land planning and in development schemes there is the need to quantify the changes and consider the trade-offs.

In ecosystem services assessment it is important to consider the interplay of ecological and social components over time and space, how services are distributed and what are the best practices of governance (Bennett et al., 2015). An understanding of the effects of drivers on multiple ecosystem services and the interactions between services provides a better understanding to sustainably manage landscapes. The supply of ecosystem services can be due to the effect of drivers on multiple ecosystem services or to interactions among ecosystem services. In the former case, the drivers can either lead to a trade-off where one service increases while another decreases or to a synergy where both services are enhanced. For example, the increase of fertilizer usage to improve crop production can have a significant negative effect on the provision of clean water. In the latter case, relationships among services can be caused by direct interactions among the services which can be unidirectional or bidirectional. For example, a positive unidirectional interaction is the one by which retaining forest patches near coffee plantations increases pollination, which in turn increases coffee production. A unidirectional negative interaction exists when, for example, afforestation enhances carbon sequestration, but the process of tree growth increases evapotranspiration, decreasing water availability (Bennett, Peterson and Gordon, 2009). Urbanisation, agriculture and deforestation affect the distribution of ecosystem services and spatial trade-offs and synergies occur. A decline in regulating services is thought to reduce ecosystem resilience.

Associations in ecosystem services, in a bundle, rise in response to a pressure or common processes and can generate synergies or trade-offs

(Mouchet et al., 2014). Maps of the distribution of ES bundles and their drivers could provide information and help guide management decisions (Spake et al., 2017). For example, Baró, Gómez-Baggethun and Haase (2017) defined, in mapping multiple ecosystem services at a municipal level covering five ES and eleven spatial ecosystem service indicators, assessed and identified five ecosystem service bundles showing significant associations both on the supply and demand sides. The study proposes land sharing strategies in urban and agricultural areas to increase landscape multi-functionality. The results showed that urban and agricultural intensity is likely associated to lower potential and richness in terms of ES supply. Conversely, forest landscapes showed a low demand for ES. The study revealed an inverse spatial pattern of ES supply and demand along an urban-rural gradient. The gradients for ES supply showed a mounting trend of all indicators as distance to the urban core increases. Urban landscape vegetation structure and the provision of ecosystem services have been found to be influenced by climatic and socio-economic factors (Dobbs, Nitschke and Kendal, 2017). Chen et al. (2020) found that both ecological and socio-economic drivers affect the distribution of ecosystem service bundles in Beijing and its surrounding areas. Mouchet et al. (2014) proposed an interdisciplinary approach to quantify associations between ecosystem services and provides guidelines to detect ecosystem service association, define bundles and identify potential drivers of ecosystem service association. A set of quantitative methods is proposed to assess ES associations. Methods to define and detect ES bundles include the association coefficient, clustering, ordination methods and overlap analysis. Quantitative methods to identify drivers of ES bundles comprise machine learning methods, regression-based models, analysis of variance and canonical analysis. Machine learning methods to identify drivers of ecosystem services include Random Forests (RF), Boosted Regression Trees (BRT), Artificial Neural Networks (ANN) and Bayesian Belief Networks (BBN).

Raudsepp-Hearne, Peterson and Bennett (2010) identified six types of ecosystem service bundles and found landscape scale trade-offs between provisioning and almost all regulating and cultural ecosystem services, and that a greater diversity of ecosystem services is positively correlated with the provision

of regulating ecosystem services. Renard, Rhemtulla and Bennett (2015) using a spatiotemporal approach analysed the changes in nine ES over 35 years and found an increase in ES provision in time across 131 municipalities. ES bundles were identified for each municipality. The spatial distribution of bundles was related to biophysical and socio-economic characteristics. The trajectory of bundle formation was related to changes in agricultural policy and global trends. ES interactions varied in time and space. Similarly, Queiroz et al. (2015) in mapping ecosystem services analysed sixteen ES in 62 municipalities in a basin in Sweden. For each service indicators were used. The distribution of services varied across the basin with regulating services most evenly distributed. Both positive and negative interactions were found between ES and out of 120 possible pairs of services, 23 were significantly negatively correlated and 25 were significantly positively correlated. More trade-offs resulted between services in urban and relatively densely forested areas, than in agricultural areas. ES diversity resulted high across the whole basin. Five groups of bundles of ES were found and named according to the predominant ES and land cover type. The number of municipalities in each group varied from six to eight. In the same way, Turner et al. (2014) analysed the spatial distribution of eleven ecosystem services in a Danish cultural landscape. Trade-offs resulted between cultural and regulating services and the other provisioning services. The study identified six ecosystem service bundles. The distributions of ES reflected historical and socio-ecological dynamics.

Urban green space provides multiple ecosystem services to urban areas with direct impact on health and security such as climate regulation, air purification, noise reduction, urban cooling and run-off mitigation, habitat provision, cognitive development, food supply and waste treatment (Gómez-Baggethun and Barton, 2013; Derkzen, van Teeffelen and Verburg, 2015). The integration of ecosystem services in spatial planning shows there is a potential for green space design aimed at increasing ES (Holt et al., 2015). Urban ecosystems are complex and shaped by human modification. Ecosystem services in urban areas could show different spatial patterns than in natural ecosystems as urban ecosystems are not consistent with that of natural

ecosystems. Urbanisation affects the provision of ecosystem services and ecosystem functions. The influence of urbanisation, with an increase of impervious land affects geomorphological and hydro-ecological conditions in urban areas which affects the supply of ecosystem services such as nutrient cycling, soil erosion, hydrological flow and the runoff of pollutants causing changes in water and sediment fluxes (Alberti, 2005). The landscape structure and configuration of patches are altered affecting ecological conditions.

A number of studies have conducted assessments of ecosystem service bundles at different scales (Turner et al., 2014; Yang et al., 2015; Raudsepp-Hearne and Peterson, 2016) and found that ecosystem services exhibit spatial clustering. However, ecosystem services are sensitive to scale (Grêt-Regamey et al., 2014) and to the ecosystem services selected. ES act differently across both spatial and temporal scales and land-use patterns affects ES provision. ES interactions (i.e. trade-offs and synergies) varies across scales depending on the land-use type. The land-use type provides different bundles at different scales (Felipe-Lucia, Comín and Bennett, 2014). The scale of analysis can alter our understanding of ES provision because the cover of land-use types can change the types and quantities of ES provided at different scales. The extent of land use at each spatial scale conditions the amount of service provided. Studies of ecosystem service bundle analysis have been conducted at a 1 km (Crouzat et al., 2015), 10 km (Turner et al., 2014) and 75 km grid resolution (Raudsepp-Hearne and Peterson, 2016). However, there are fewer studies of ecosystem service flows at a local and regional scale (de Groot et al., 2010). This present research analyses and identifies the composition of ecosystem service bundles in urban areas at a 2 m spatial resolution.

1.2.1.1 Ecosystem Service Modelling

In ES assessment and mapping Dunford, Harrison and Bagstad (2017), describe five general types of models that are used:

1. Conceptual models. Conceptual models are used to gain an understanding of linkages between different components of the system being studied. The carbon and water cycles, for example, provide the underlying conceptual models for a number of more detailed computer models used to predict ES, such as carbon sequestration by vegetation or the role of vegetation in mediating floods. A conceptual diagram is drawn to illustrate how the model components linked, then to determine how to quantify those linkages.

2. Statistical models. Statistical models can help to establish relationships by drawing on collected data. For example, if a conceptual model suggests that freshwater provisioning is driven by rainfall and forest cover in a catchment area, corresponding data can be collected, and regression-based approaches can be used to explore the strength of these relationships. Sufficiently strong relationships that are identified can then be used in a deterministic model to predict expected freshwater provisioning in areas for which data are not present.

3. Deterministic models. A deterministic model assumes links between cause and effect. Deterministic models are usually based on fundamental physical laws derived from a process-based understanding of the science. Deterministic models underpin many common ES assessment approaches.

4. Probabilistic models. Probabilistic models recognise that random behaviour is often part of a system; they express likelihoods of events occurring (e.g., the return period of a flood of a given magnitude). Probabilistic approaches use probability distributions functions (PDFs) as input parameters. Instead of using mean rainfall, a probabilistic approach might use a range of inputs sampled from a normal distribution around the mean up to the maximum and minimum recorded observations.

5. Rule-based modelling. Rule-based models can be applied, using Boolean (yes/no) decisions and if-then statements to construct a path from input to output. They are often represented as nested decision trees. These are common in remote sensing and biological classification keys and use if-then options to decide between possible output classes. Rule-based models can also be incorporated into context-aware artificial intelligence (AI)-supported model

selection platforms that account for context by selecting from a library of possible data and models. Agent-based models (ABMs) are a special type of rule-based model.

Furthermore, the outputs of one model may be used to provide inputs to another model creating modelling chains. This can allow *integrated modelling systems* to be set up that take into consideration cross-sectoral interactions, synergies and trade-offs including, for example, the implications for one ecosystem service as a result of changes in another. There are four main applications of models which provide information on aspects of the environment.

Firstly, natural environment models that do not provide direct information about ecosystem services but can assess underlying ecosystem structures and functions from which ecosystem services can be understood. These are species distribution models, land use/land cover (LULC) models and general biophysical models which are common natural systems models that can provide ES assessment. Land use land covering modelling are key inputs to many ES mapping approaches. Land cover data are often derived from remote sensing or habitat mapping and land use can be modelled from this baseline. LULC data have obvious value in understanding how ecosystem service flows are changing over time. Three common approaches are detailed. First, Lowry-type models can quantify where the location of an attribute of interest is a function of the attraction and travel costs associated with different locations. Second, by assigning probabilities to transitions between land use types, transition probability approaches can project land use change into the future. These probabilities can themselves be driven by other spatial and/or scenario variables to produce more complex patterns of change. Third, state-and-transition models (STMs) are conceptual models that use simple, diagrammatic approaches to address non-linear shifts in ecosystems in response to external environmental or anthropogenic disruption. A large number of biophysical models address major environmental systems, including climatic, ecological, hydrological and geochemical models of key earth systems such as air, soil and water.

Secondly, models that are focussed on ES, both on individual services and those intended to enable assessment of a suite of different ES. These make use of matrix-based approaches and transferable ES modelling frameworks such as InVEST, ESTIMAP and ARIES (Vigerstol and Aukema, 2011; Bagstad et al., 2013; Burkhard and Maes, 2017; Ochoa and Urbina-Cardona, 2017). Matrix-based approaches sit on the border between ES mapping and modelling. They combine Geographical Information System (GIS) and spreadsheets analysis of LULC input data to produce maps of ES supply and/or demand. InVEST was developed as part of the Natural Capital Project, a partnership between Stanford University, the Nature Conservancy, and the World Wildlife Fund. The InVEST modelling framework consists of a suite of biophysical models that use land use and land cover patterns to estimate levels and economic values of ecosystem services, biodiversity conservation, and the market value of commodities provided by the landscape. It follows an ecological function production approach. It is a spatially integrated modelling tool that allows to predict changes in ecosystem services. Artificial intelligence for ES (ARIES) is a flexible modelling framework that uses AI to select the most appropriate modelling components (deterministic, probabilistic, or ABM) to map ES. ARIES may be more appropriate under conditions of data scarcity (Bagstad et al., 2013).

Thirdly, modelling systems that take an integrated approach to ecosystem services, which allows for an assessment of trade-offs and synergies between groups of services. Two examples of classes of integrated assessment models which differentiated by their application at global or regional scales are GLOBIO-ES and CLIMSAVE Integrated Assessment Platform (IAP). GLOBIO-ES is an example of a dynamic global system model. The CLIMSAVE IAP is an example of a regional integrated assessment model. MIMES (Multiscale Integrated Model of Ecosystem Services) is a multi-scale, integrated shell of models that determine stock and flows of selected ecosystem service models. Finally, models designed to explore ES with decision-makers or stakeholders. These are Bayesian Belief Networks (BBNs), Multi-Criteria Decision Analysis (MCDA) and Participatory modelling with stakeholders.

InVEST and ARIES use a variety of spatial data as model inputs and encode ecological production functions in deterministic models (InVEST and ARIES) and probabilistic models (ARIES). In this study, the Integrated Valuation of Environmental Services and Trade-offs (InVEST) modelling suite version 3.4.4 was used to model ecosystem services. K-means clustering and Principal Component Analysis (PCA) was conducted to identify and detect ecosystem service bundles and analyse the variation of all ES (i.e. the entire bundle) across the landscape and determine the gradients along which the entire bundle of ecosystem services changed comprising the urban areas of Bedford, Luton and Milton Keynes. Furthermore, the correlation analysis and PCA allowed to assess synergies and trade-offs between ecosystem services and the spatial variation of ES across the landscape.

Bayesian Belief Networks (BBNs) are well-suited to account for uncertainties in ES research. Its potential use to combine empirical data and expert knowledge make it suitable to model ecological systems. BBNs can be used to make predictions of the provision of ecosystem services and model multiple ecosystem services (Landuyt et al., 2012). It is a graph model that consists of two components: a directed acyclic graph or DAG and conditional probability tables or CPTs. The DAG consists of a set of nodes and the dependencies between the nodes are represented by directed arrows which represent cause–effect relations between dependent and independent nodes. The strengths of the causal relations between the networks variables are stored in conditional probability tables CPTs (Landuyt et al., 2013). An influence diagram can be used to illustrate relevance and influence between variables. The diagram is converted into a Bayesian Belief Network consisting of nodes and arrows showing relevance between predictor variables and response variable (Marcot et al., 2006). BBNs can be coupled to geographical information systems (GIS). In this study BBNs were used for predicting ES trade-offs and synergies and to test the factors, supported by evidence, that influence ES trade-offs and synergies.

1.2.2 Theory and Method of Landscape Ecology

Landscape ecology emphasizes the interaction between spatial patterns and ecological processes – that is, the cause and consequences of spatial heterogeneity across of a range of scales (Turner and Gardner R.H., 2015). It considers the role of humans in creating and affecting landscape patterns and process. Landscape structure consists of two components, composition and spatial configuration and define the spatial pattern or heterogeneity of the landscape. Landscape structure may include connectivity (Mitchell et al., 2015). Landscape structure is quantified using landscape metrics and patch-based metrics. Landscape composition is a non-spatially explicit characteristic and defined by the spatial elements found on a map. Composition metrics measure landscape characteristics such as the proportion of the landscape in each patch type, patch richness, patch evenness, and patch diversity. Examples include area (and core area) metrics, e.g. number and proportion of classes or types and diversity metrics. Composition refers to features associated with the variety and abundance of patch types within the landscape, but without considering the spatial character, placement, or location of patches within the mosaic (McGarigal, 2002). There is a collection of metrics that describe the composition of the landscape. These are entirely non-spatial measures of the landscape that deal with the number and area of patch types (classes) at the landscape level. Some of the metrics include:

Proportional abundance of each class is the proportion of each class relative to the entire map. Richness refers to the number or variety of patch types present in a landscape. Evenness is based on the distribution of area among patch types and typically given as the observed level of diversity divided by the maximum possible diversity given the patch richness, which equals one when the area is distributed evenly among patch types. Diversity is a compound measure of landscape diversity based on the richness and evenness of patch types, and indexed by a variety of measures, including the following: Shannon's diversity index (SHDI) which is based on information theory; it represents the amount of "information" per individual (or patch type, in this case); larger values indicate a greater number of patch types and/or greater evenness among patch types.

Simpson's diversity index (SIDI) represents the probability that any two cells selected at random would be different patch types; the larger the value the greater the likelihood that any 2 randomly drawn cells would be different patch types. Biodiversity is part of landscape diversity (gamma) contributing to landscape resilience.

Landscape configuration relates to spatially explicit characteristics of land cover types in a given landscape, namely patch geometry or with the spatial distribution of patches. Configuration metrics measure spatial characteristics such as size and shape metrics for example ratio-area perimeter, radius of gyration or the amount and type of edge or the spatial arrangement of patch types in relation to one another for example neighbourhood, contagion and interspersed metrics (Leitão and Ahern, 2002). Landscape metrics exist at the patch, class (patch type) and landscape level. At the class and landscape level, some of the metrics quantify landscape composition, while others quantify landscape configuration. Patch metrics are defined for individual patches, and characterize the spatial character and context of patches (McGarigal, 2002).

Spatial configuration refers to the spatial character and arrangement of patches and arrangement, position, or orientation of patches within the class or landscape. Aspects of configuration, such as patch isolation or patch contagion, are measures of the placement of patch types relative to other patches, other patch types, or other features of interest. Other aspects of configuration, such as shape and core area, are measures of the spatial character of the patches. Configuration also can be quantified in terms of the spatial relationship of patches and patch types. The principle aspects of configuration and a sample of representative metrics are: Patch area and edge, Patch shape complexity, Core Area, Aggregation, Subdivision and Isolation. The size and shape of patches determine their ecological and functional characteristics. Landscape metrics quantify the spatial characteristic of landscape patterns. Landscape metrics have been applied to indicate cultural ES and regulating ES (Frank and Walz, 2013). Landscape metrics describe structural aspects of ES (Syrbe and Walz, 2012; Inkoom et al., 2018). Syrbe and Walz (2012) suggest that the spatial arrangement

of landscapes and land use influence the generation of ecosystem services and human wellbeing. ES are influenced by landscape structure. Landscape structure is assumed to influence the provision of ecosystem services (Eigenbrod, 2016).

Urban form and morphology may be an important factor influencing the provision of ecosystem services (Holt et al., 2015). Urban form (i.e. the patterns and configuration associated with different land uses, histories etc.) is related to the character and purpose of built infrastructure. However, this urban form affects urban green spaces. The amount and character of green surfaces determines ecosystem processes. Ecosystem services are indicative of environmental quality. Urban development affects the environmental quality of the urban landscape (Tratalos et al., 2007). Urban quality tends to decline as urban density increases. Urban form affects the ecological quality of the urban environment.

Spatial resolution has been found to affect the supply of ES and the supply of ES differ by urban form (Rioux et al., 2019). Map aggregation has been found to affect ES supply and affect land cover configuration and structure of land cover classes. In general, at coarser resolutions there is an increase in the proportion of impervious surfaces and a decrease in the proportion of urban green space. As a result, this affects the supply of ES. Furthermore, Rioux et al. (2019) found variation in the proportion of green space cover between urban forms. Aggregating land cover data can result in underestimating green space cover and consequently, ES quantity. High resolution land cover data is recommended to map ES.

Urban form such as residential, commercial and district areas are associated with urban green space. However, there is limited knowledge of the effects of fragmentation on ecosystem service provision within urban forms. It is assumed that fragmentation could drive trade-offs and synergies among ecosystem services. Habitat fragmentation reduces the ability of plant and animal species to move across the landscape. Most services depend on the movement of matter and species across landscapes. Conversely, some ecosystem services depend on ecosystems restricting the flow of organisms or organisms such as flood regulation. Fragmentation results in numerous effects to structure and

landscape configuration which in turn can positively or negatively affect the flow of soil, water, energy, and organisms across landscapes. It is assumed that trade-offs and synergies between ecosystem services might not always be unidirectional or constant but could vary depending on the level of landscape fragmentation. Generally, ecosystem service supply is believed to decline with increasing fragmentation but the flow of ecosystem services to beneficiaries will either increase or decrease (Mitchell et al., 2015). In this study, the influence of landscape configuration on ES provision is addressed.

Habitat fragmentation involves the loss of the original habitat (attrition), reduction in habitat patch size (shrinkage), and increasing isolation of habitat patches (Andren, 1994). Furthermore, landscape fragmentation causes three main changes to patches of natural land cover across a landscape: (i) an increase in the isolation of patches and their interspersions with the surrounding human-dominated land (e.g., agricultural or urban areas); (ii) an increase in the number of patches and the amount of patch edge; and (iii) a decrease in average patch area (Mitchell et al., 2015). Fragmentation affects biodiversity which is associated with the supply of many ES (Fahrig, 2003). Fragmentation affects the number, size, shape, spatial arrangement, and isolation of patches of natural land cover, which in turn can positively or negatively affect the flow of ES. Landscape fragmentation alters the provision of ecosystem services with effects on landscape structure, including changes to landscape configuration and heterogeneity (Mitchell et al., 2015).

Landscape connectivity is predicted to affect the supply of ecosystem services through the movement of organisms and matter through a landscape but also by altering indirectly the levels of biodiversity and ecosystem function (Mitchell, Bennett and Gonzalez, 2013). It is assumed that corridors mitigate the effects of habitat fragmentation by facilitating connectivity between patches. Fragmentation can have either negative or positive effects on service flow depending on the ES in question, facilitating or restricting movement of species and matter. Landscape metrics can be useful to describe, and model pattern-process relationships, provide insights to assist in spatial concept design and

assist in the selection of planning strategies (Leitão and Ahern, 2002). Land use and land cover classifications can be used as a proxy for ecosystem service supply (Meacham et al., 2016; Haas and Ban, 2018). Landscape metrics have been applied to cultural and regulating ES. Zhang and Gao (2016) found that landscape structure affects the provision of ecosystem services. Haas and Ban (2018) determined the dependencies of service provision on land cover type and spatial attributes using landscape metrics. Land use and land cover classifications were used to characterise providing ES, where the derived land use land cover class stands representative for at least one ecosystem function or service. The dependencies of service provision on spatial attributes were based on published works and included area, connectivity, core, diversity, edge and proximity.

Landscape structure, composition and configuration, is assumed to affect the provision of ES and could drive ES trade-offs and synergies. While landscape composition has been shown to affect the provision of multiple ES (Lamy et al., 2016) less is known with reference to landscape configuration and connectivity. This study uses a BBNs modelling approach to assess the sensitivity of ES trade-offs and synergies to landscape configuration and connectivity in order to explore the relative influence of those drivers in determining ES trade-offs and synergies and predict ES trade-offs and synergies.

In order to assess whether landscape configuration and connectivity affect ES trade-offs and synergies in urban areas this study employs i) BBN modelling, ii) landscape metrics and iii) connectivity modelling tools. BBNs were used to assess the sensitivity of ES trade-offs and synergies to landscape configuration characteristics. Landscape metrics were used to measure the landscape structure of urban green space at the patch and class level. A BBN modelling approach was used for predicting ES trade-offs and used it to test the relationships between landscape configuration characteristics and ES trade-offs and synergies. Connectivity modelling was used to model functional connectivity of urban green space. Furthermore, the BBN modelling approach was used for predicting ES trade-offs and synergies and used it to test the relationships

between landscape and patch structural characteristics (patch area, connectivity and bird species abundance) and ES trade-offs and synergies. The sensitivity of the model output is assessed in order to explore the influence of those drivers in determining predicted ES trade-offs and synergies. This integrated approach and combined tools may lead to new insights regarding ES trade-offs and synergies in urban areas.

1.2.2.1 Landscape Connectivity

Landscape connectivity is the degree to which the landscape facilitates or impedes movement of species and matter (Leitão et al., 2006; Taylor et al., 1993). Connectivity is an emergent property of the landscape which results from the interaction between landscape structure and landscape function (e.g. water flow, nutrient cycling, and maintenance of biological diversity). Landscape ecologists use connectivity (corridors) to describe a landscape's structural and functional continuity in space and time (Forman and Godron, 1986). Landscape connectivity is used to refer to structural and functional connectivity (LaPoint et al., 2015). The term is also used to refer to both biotic (movement of organisms) and abiotic (movement of water, nutrients, soil) connectivity which is predicted to influence the provision of different ecosystem services (Mitchell, Bennett and Gonzalez, 2013). Landscape connectivity could affect ES provision not only directly through the movement of species and materials but also indirectly by altering the levels of biodiversity and function. It is deemed that different ES could respond in contrasting ways to landscape connectivity change creating trade-offs and synergies. The trade-offs could create ES bundles.

Landscape composition and configuration define the structural connectivity of a landscape via its spatial structure, whereas the actual movement of organisms or materials in response to this structure defines the functional connectivity of the landscape (Mitchell, Bennett and Gonzalez, 2013). Landscape structure is usually measured with landscape metrics. Corridor-based metrics of habitat connectivity have been identified as strong determinants of biodiversity, while more generic connectivity metrics based on habitat proximity are less

effective (Beninde, Veith and Hochkirch, 2015). As biodiversity underpins the provision of ES, connectivity could be a predictor for ES trade-offs and synergies. An approach to model functional connectivity is according to graph theory, depicting habitats and corridors as networks of nodes and links, and calculating measures of connectivity based on this framework (Saura and Torné, 2009). Connectivity models from circuit theory are applied to graphs to build connectivity maps that illustrates pathways of movement across a study area. Circuit theory operates on multiple map continuous map layers and considers multiple alternative connectivity pathways. This is believed to reflect ecological reality more accurately than either Euclidean distance or least-cost analysis which consider only a single optimal path. Circuits are defined as networks of nodes connected by resistors (electrical components that conduct current) and are used to represent and analyse graphs. Circuitscape was developed to apply circuit theory to problems in landscape ecology and connectivity conservation (Dickson et al., 2019). The computation typically starts with the raster cell map of a landscape exported from a GIS. The landscape is coded with resistance or conductance values assigned to each cell based on landscape features, such that conductance values are proportional to the relative probability of movement through each habitat type. Graphs are networks comprised of sets of nodes (habitat patches) connected by edges (links) (Mc Rae et al., 2008). Edges represent connections between nodes. The weight of each edge represents the strength of the connection between each node. The resistance of a resistor is the reciprocal of its conductance and can be thought of as representing isolation or movement cost between nodes. A connectivity measure from circuit theory is the resistance distance, a distance metric defined as the effective resistance between a pair of nodes. The basic concepts of circuit theory, resistance, conductance, current, and voltage all apply. As additional links are added individuals have more pathways available to them.

Circuit theory can be related to movement ecology via random-walk theory, providing concrete ecological interpretations of circuit-theoretic parameters and predictions. Circuit theory connectivity uses a corridor-based approach using Circuitscape software to represent connectivity as a raster map

of cumulative current, which corresponds to species flow or inverse cost-distance. The use of circuit theory to depict resistance or conductance provides a method for designing habitat corridors. Ecological networks are composed of cores areas, ecological corridors and buffer zones (Bennett and Mulongoy, 2006). These areal components are configured and managed to conserve ecosystems and promote the sustainable use of natural resources. The structure of an ecological network and how the system components are connected is important and may confer resilience to the supply of ecosystem services (Dakos et al., 2015). This study combined circuit models and BBNs to assess whether connectivity could drive ES trade-offs and synergies in urban areas.

Landscape connectivity is expected to affect the provision of ecosystem services (Mitchell, Bennett and Gonzalez, 2013). However, we do not fully understand how the changes in landscape connectivity affect the provision of ecosystem services. A literature review suggests that biotic and abiotic connectivity affect the provision of ES (Mitchell, Bennett and Gonzalez, 2013). Structural and functional connectivity is assumed to affect biodiversity and the provision of ES. However, few studies provide empirical evidence. In this research, these gaps are addressed using connectivity models and BBNs models to test the sensitivity of ES trade-offs and synergies to landscape configuration and habitat connectivity and test the relationships between ecosystem service trade-offs and synergies and landscape patch structural characteristics (patch area, connectivity and bird species abundance). This modelling approach represents a method to assess the influence of landscape configuration and connectivity features on predicted ES trade-offs and synergies and thereby relevant to planning decisions and landscape scale research.

1.2.3 Urban and Land Planning

More than half of the world's population lives in cities (Dye, 2008) and more than two thirds are expected to live in cities by 2050 (UN, United Nations, 2019). Concentration of population in cityscapes dominated by technology and built infrastructure has fostered the conception of an urban society that is increasingly

decoupled and independent from ecosystems (Ausubel, 1996). Urbanization and soil sealing have led to rapid changes in the biogeochemical cycles, hydrological processes and ecosystem functions (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013). Urban ecosystem services provide food supply, water flow regulation and runoff mitigation, urban temperature regulation, noise reduction, air purification, recreation, and contributions to mental and physical health. Gómez-Baggethun and Barton (2013) emphasize that urban ecosystem services can enhance resilience and quality of life in cities and identifies a range of economic costs and socio-cultural impacts that can derive from their loss. In a study, Peña et al. (2018) suggest that the provision of multiple ecosystem services could help decision-makers develop management strategies towards sustainability in urban areas. Baró, Gómez-Baggethun and Haase (2017) showed that urbanisation, with higher population densities and urban-related pressures, entail increased needs for provisioning, regulating and cultural ES, generally leading to mismatches between ES supply and demand.

The impacts of climate change coupled with land-use and land cover change will affect the maintenance of ecosystem services in urban areas. Although not widely applied in the planning process, the ecosystem service approach can provide an opportunity for land-use planning to develop ecologically sustainable urban areas (Niemela et al., 2010). Enhancing the provision of ES bundles in urban areas counteracts climate change, flood risk and air pollution which are the areas most impacted by climate change. Large and contiguous core natural areas, smaller green areas and ecological corridors are crucial for maintaining interconnected habitats for species and thus biodiversity. Improving the functional and spatial connectivity of landscapes is crucial for urban areas to mitigate and adapt to climate change and increase the values that ES provide. Thus, both local and regional level ecological networks are vital for maintaining ecosystem services in urban areas. This requires developing policies and plans to compensate urban development and enhance ecosystem services and biodiversity. Urban ecological corridors and networks have an important significance for good urban ecosystems and sustainable development (Zhao et al., 2019). Integrating ES in policies, plans and

development schemes with a sustainable green infrastructure would be beneficial to local residents and society as a whole. In urban ecosystems Beichler et al. (2017) assert that there is a need for comprehensive approaches that take multiple ecosystem services, the status of the ecosystem, human input and human modification into account to bring forward research on the spatial relations between ecosystem services. In addition, in human dominated systems Yang et al. (2015) found that socio-economic factors were the main drivers for in the formation of ecosystem service bundles and there were fewer trade-offs at larger scale than at a smaller scale.

1.2.3.1 Green Networks

At the local and regional level strategies to counteract spatial fragmentation take the form of greenways, green belts, and green networks. Green Infrastructure (GI) is a network of natural, semi-natural areas and green spaces that delivers essential ecosystem services, which underpin human well-being and quality of life (Peña et al., 2018). Generally, there are two main components to green infrastructure: hubs and links. Hubs act as an “anchor” for a variety of ecosystem services, providing source and sink habitats for species dispersing through the landscape (Benedict and McMahon, 2002). This component may include elements, such as reserves, parks and open spaces, residual lands, forests and farmlands. Links are the connections binding the ecosystems together, facilitating the flow of ecological processes; links may include, green corridors, green belts and stepping stones (Williamson, 2003).

Policies, plans and related activities incorporated in GI are carried out at spatial scales from the local to the transnational scale. At the local scale the GI components are coarsely defined units of individual green spaces. As the scale increases the resolution becomes progressively finer and a network is revealed (Laforteza, Davies and Sanesi, 2013). Green infrastructure and nature-based solutions could enhance the provision of ES and help build a resilient supply of ES (McPhearson et al., 2015; Laforteza et al., 2018). Landscape fragmentation occurs when areas of continuous natural ecosystems are broken up into smaller

elements as a result of new landscape developments and changes. Integrating ecosystem services such as plant biodiversity, food production, microclimate control, soil infiltration, carbon sequestration, visual quality into small-scale greening projects could allow for creativity and local empowerment that would inspire broader transformation of green infrastructure at the city level (Lovell and Taylor, 2013). Landscape connectivity and ecological networks are assumed to maintain and conserve biodiversity. Likewise habitat connectivity is predicted to influence the provision of ecosystem services (Mitchell, Bennett and Gonzalez, 2013). Landscape metrics are useful tools for applying landscape ecological concepts in planning (Leitão and Ahern, 2002).

In this research, a BBN modelling approach is used to assess whether landscape configuration and connectivity affect ES trade-offs and synergies and in testing the factors that influence ES trade-offs and synergies in urban areas. This may provide insights to landscape planning and in landscape research. An urban morphology that enhances green space is important in the design of healthier and climate-resilient urban ecosystems. Urban ecosystems provide a range of ecosystem services such as green space, air filtering, microclimate regulation and run-off mitigation (Bolund and Hunhammar, 1999). Connectivity is assumed to affect the provision of ES and could drive ES trade-offs and synergies in urban areas. A better understanding of how connectivity change affects ES provision would be particularly valuable for landscape management. Landscape connectivity affects the supply of ES by controlling the pattern and rate of the biotic and abiotic flows for service provision. ES respond either positively or negatively to landscape connectivity change. Landscape connectivity can affect ES provision by altering biodiversity and ecosystem functions that contribute to ecosystem services. Ecological networks are crucial for maintaining interconnected habitats for species and thus biological diversity.

In this study, a BBN approach is used to model and predict ES trade-offs and synergies and test the relationships between landscape structure (patch area, connectivity and bird species abundance) and ES trade-offs and synergies and the findings could have important implications for planners and ecologists. A

BBN modelling method is used to test whether landscape and patch structural characteristics drive ES trade-offs and synergies and affect ES provision. Integrating an ecosystem service approach and modelling tools in land use planning, management and green space design and ecosystem management along with field surveys and validation methods supports policies for urban conservation and optimise land use patterns. This approach allows to model and predict ES trade-offs and synergies and assess the structural components that affect ES trade-offs and synergies and analyse the relationships between urban habitat structure and ES trade-offs and synergies. The study area of this project was the combined built-up area of three large towns which collectively exhibit a high diversity of urban forms. This approach allows the results to be more widely applicable in other urban areas across the UK, giving this study a greater relevance than a rigorous study of a single location would have. The BBN approach allows the prediction of ES trade-offs and synergies across urban landscapes at a 2 m spatial resolution to be responsive to the variation in urban habitat structural characteristics, and thereby relevant to planning and landscape scale research.

1.3 Aim, Research Questions, Objectives and Hypotheses

This research aims to understand how ecosystem services bundle at 2 m spatial resolution in urban areas at landscape scale and analyses the composition of ES bundles and assesses whether configuration and connectivity drive ecosystem service trade-offs and synergies. A BBN modelling approach is used to test the influence of landscape configuration and connectivity on ecosystem service trade-offs and synergies and ES provision in urban areas. It targets to develop models as diagnostic and decision support tools to help maintain the ecological functioning of the urban landscape. Accordingly, the following questions are addressed in this research:

- a) Do multiple ecosystem services coexist and form spatial ecosystem bundles at 2 m spatial resolution and at a landscape scale in urban areas?

- b) Is it possible to model and predict ecosystem service trade-offs and synergies and does landscape configuration affect ecosystem service trade-offs and synergies and the provision of ES?
- c) What decision support tools might help in the urban planning process for predicting ecosystem service trade-offs and synergies and does connectivity affect ES trade-offs and synergies?

The objectives of this research are:

- a) To test whether ecosystem services form distinct bundles at a 2 m spatial resolution in urban areas and to identify and analyse the composition of ecosystem service bundles and the spatial variation of all ES (i.e. the entire bundle) at a landscape scale.
- b) To test a BBN modelling approach for predicting ES trade-offs and synergies and to assess whether landscape configuration affects ecosystem service trade-offs and synergies.
- c) To test a BBN modelling approach for predicting ES trade-offs and synergies and assess whether landscape connectivity affects ecosystem service trade-offs and synergies in urban areas.

With the above questions and objectives, three hypotheses are tested:

- a) Ecosystem services cluster to form bundles and there were specific trade-offs and synergies between ecosystem services. For example, we might expect carbon storage to bundle with habitat quality and erosion control because urban trees and woodland vegetation provide climate regulation, habitat quality and protect from soil erosion.
- b) A Bayesian Belief Network modelling approach is proposed as an effective modelling method to assess the influence of habitat configuration on ES trade-offs and synergies. Landscape configuration affects ecosystem service trade-offs and synergies. For example, we might expect that habitat quality from large patches to not be adversely affected because larger patches of green space are less likely to be affected by the surrounding built-up matrix.

- c) A Bayesian Belief Network modelling approach is proposed as an effective modelling method to assess the influence of landscape connectivity on ES trade-offs and synergies. Landscape connectivity affects the relationship between connectivity and ecosystem service trade-offs and synergies. For example, we might expect that erosion control from small patches with moderately low connectivity to be adversely affected because small patches of moderately low connected green space provide less woodland vegetation cover to protect from soil erosion.

1.4 Brief Description of Approach and PhD Thesis Structure

Overall, this study developed multiple combined approaches to assess how ecosystem services bundle at a 2 m spatial resolution in urban areas and assess the influence of landscape configuration and connectivity on ES trade-offs and synergies and the provision of ES. The integrated approach of modelling tools of ES, GIS, landscape ecology analytics, Bayesian Belief Networks and connectivity modelling was utilised to develop models as diagnostic and decision support tools to test whether landscape configuration and connectivity affect the provision of ES in urban areas. The modelling approach allows to assess whether modelled ES trade-offs and synergies across urban areas are responsive to the variation of landscape and patch structural characteristics. Furthermore, a comparative analysis was conducted on three towns generated by the models. This research is significant because it provides quantitative empirical information for urban planning and it contributes to the knowledge of landscape ecology science in urban systems.

The thesis consists of six chapters; three chapters were written as a collection of papers to achieve the objectives of the project. The chapters are continuous and interlinked. The structure of this thesis illustrates its area of application and its potential benefits (Figure 1.2).

Chapter 1 covers the background of the thesis and presents the updated literature review which captures the theory, concept and application of the

research methods. This chapter provides aims, questions, research objectives and hypotheses of the study. The chapter also describes the location and geographical areas of Bedford, Luton and Milton Keynes, UK.

Subsequently, the land use land cover maps of the study areas are utilised in Chapter 2 to address the first objective. The chapter examines the composition of ES bundles and the spatial variation of ES across the landscape using ES modelling tools, K-means clustering and Principal Component Analysis and GIS. In this chapter, the InVEST modelling framework is used to map six ecosystem services. K-means cluster analysis is used to identify the ES bundles and their geographical patterns are mapped using GIS. Principal component analysis is used to identify and analyse spatial trade-offs and synergies of multiple ecosystem services at a 2 m spatial resolution. The trade-offs and synergies are analysed and evaluated.

Chapter 3 uses the data analysis from Chapter 2 to address the second objective. This chapter tests whether landscape configuration influences ES trade-offs and synergies and the provision of ES using BBNs models. The modelling method is used for predicting urban ES trade-offs and synergies and used it to test the relationships between urban habitat configuration and ES trade-offs and synergies. The sensitivity of model output to the predictors (i.e. configuration metrics) is assessed in order to explore the relative influence of those drivers in determining predicted ES trade-offs and synergies. Principal component analysis is used to identify a core set of landscape configuration metrics at the class and patch level and subsequently the BBN modelling method is used to assess the influence of landscape configuration on ES trade-offs and synergies. This chapter addresses the important topic of the influence of landscape configuration on ES trade-offs. It also aids the understanding on how models can be appropriately used as a valuable tool for this topic.

Consecutively, in Chapter 4 circuit theory is used to model landscape connectivity. The circuit model runs on the resistance map using random walk functionality to calculate the total resistance between pairs of user-defined 'nodes' representing core habitats. When each pairwise result is summed

together, a cumulative current map is produced which expresses the intensity of wildlife flow. In this study, BBNs are used for predicting ES trade-offs and synergies and used to test the relationships between landscape and patch structural characteristics (patch area, connectivity and bird species abundance) and ES trade-offs and synergies. The sensitivity of model output to the predictors (patch area, connectivity and bird species abundance) is assessed in order to explore the relative influence of those drivers in determining predicted ES trade-offs and synergies. This approach provides useful information of the sensitivity of ES trade-offs to connectivity, thus providing ecological understanding that is relevant to planning decisions and urban conservation.

In Chapter 5, the key findings of each chapter objective are discussed. The chapter also explains the research limitations, the implications of the findings, and a perspective on future work required in this area. It highlights how the thesis has made an original contribution to the knowledge in the literature. It will guide the effective implementation of sustainable policies, planning and management of ES.

Finally, Chapter 6 states the overall conclusions of the thesis while summarising the achievements of each objective. It also delivers the key messages of this research and outlines the recommendations made in this study. Moreover, a discussion on the implementation of the model in UK cities and towns and other regions is presented.

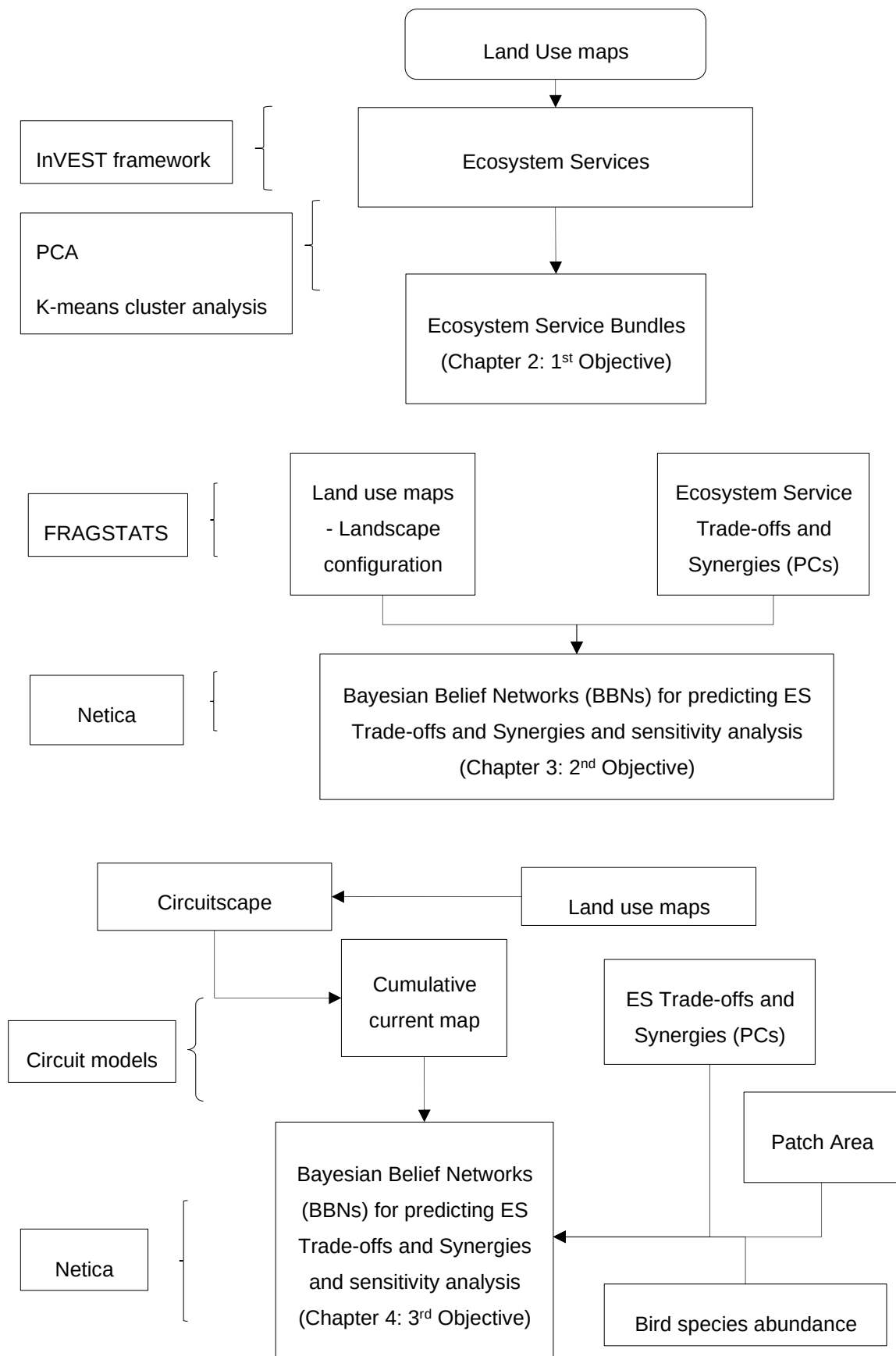


Figure 1.2 Thesis framework

1.5 Study Area

The study area was the combined urban areas of three large towns: Milton Keynes, Bedford, and Luton, UK (Figure 1.3). These towns exhibit a broad range of urban forms and histories, including historic urban centres, areas of industrial expansion and planned new town development. Bedford (52°80N, 0°270W) originated as a medieval market town and is built on the River Great Ouse and exhibits a radial road pattern around the town centre. Its 2011 population was 106,940 and the town covers 36 km², with a population density of 2971 inhabitants km⁻² (Office for National Statistics, 2013). Luton is a larger industrial town typified by extensive industrial parks and nineteenth century residential 'terraces' that make up much of its urban pattern (51° 520 N, 0° 250 W). In the 2011 census population of 258,018 and covers 58 km², with a population density of 4448 inhabitants km⁻² (Office for National Statistics, 2013).

Milton Keynes is a planned 'new town' developed during the 1960s (52°00N, 0°470W), noteworthy for its unique road layout and urban form (Grafius et al., 2016). The town is structured around a grid of major roads designed for speed and ease of automotive travel, rather than the radial pattern common to many more historic English urban landscapes (Peiser and Chang, 1999). The urban area possessed a population of 229,941 in 2011, covering an area of 89 km² with a population density of 2584 inhabitants km⁻² (Office for National Statistics, 2013). Milton Keynes is also characterised by a high coverage of public green space, possessing many parks and wooded foot and cycle paths (Milton Keynes Council, 2015).

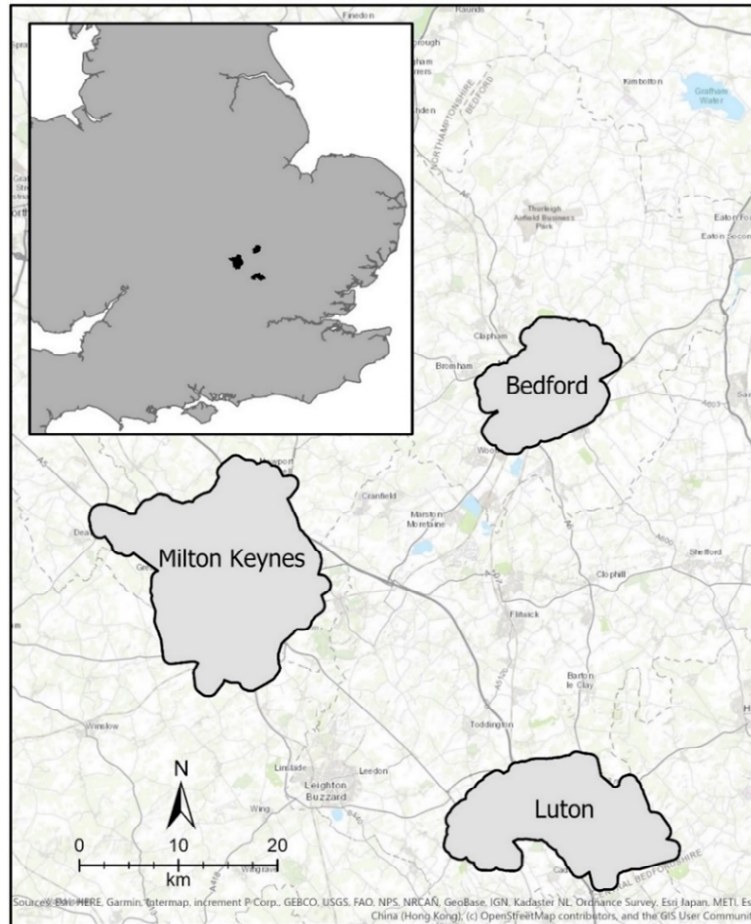


Figure 1.3 Location map of the three towns in the UK

1.6 List of Outputs from Thesis

- a) Karimi, J.D., Corstanje, R., & Harris, J. Bundling ecosystem services at a high resolution in the UK: Trade-offs and synergies in urban landscapes (Chapter 2). In 3rd revision. Landscape Ecology (IF 3.385, Q1).
- b) Karimi, J.D., Corstanje, R., & Harris, J. Understanding the importance of landscape configuration on ecosystem service bundles at a high resolution in urban landscapes in the UK (Chapter 3). In 3rd revision. Landscape Ecology (IF 3.385, Q1).
- c) Karimi, J.D., Harris, J. & Corstanje, R. Using Bayesian Belief Networks to assess the influence of landscape connectivity on ecosystem service trade-offs and synergies in urban landscapes in the UK (Chapter 4). Manuscript had submitted to Landscape Ecology.

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2 BUNDLING ECOSYSTEM SERVICES AT A HIGH RESOLUTION IN THE UK: TRADE-OFFS AND SYNERGIES IN URBAN LANDSCAPES

James D. Karimi; Ron Corstanje; Jim A. Harris

School of Energy, Environment and Agrifood, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK

Abstract

Context

Ecosystem service bundles can be defined as the spatial co-occurrence of ecosystem services in a landscape. The understanding of the delivery of multiple ecosystem services as bundles in urban areas, and at fine scale is limited. This study modelled ecosystem services in an urban area comprising the towns of Milton Keynes, Bedford and Luton.

Objectives

The objectives of this study were to assess (1) how ecosystem service bundles scale at a 2 m spatial resolution and (2) identify and analyse the composition of ecosystem service bundles.

Methods

Six ecosystem services were modelled with the InVEST framework at a 2 m resolution. The correlations between ecosystem services were calculated using the Spearman rank correlation coefficient method. Principal Component Analysis and K-means cluster analysis were used to analyse the distributions, spatial trade-offs and synergies of multiple ecosystem services.

Results

The results showed that regulating services had the tendency to form trade-offs and synergies. There was a significant tendency for trade-offs between supporting service habitat quality and pollinator abundance. Four bundle types were identified which showed specialised areas with prevalent soil erosion with high levels in water supply (bundle 1), areas with high values in nutrient retention and habitat quality (bundle 4), areas with high levels in carbon storage (bundle 2) and urban areas with high values in pollinator abundance and nutrient retention (bundle 3).

Conclusions

This study demonstrates the existence of synergies and trade-offs between ecosystem services and the formation of ecosystem service bundles in urban areas. This study provides a better understanding of the interactions between services and improve the management choices in ecosystem service provision in urban and landscape planning.

Keywords: Ecosystem service bundles; Urban; Model; Trade-offs; Synergies; Spatial analysis; Indicators

2.1 Introduction

Ecosystem services are the goods and services that ecosystems provide to society and may be classified as provisioning, supporting, regulating and cultural services (Millennium Ecosystem Assessment, 2005). The ecosystem service approach involves identifying, measuring, mapping or modelling the stocks and flows of different ecosystem services and the synergies and trade-offs that may occur among them as a result of different decisions. Ecosystem service (ES) bundles have been defined as “sets of ecosystem services that repeatedly appear

together across space or time” (Raudsepp-Hearne, Peterson and Bennett, 2010). Urbanisation, agriculture and deforestation can affect the distribution of ecosystem services and lead to spatial trade-offs and synergies between services. A spatial trade-off occurs when an ecosystem service delivery declines with respect to an increase in the delivery of another. This may be due indirectly to simultaneous response to the same driver of change on multiple ecosystem services or due to direct interactions between ecosystem services. For instance, an increase in crop production and therefore nutrient runoff could result in a decrease in water quality. Synergies occur as a result of positive interactions between ecosystem services or multiple ecosystem services can coexist. For example, restoring riparian wetlands enhances flood protection and nutrient retention which increases crop production (Bennett, Peterson and Gordon, 2009). At a landscape scale, a pattern of trade-offs between provisioning ecosystem services and both regulating and cultural ecosystem services has been found. Synergies have been found between almost all regulating services (Kong et al., 2018). It has been found that either landscape heterogeneity or deliberate management in homogeneous landscapes enhances the delivery of ecosystem services (Crouzat et al., 2015).

Spatial trade-offs and synergies may be the result of interactions between ecosystem services due to the impact of drivers such as changing land use and climate change or the result of natural ecological processes (Fu et al., 2015). A better understanding of the relationships between ecosystem services and the affecting drivers can help in managing ecosystem services (Bennett, Peterson and Gordon, 2009). Attempts to enhance the production of one ecosystem service can result in the decline in the provision of other ecosystem services. For example, increasing fertiliser use to improve crop production can have a negative effect on the provision of clean water leading to a trade-off wherein the provision of one service increases, crop yields, while another declines, i.e. water quality (Bennett et al., 2009).

A number of studies have conducted assessments of ecosystem service bundles at different scales (Turner et al., 2014; Yang et al., 2015; Raudsepp-

Hearne and Peterson, 2016) and found that ecosystem services exhibit spatial clustering. However, ecosystem services are sensitive to scale (Grêt-Regamey et al., 2014) and to the ecosystem services selected. Studies of ecosystem service bundle analysis have been conducted at a 1 km, 10 km and 75 km grid resolution (Turner et al., 2014; Crouzat et al., 2015; Raudsepp-Hearne and Peterson, 2016). However, there are fewer studies of ecosystem service flows at a local and regional scale (de Groot et al., 2010). The aim and novelty of this study was to analyse how ecosystem service bundles are represented at a 2 m spatial resolution. Ecosystem services are produced at different scales, depend on social-ecological processes and appear to be context dependent (Andersson et al., 2015). Ecosystem services are influenced by land use and ecosystem service bundles are produced as a result of social–ecological systems (Hamann, Biggs and Reyers, 2015). Spatial bundle analysis may reveal how ecosystem services are related to human modified areas. This knowledge can assist in urban and landscape planning. Such studies address services such as climate regulation, runoff mitigation, air purification, pollination and seed dispersal, urban temperature regulation and noise reduction.

Urban green space provides multiple ecosystem services to urban areas with climate regulation, air purification, run off mitigation, cooling (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013) and it is deemed that the provision of ecosystem service bundles depend on the composition and configuration of urban green space (Andersson et al., 2015; Derkzen, van Teeffelen and Verburg, 2015). The integration of ecosystem services in spatial planning shows there is a potential for green space design aimed at increasing ecosystem services (Andersson et al., 2014; Holt et al., 2015). Ecosystem services in urban areas could show different spatial patterns than in natural ecosystems as urban ecosystems are not consistent with that of natural ecosystems. Urbanisation affects the provision of ecosystem services and ecosystem functions. The influence of landscape configuration, geomorphology and hydro-ecological conditions in urban areas affects the provision of ecosystem services of nutrient cycling, soil erosion, hydrological flow causing changes in

water and sediment fluxes (Alberti, 2005). In this study the Integrated Valuation of Environmental Services and Trade-offs (InVEST) modelling framework developed by the Natural Capital project was used to model six ecosystem services at a 2 m spatial resolution. The services were modelled across three urban areas: the towns of Bedford, Luton and Milton Keynes. The three towns were chosen as they exhibit a high diversity of urban forms. The combined analysis of ESs and urban structure allows the results to be more general. This enables relationships to be drawn between ESs and urban structure that could inform sustainable urban planning.

The objectives of the study were to test: (1) how ecosystem service bundles scale at a 2 m spatial resolution and (2) identify and analyse the composition of ecosystem service bundles in urban areas. This was done by modelling six ecosystem services and determining the ES gradients along which the entire bundle of the ecosystem services changed. A K-means clustering was done to identify the ES bundles. We hypothesize that by answering these objectives ecosystem services will cluster to form distinct bundle types, illustrating types of spatial trade-offs and synergies between ecosystem services which when identified will improve and inform management choices. For example, we might expect carbon storage to bundle with habitat quality and erosion control because urban trees and woodland vegetation provide climate regulation, habitat quality and protects from soil erosion. For example, we might expect pollinator abundance to bundle with nutrient retention because grasslands provide floral resources for pollinators and retain nutrients. The results may provide insights to mitigate the spatial trade-offs and enhance synergies in the provision of ecosystem services in development planning and green space design.

2.2 Methods

2.2.1 Land Use Land Cover data

The fine scale (2 m) land use/land cover map used in this study (Figure 2.1) was created from colour infrared aerial photography originally at 0.5 m resolution obtained from LandMap Spatial Discovery (<http://landmap.mimas.ac.uk/>). The imagery was taken on 2 June 2009 for Bedford, 30 June 2009 and 24 April 2010 for Luton, and 8 and 15 June 2007 and 2 June 2009 for Milton Keynes, based on cloud-free image availability. Buildings and water features were identified from UK Ordnance Survey MasterMap layers, and remaining paved surfaces were separated from vegetation through the use of a Normalised Difference Vegetation Index (NDVI) threshold. Vegetation was classified into broadleaf trees, coniferous trees, and grass/herbaceous and distinguishing vegetation types by height. Digital Terrain Models (DTMs), produced from airborne LiDAR at a 5 m resolution were used to calculate basin maps (Grafius et al., 2016). The DTMs though did not cover the study area with gaps in the data at the borders. The nutrient retention output maps therefore resulted striped at the borders. This explains the stripes at the borders on the ecosystem service bundle raster map. However, this did not affect the results and conclusions of the analysis. The gaps comprised a limited extent of the study area and a small size of the data. All raster input maps were resampled to a 2 m spatial resolution using the raster Resample tool in ArcGIS (ESRI, 2017).

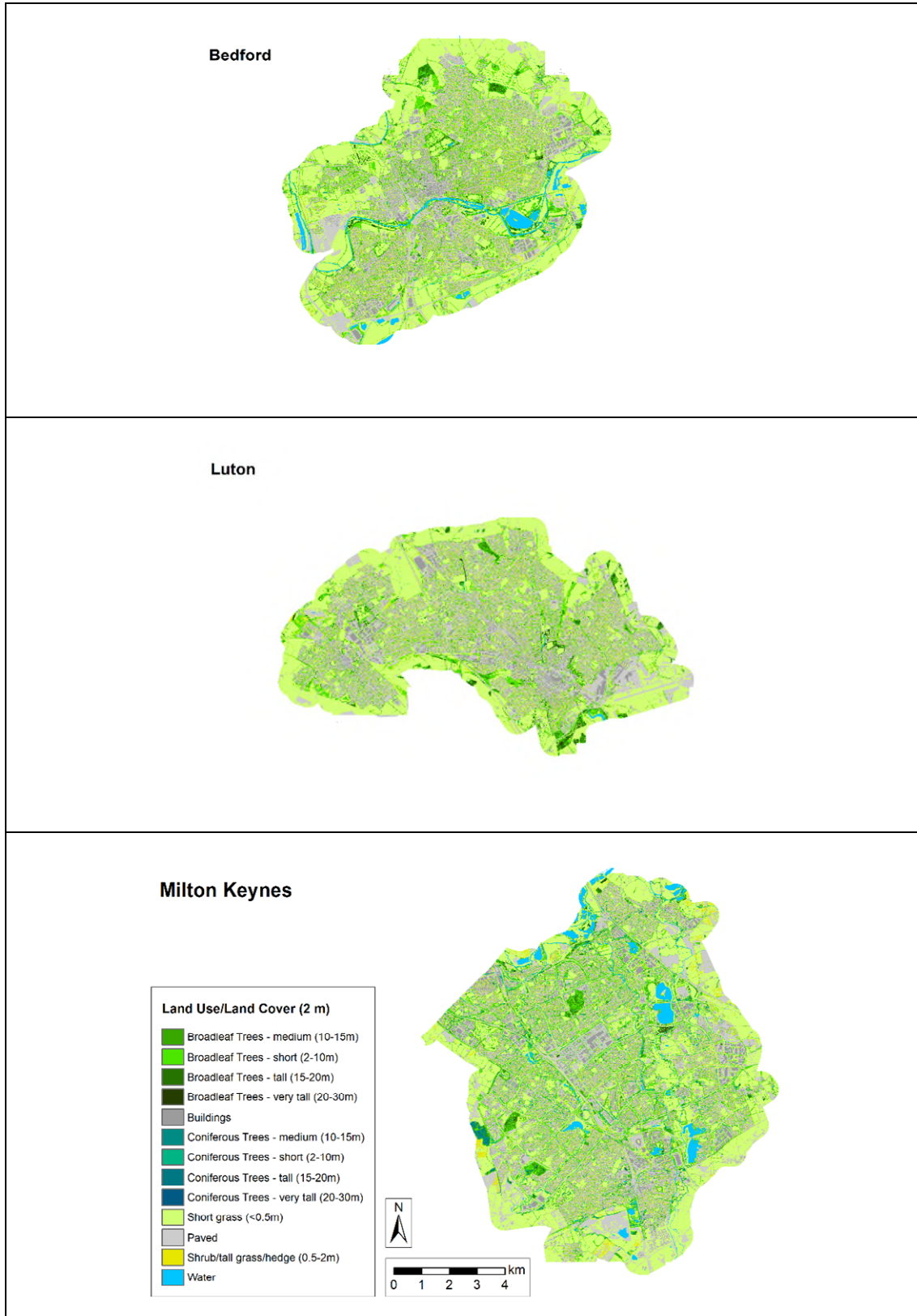


Figure 2.1 Study area showing land use land cover classification for Bedford, Luton, and Milton Keynes, UK

2.2.2 Ecosystem Services

A total of six ecosystem service models were chosen for the towns of Bedford, Luton and Milton Keynes (Table 2.1). The ecosystem services were Habitat provision, Carbon storage, Erosion control, Water provision (Quick flow and Baseflow), Nutrient retention (Nitrogen and Phosphorous retention) and Pollination. The ESs were chosen based on methods and as defined in the MA (Millennium Ecosystem Assessment, 2005). The ESs are also mentioned in the main classification CICES (Haines-Young and Potschin, 2018). The ESs generated by green space for the combined three urban areas allows an analysis between the provision of ecosystem services and the structure of the urban landscape. This approach allows the results to be more widely applicable to other urban areas across the UK. The ecosystem services were modelled with Integrated Valuation of Environmental Services and Trade-offs (InVEST) modelling suite version 3.4.4. The six models were Habitat Quality, Carbon Storage and Sequestration, Nutrient Delivery Ratio (NDR), Sediment Delivery Ratio (SDR), Seasonal Water Yield (SWY) and Pollination. Eight indicators were chosen as representatives of provisioning, supporting and regulating services. Carbon storage plays a role in regulating climate and has a cooling effect. In addition, carbon storage act as sinks of CO₂. The carbon storage indicator measures the capability of carbon storage in carbon pools and the amount of carbon stored in the landscape by land cover type (A summary of the ecosystem services and indicators are shown in Table 2.1).

Table 2.1 Selected ecosystem services, method of estimation and indicators used in this study. Notes on interpretation of ecosystem services and indicators.

ES category	Ecosystem service	Method of estimation	Indicator	Units	Notes
Supporting services	Habitat provision	InVEST 3.4.4	Habitat quality	Unitless (0-1)	Habitat quality measures the quality of habitats based on the impacts of threats on habitats. The habitat quality model estimates the extent of habitat and vegetation types across a landscape, and their state of degradation
Regulating services	Carbon storage	InVEST 3.4.4	Carbon stored	Mg C/2 m ²	The carbon storage indicator measures the capability of carbon storage in carbon pools and the amount of carbon stored in the landscape by land cover type.
	Erosion control	InVEST 3.4.4	Potential soil erosion	Mg /2 m ²	The potential soil erosion indicator measures the amount of total potential soil loss per pixel in the original land cover and indicates areas for protection. It represents the inverse of a positive ecosystem service and a measure of erosion control; the ability of urban green space to mitigate erosional losses.
	Nutrient retention	InVEST 3.4.4	Nitrogen retention	kg /2 m ²	N retention is a measure of nutrient retention by natural vegetation and enables vegetation growth. Nitrogen

					and phosphorous are the nutrients most often considered in the valuation of the nutrient service.
			Phosphorous retention	kg /2 m ²	P retention is a measure of nutrient retention by vegetation. The service nutrient retention plays an important role also for the resilience of the water ecosystems and in the filtration of pollutants and is of interest for surface water quality.
Pollination	InVEST 3.4.4	Pollinator abundance index	Unitless (0-1)		Pollination abundance index gives an indication of bee visitation rate to floral quality green space. The model was used here in consideration of the benefits of pollination to urban residents.
Provisioning services	Water supply	InVEST 3.4.4	Baseflow	mm	Baseflow and quick flow are indicators for water provision. Baseflow is the amount of water infiltrating into the aquifer and the longer-term discharge derived from natural storages.
			Quick flow	mm	Quick flow or surface runoff could give an indication of runoff mitigation by land cover type. Quick flow is the amount of surface runoff that can potentially enter the stream.

2.2.2.1 Provisioning services

The Seasonal Water Yield model was run to compute spatial indices that quantifies the relative contribution of a parcel of land to the generation of both baseflow and quick flow. Climate, soil, topography and land cover properties determine the values of baseflow and quick flow. The saturated hydraulic conductivity map dataset at a resolution of 250 m was obtained from the 3D soil hydraulic database of Europe at 250 m resolution (Tóth et al., 2017) and the soil groups determined as specified in the InVEST user manual (Sharp et al., 2016). In the input table for each land use land cover (LULC) type the runoff curve number (CN) for each soil type was then assigned (USDA-NRCS, 2004). The threshold flow value was set to 250,000, which coincides with a 1 km² contribution area (Scordo et al., 2018). The model's default parameters for alpha α parameter (0.08333), beta β parameter (1) and gamma γ parameter (1) were used according to the recommendations in the InVEST user manual (Sharp et al., 2016). The baseflow maps and the quick flow maps which represent the contribution of a pixel to slow release flow and surface runoff in mm, respectively, were retained for the analysis.

2.2.2.2 Supporting services

The habitat quality model combines information on LULC suitability and threats to biodiversity to produce habitat quality maps. Habitat quality and degradation maps were derived from the habitat quality model. The land use maps were expanded to include a buffer of 2 km using UK MasterMap data (Ordnance Survey (GB), 2017) for paved land and buildings and land cover maps (Digimap, 2015). InVEST models habitat quality as a proxy for biodiversity and for quantity and quality of available resources. A habitat to be considered of high quality must be relatively intact and function within the range of past variability. Habitat quality depends on a habitat's proximity to human land uses and the intensity of these land uses. Human land uses refer to the way in which humans employ the land and its resources. Thus, habitat quality is degraded proportionally to the rate of

increase of nearby land-use. A habitat score is a weighting from 0 to 1 assigned to each land use/land cover type where 1 indicates the highest habitat suitability. In this study, for the three towns trees (broadleaf and coniferous), grass and water were considered as green space habitats and assigned a habitat score of 1 in the sensitivity table. Built-up areas were considered non-habitat and assigned a score of 0. Habitat quality scores were assigned based on biodiversity generally, i.e. land use land cover type (Table 2.2). Each LULC was classified as habitat or not without reference to any particular species group. The relative habitat sensitivity scores were assigned to each land cover type for each threat. In this study, paved land and buildings were treated as 'threats'. The habitat quality model considers the effects of threats to biodiversity and habitat quality. The maximum distance over which paved land affects habitat quality was set to 2 km. The maximum distance over which buildings affect habitat quality was set to 1 km. Paved land was set a larger distance as paved roads attract more traffic and degrades habitat over a larger distance. The raster maps represent the distribution of habitat quality scores. The half-saturation constant was set to 0.5, the default for the model but can be set equal to any positive number. The half-saturation constant is a parameter and is set by the user. The InVEST model uses a half-saturation curve to convert habitat degradation scores to habitat quality scores (Sharp et al., 2016). It determines the spread and central tendency of habitat quality scores. It helps with the visual representation of heterogeneity in quality across the landscape. The habitat quality map was retained for the analysis (see Appendix A, Figure A.5).

Table 2.2 Habitat sensitivity table showing the land cover types, habitat suitability scores and the relative sensitivity of each habitat (i.e. land cover type) to each threat

LULC	Name	Habitat	Paved	Buildings
1	Grass	1	0.75	0.85
2	Broadleaf trees	1	0.5	0.6
3	Coniferous trees	1	0.5	0.6
4	Paved	0	0	0
5	Buildings	0	0	0
6	Water	1	0.1	0.2

2.2.2.3 Regulating services

Potential soil erosion maps were derived from the SDR model (Appendix A, Figure A.6). The sediment delivery ratio model calculates erosion risks and sediment generation and flow based on topography, climate, soil and vegetation properties. The model uses a universal soil loss equation (USLE) to estimate soil erosion rates of the study area. In this study the USLE equation was adapted to UK soils. The sediment delivery model is a spatially explicit model operating at the spatial resolution of a digital elevation model (DEM) raster. For each cell, the model computes the amount of annual soil loss from that pixel, then computes the sediment delivery ratio (SDR), which is the proportion of soil loss actually reaching the stream. The model estimates soil losses and sediment delivered to the stream and retained by vegetation and topography on an annual time scale. Annual soil loss per pixel in the model is calculated according to the revised universal soil loss equation (RUSLE):

$$soil\ loss = R \times K \times LS \times C \times P \quad (2-1)$$

where R is the rainfall erosivity ($\text{MJ mm (ha hr)}^{-1}$), K is the soil erodibility ($\text{Mg ha h (MJ ha mm)}^{-1}$), LS is the slope length-gradient factor, C is a crop-management factor, and P is a support practise factor. The sediment delivery ratio (SDR) is calculated for each pixel i according to:

$$SDR_i = \frac{SDR_{max}}{1 + \exp\left(\frac{IC_0 - IC_i}{k}\right)} \quad (2-2)$$

where SDR_i is the maximum theoretical SDR, IC is a connectivity index after Borselli, Cassi and Torri (2008), and IC_0 and k are calibration parameters that define the shape of the SDR function. The model generates a sediment export map which is the amount of sediment exported from each pixel that reaches the stream. Similarly, a potential soil loss map which is the amount of potential soil loss per pixel in the original land cover calculated from the USLE equation. A measure of sediment retention is produced as the difference in the amount of sediment delivered by the current land cover and a land cover where all land use types have been cleared to bare soil. For the rain erosivity (R) factor (Panagos et al., 2015), the map (REDEC ESDAC database) was resampled to a 2 by 2 meter cell size. The mean values of the map were used for the study. For the soil erodibility (K) factor (Panagos et al., 2014), a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff, the map (LUCAS ESDAC database) was resampled to a 2 by 2 meter grid cell size. The mean values of the map were used to run the model. For the input table the cover management factor C was parameterised for each land cover class after Morgan (2005): 0.002 for broadleaf trees; 0.004 for coniferous trees; 0.01 for grassland, 0 for buildings, water and paved surfaces. The P factor incorporates the support practices aiming at reduction of run-off from the area and refers to US farming practices. It was omitted in this study and assigned the value of 1. The threshold flow accumulation parameter was set to 250,000 (1 over the pixel area in km^2). The model's default parameters Borselli k parameter (2), Borselli IC_0 parameter

(0.5) and maximum SDR value (0.8) were used according to the recommendations in the InVEST user manual (Sharp et al., 2016).

Nitrogen (N) and phosphorous (P) retention maps were derived from the Nutrient Delivery Ratio model. The Nutrient delivery model assessed the service of nutrient retention by vegetation. The N and P retention maps were obtained using a multiplying operation between the NDR map and the nutrient loads (for surface transport) map generated by the model using the equation $N\ retention = (1 - NDR) \times load_N$ using the Raster Calculator in ArcGIS, respectively for nitrogen and phosphorous. The model uses a mass balance approach, describing the movement of mass of nutrient through space. The model quantifies the amounts of nitrogen and phosphorus entering watercourses with run-off and produces raster maps showing how much load from each pixel eventually reaches the stream (Sharp et al., 2016). The threshold flow accumulation was set to 250,000, which coincides with a 1 km² contribution area (Benez-Secanho and Dwivedi, 2019). The model's default parameters for Borselli *k* parameter was set to 2, Subsurface critical length of Nitrogen to a global average of 200 m, Subsurface critical length of Phosphorous to a global average of 200 m, Subsurface maximum retention efficiency of Nitrogen to its default value of 0.8, the Subsurface maximum retention efficiency of Phosphorous to its default value 0.8 according to the recommendations in the InVEST user manual (Sharp et al., 2016). The nutrient retention output maps resulted striped at the borders due to missing values in the DTMs. The N and P retention maps were retained for the analysis.

Pollinator abundance was derived from the pollination model. The model was used to produce two maps, it uses estimates of the availability of nest sites and floral resources within bee flight ranges to derive an index of the abundance of bees nesting on each cell on a landscape PS (Pollinator supply) and the other showing an index of the abundance of bees visiting each cell using floral resources, and bee foraging activity and flight range information PA (Pollinator abundance). The species considered were bumble bees (*Bombus* spp.). For the model the input table contained information on the mean foraging distance of six

species (Redhead et al., 2016). For the species *B. pratorum* the range foraging distance was set to 674 m (Knight et al., 2005). For each land cover a relative index of the availability of the given nesting type and floral resources was set on a scale of 0 to 1. The ground availability index for nesting suitability was set for grass to 0.5 (Grafius, Corstanje and Harris, 2018), shrub/tall grass to 1, broadleaf trees to 0.8, coniferous trees to 0.8. Paved impervious surfaces was set to 0.3 and for buildings the score was set to 0.1 for continuous urban fabric and for discontinuous urban fabric to 0.3 (Zulian, Maes and Paracchini, 2013). The pollinator abundance index maps for each of the six species were summed and divided by six using the Raster Calculator tool in ArcGIS to produce a relative mean index of pollination service provision map. The relative index mean pollinator abundance maps were retained for the analysis.

Carbon storage was calculated using the Carbon Storage and Sequestration model. The model analyses four major potential carbon sinks 1) above ground biomass (all living plant bodies); 2) root biomass (all the root systems of the above ground biomass); 3) soil organic carbon (carbon pools present in the soil); and 4) humus carbon: dead organic carbon. The model aggregates the amount of carbon stored in these pools according to the land use maps and classifications.

$$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead} \quad (2-3)$$

In the formula, C_{total} , C_{above} , C_{below} , C_{soil} and C_{dead} represent total carbon (Mg ha^{-1}), above ground biomass (Mg ha^{-1}), root biomass (Mg ha^{-1}), soil organic carbon (Mg ha^{-1}), and humus carbon (Mg ha^{-1}), respectively. A report is generated with the total amount of carbon storage in the landscape. The model generates a raster map which shows the amount of carbon currently stored in Mg in each grid cell. A study was chosen as a primary source to assign above ground biomass and the below ground biomass (Milne and Brown, 1997). A study was chosen as

primary source of carbon soil and humus carbon estimates of broadleaf and coniferous trees (Vanguelova et al., 2013). In the input table buildings, paved surfaces, and water were all set to zero. The total carbon storage maps for the four carbon pools were retained for the analysis.

2.2.3 Data Analysis

JMP (SAS Institute Inc., 2018) and R (R Development Core Team, 2016) software were used for statistical analysis. The ecosystem service output maps for each town were set to the extent of study area (LULC maps) and converted into tables using R. The tables were combined and the ecosystem services data were standardised by subtracting the column mean and dividing by the column standard deviation. As the ESs showed non normal distributions the correlations between ecosystem services were calculated using Spearman's rank correlation method. Subsequently a correlation test was used to assess significance levels. Negatively correlated ESs ($P < 0.001$) were considered trade-offs, whereas positively correlated ESs were considered synergies. Principal component analysis (PCA) was conducted in JMP to detect trade-offs and synergies among ecosystem services. The scree plot was used to determine the number of PC axes to retain by the eigenvalues that were greater than 1 (Plieninger et al., 2013) and then a factor analysis was applied to the principal components with Varimax rotation. A K-means cluster analysis was conducted in R using the 'stats' package and a maximum of 1,000 iterations was used to find the cluster solution with the lowest within-cluster sum of squares. The elbow method (Yuan and Yang, 2019) was used to determine the number of clusters and the composition of ES within the cluster were examined. The K-means function returned the mean average values and assigned cluster membership to each observation. The clusters were then converted into maps using R and used to map ecosystem service bundles for each town. The mapping of ecosystem services and bundles was done in ArcGIS Desktop 10.5.1.

2.3 Results

2.3.1 Correlations between Ecosystem Services

Of the possible 28 pair-wise correlations, 17 pairs were significantly correlated (10 positive, 7 negative) with the strongest correlations between N retention and P retention, and N (and P) retention and carbon storage. 11 services were not correlated ($r < 0.1$), 9 were weakly correlated ($0.1 \leq r < 0.3$), 4 were moderately correlated ($0.3 \leq r < 0.5$) and 4 were highly correlated ($r \geq 0.5$). Provisioning services had primarily weak positive correlations with other services except for carbon storage (Table 2.3). Pollinator abundance had primarily weak and no correlations with other services and had a high negative correlation with habitat quality ($r = -0.73$). N retention had a high negative correlation with carbon storage ($r = -0.82$), in other words, places with high N retention had low values in carbon storage, and vice-versa, suggesting a trade-off. P retention had a high negative correlation with carbon storage ($r = -0.83$). Potential soil erosion had weak positive correlations with provisioning services. Carbon storage was the ecosystem service with the highest number of negative correlations with other services and correlated negatively with six other ecosystem services.

Table 2.3 Correlation matrix showing correlation coefficients between ecosystem services. The correlations were estimated with a pairwise Spearman rank correlation method. Blue shading indicates positive correlations, orange indicates negative correlations, in white no correlation. High correlation = 0.5-1, Medium correlation = 0.3-0.5, Weak correlation = 0.1-0.3, No correlation = 0-0.1. 1 (Legendre and Legendre, 1998). Level of significance: * P < 0.001**

	Pollinator Abundance	Baseflow	N Retention	P Retention	Quick flow	Habitat Quality	Carbon Storage	Potential Soil Erosion
Pollinator Abundance	-							
Baseflow	-0.09 ***	-						
N Retention	0.07 ***	0.11 ***	-					
P Retention	0.07 ***	0.11 ***	0.98 ***	-				
Quick flow	-0.05 ***	0.34 ***	0.32 ***	0.31 ***	-			
Habitat Quality	-0.73 ***	-0.08 ***	-0.05 ***	-0.06 ***	0.15 ***	-		
Carbon Storage	-0.14 ***	-0.12 ***	-0.82 ***	-0.83 ***	-0.33 ***	0.14 ***	-	
Potential Soil Erosion	0.09 ***	0.22 ***	0.09 ***	0.05 ***	0.17 ***	-0.06 ***	-0.24 ***	-

2.3.2 Ecosystem Service Bundles

PCA axes were selected according to the Kaiser-Guttman criterion, which selects the axes whose eigenvalues are greater than eigenvalue > 1 (Legendre and Legendre, 1998). The first three PCA axes were sufficient to characterize the variation of the set of ecosystem services indicators (See Appendix A, Figure A.1, Figure A.2 and Figure A.3). These principal components were used to identify trade-offs and synergies among the ecosystem services. Results of the principal component analysis showed that the first three components accounted for 73.68 % of the total variation (Appendix A, Figure A.4). The first component explained 38.97 % of the variance, corresponding to N retention, P retention and carbon storage. The second component explained 20.09 % of the variance, corresponding to habitat quality and pollinator abundance. The third component for 14.62 % of the variance, corresponding to baseflow, quick flow and potential soil erosion.

The PCA revealed trade-offs and synergies among ecosystem services as shown in the loading plot graphs (Appendix A, Figure A.4). Table 2.4 illustrates how the ecosystem services loaded among the first three PCs orthogonal axes of the component analysis factor matrix. The first axis revealed a spatial trade-off between regulating services nutrient retention and carbon storage. As values of nutrient retention increased, carbon storage decreases, indicating a trade-off. This appears to give a separation between areas with grass with higher values in nutrient retention from areas with trees with higher values in carbon storage. The second axis showed a trade-off between habitat quality and pollinator abundance values. This appears to show a divide between suburban areas with higher values in habitat quality from urban areas with higher values in pollinator abundance, describing a gradient of stronger trade-offs from urban to suburban areas. The third factor axis represented a synergy between baseflow, quick flow and potential soil erosion as values of baseflow and quick flow increased, potential soil erosion increases. This axis is highly descriptive of baseflow and quick flow

and appears to describe a gradient of stronger synergies with higher values between ESs from less built-up to more built-up areas.

Table 2.4 Results of the principal component factor analysis for the first three factors after Varimax rotation. Factor loadings ≥ 0.40 are shown in bold

	Factor 1	Factor 2	Factor 3
Pollinator abundance	0.16	-0.83	-0.02
Baseflow	-0.02	-0.02	0.83
N retention	0.97	-0.07	0.09
P retention	0.97	-0.10	0.10
Quick flow	0.28	0.35	0.57
Habitat Quality	-0.10	0.89	-0.07
Carbon storage	-0.93	0.16	-0.10
Potential soil erosion	0.07	-0.11	0.57

The K-means cluster analysis allowed to identify four distinct bundle types for Bedford, Luton and Milton Keynes respectively (Figure 2.2). The four ecosystem service bundles were clustered spatially. Bundle 1 had high above mean values in potential soil erosion and moderate values in P retention, N retention, baseflow and quick flow and comprised suburban areas where land cover is primarily grass although it also occurred in urban areas with a scattered distribution. It had above mean values for habitat quality and pollinator abundance. It had below mean values for carbon storage. It indicated areas with prevalent soil erosion (Figure 2.2; Table 2.5). The key process underpinning the bundle could be water supply. Bundle 2 had high above mean values in carbon storage and moderate above mean values in habitat quality and comprised urban areas where land cover is primarily broadleaf and coniferous trees. All the other services were below the mean. It had low values for N retention and P retention, indicating areas with low values in nutrient retention (Figure 2.2; Table 2.5). Bundle 3 had high above mean values in pollinator abundance, nutrient retention,

and occurred in patches mainly in urban areas where land cover is primarily grass (Figure 2.3c). It had above mean values for baseflow. All other services were below the mean. It had low values for habitat quality and carbon storage. Bundle 4 had the highest above mean values in nutrient retention and habitat quality with moderate above mean values for quick flow (Figure 2.3d). It had low values for carbon storage. It comprised suburban areas where land cover is primarily grassland. From the cluster analysis each bundle was characterised by a higher provision of ecosystem services making it possible to name them. Bundle 1 characterised by potential soil erosion, P retention and baseflow corresponded to the (1) *Potential Soil Erosion* bundle; Bundle 2 characterised by carbon storage and habitat quality corresponded to the (2) *Urban Trees and Woodland* bundle; Bundle 3 characterised by pollinator abundance, N retention and P retention corresponded to the (3) *Urban Grassland* bundle; Bundle 4 characterised by N retention, P retention and habitat quality corresponded to the (4) *Suburban Grassland* bundle.

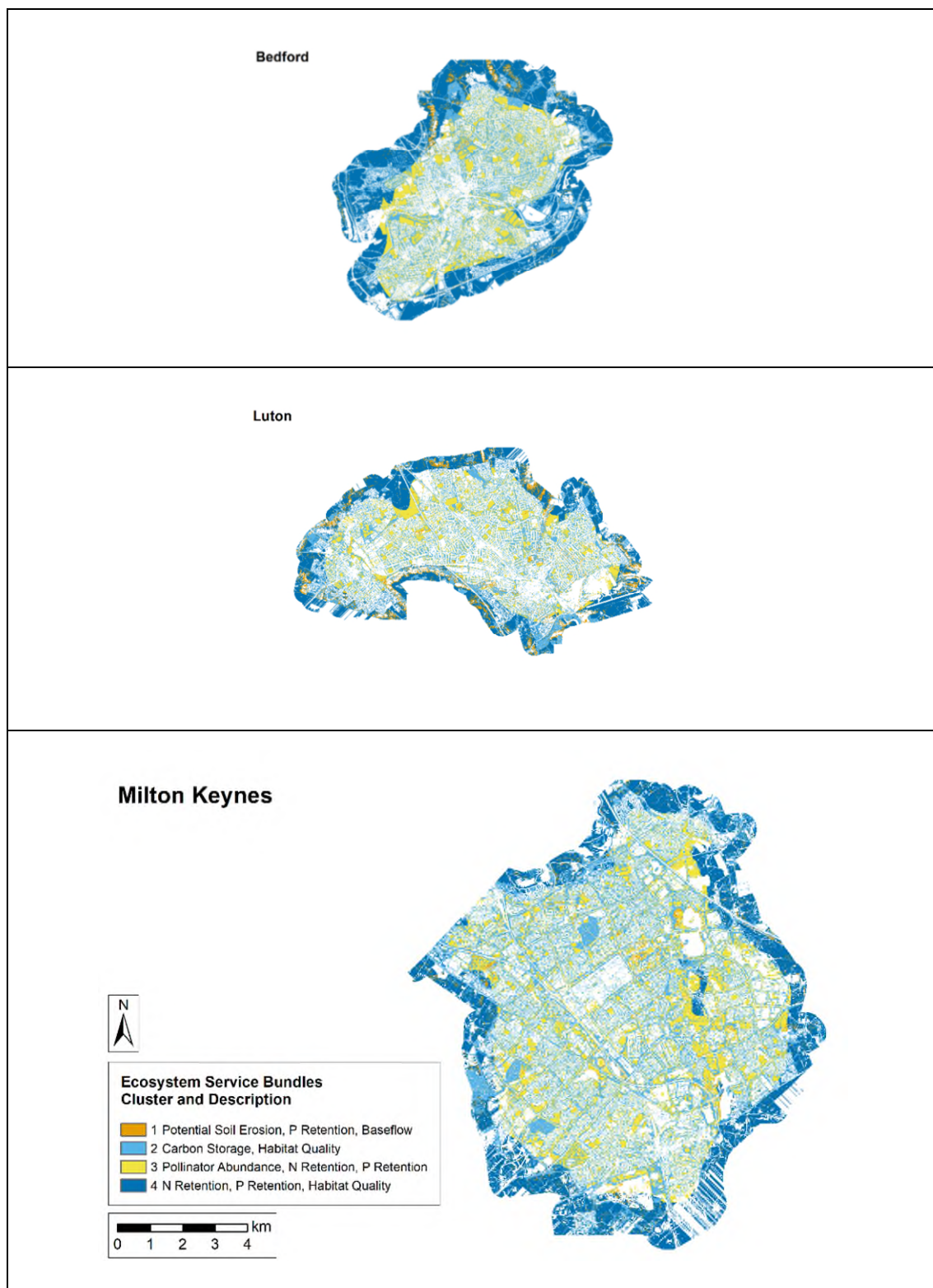


Figure 2.2 The maps show the spatial distribution of each ecosystem service bundle at 2 m resolution for the towns of Bedford, Luton and Milton Keynes

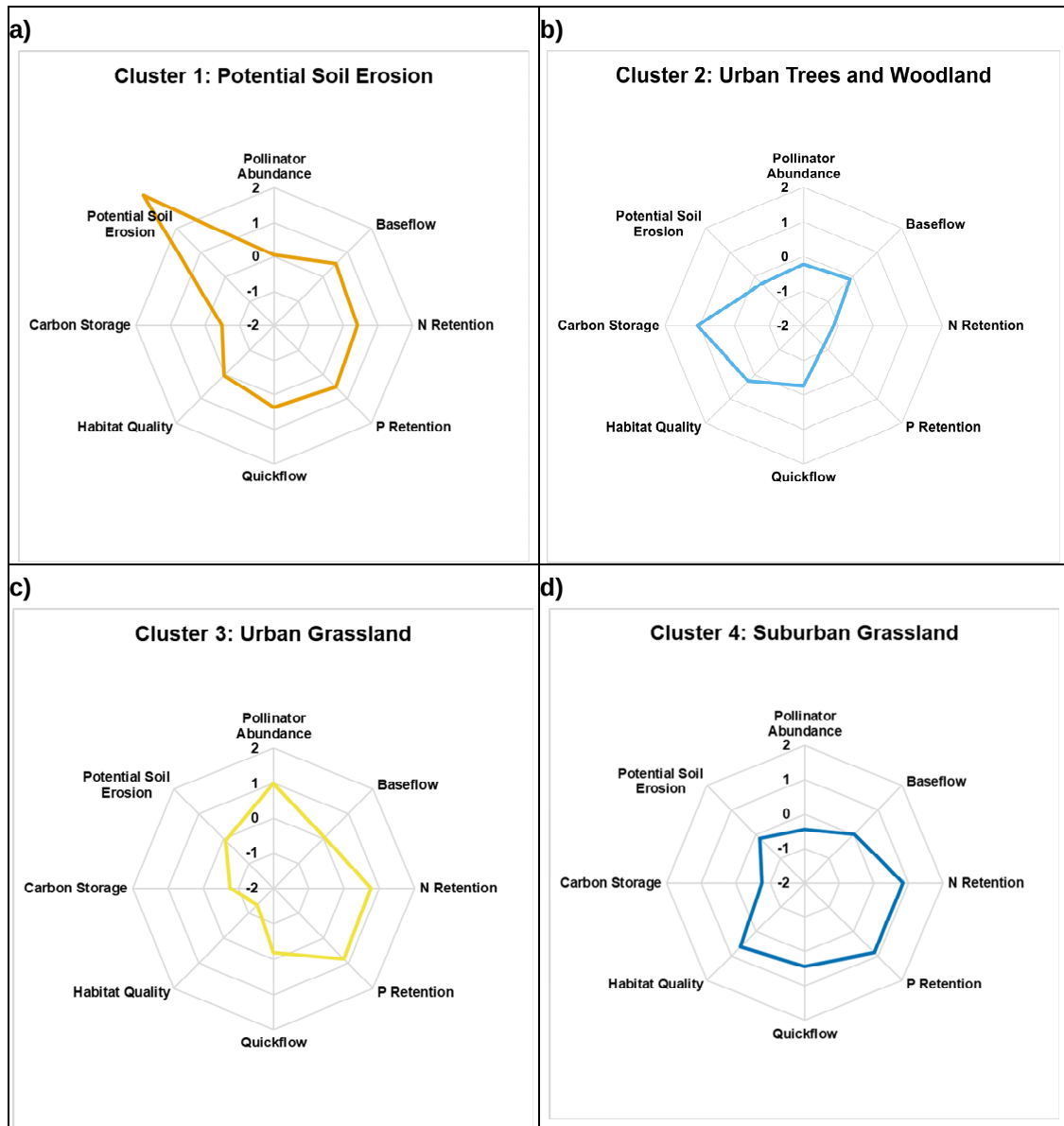


Figure 2.3 Radar charts showing Ecosystem Service Bundle types and the provision of different ESs in a cluster. K-means cluster analysis revealed four distinct ecosystem service bundle types. The charts show the average values of each service in the bundle type. (a) Cluster 1: *Potential Soil Erosion* bundle type, (b) Cluster 2: *Urban Trees and Woodland* bundle type, (c) Cluster 3: *Urban Grassland* bundle type, (d) Cluster 4: *Suburban Grassland* bundle type. Values are standardized and displayed on a scale from - 2 to 2 where 0 is the individual service mean value, not the bundle type mean

Table 2.5 Mean values for each ecosystem service (ES) within each of the clusters

Cluster	Pollinator abundance	Baseflow	N Retention	P Retention	Quick flow	Habitat quality	Carbon storage	Soil erosion
1	0.05	0.53	0.41	0.52	0.38	0.06	-0.50	3.34
2	-0.23	-0.11	-1.14	-1.18	-0.26	0.26	1.07	-0.29
3	0.98	0.04	0.78	0.83	-0.20	-1.34	-0.76	-0.08
4	-0.43	0.01	0.86	0.85	0.43	0.63	-0.76	-0.16

With regards to spatial extent, the data (Appendix A, Table A.1, Table A.2 and Table A.3) showed that for Bedford Bundle 2 had the highest spatial coverage. Bundle 3 was the most widespread with regard to areal coverage for Luton and Milton Keynes. For the combined areas Bundle 3 had the highest spatial coverage, whereas Bundle 4 had the lowest spatial coverage.

2.4 Discussion

The aim of this study was to test how ecosystem service bundles scale at a 2 m resolution. It was found that ecosystem services clustered spatially to form bundles showing signs of trade-offs and synergies between ESs and distributed in specialised urban areas according to land cover type. The interactions between ESs and the synergies and trade-offs within a bundle could be explained by the linkages between ecosystem processes, functions and ecosystem services i.e. ecosystem processes leading to functions which results in services.

2.4.1 Correlations

The many positive and negative associations between services reflect the complex interactions. Supporting services had primarily no correlations with other services except with pollinator abundance. Most studies have found trade-offs between regulating and provisioning services (Raudsepp-Hearne, Peterson and Bennett, 2010). In this study, baseflow and quick flow had negative correlations with carbon storage indicating a trade-off. Thus, one may deduce that higher values in slow release flow and surface runoff correspond to areas with lower values in carbon storage. Habitat quality had a high negative correlation with pollinator abundance implying a trade-off. Thus, one may deduce that habitat quality and pollinator abundance cannot coexist without affecting the provision of the other. Some studies have reported a higher pollinator abundance in urban areas compared to farmland sites (Baldock et al. 2015). Within urban areas, pollinator abundance and habitats are often highly varied as a result of the patchy distribution of the resources, with some green space sites rich in nesting and floral resources acting as habitats favourable to pollinators. Landscape heterogeneity introduced by moderate levels of urbanisation may also have a positive influence on some pollinators (Bellamy et al., 2017). Gardens and allotments in urban areas can provide a high floral abundance for pollinators and could explain the relatively higher pollinator abundance in these areas (Baldock et al., 2019).

Regulating service carbon storage had high negative correlations with nutrient retention implying a trade-off. Such correlations most likely reflect biogeochemical processes and land cover properties. By contrast, carbon storage had a weak positive correlation only with habitat quality. Potential soil erosion had a positive correlation with baseflow and quick flow suggesting a synergy. This could be related to hydrological and climatic processes.

2.4.2 Trade-offs and Synergies among Ecosystem Services

The results indicated that spatial trade-offs and synergies exist among the ecosystem services indicators. The spatial trade-offs between nutrient retention on the one side and carbon storage on the other indicate a gradient of spatial trade-offs between grasslands with higher values in nutrient retention and woodland areas with higher values in carbon storage. This was the most evident separation between services revealed by the first axis of the PCA. This gradient of ecosystem service trade-offs could be explained by landscape configuration, land cover type and plant ecophysiology. Grasslands and forests have different ecological traits which affect the allocation of nutrients and carbon. Some herbaceous species are better equipped to utilize nitrate than woody species, whereas woody species are better equipped to store carbon. Urban grasslands have a considerable capacity for nutrient retention (Raciti, Groffman and Fahey, 2008; Groffman et al., 2009). This is related to plant species structural and physiological characteristics and to N and C dynamics between plants, soil and climate (Groffman et al., 2004, 2009; de Vries et al., 2012). The trade-off relationship was noticeable by examining the principal components maps. The PC1 map showed spatial trade-offs between areas with high levels in nutrient retention and low levels in carbon storage (grassland) and areas with high levels in carbon storage (trees). This could be due to land use configuration, land cover type and plant ecological traits.

In this study, an evident separation between services was between suburban areas with higher values in habitat quality from urban areas with higher values in pollinator abundance revealed by the second axis in the PCA. The PC2 map showed trade-offs between areas with high levels in habitat quality and low levels in pollinator abundance (suburban areas) and areas with high pollinator abundance (urban areas). This appeared to be related to land use with a higher variety of habitats, grassland and trees, and more connected habitats in urban areas. The higher pollinator abundance in urban areas may be due to a higher abundance of floral resources and habitats for pollinator species (Bellamy et al., 2017; Baldock et al., 2019). For the three towns the maps showed higher habitat

quality in suburban areas than in urban areas. The increasing trade-offs are most likely due to land use and proximity to less built-up areas.

The PC3 map showed the synergies between baseflow, quick flow and soil erosion. For the three towns the synergies between ESs appeared to increase from less built-up areas to the city centre. For the town of Bedford, the map showed higher synergies between surface run-off and slow release flow in urban areas. The provision of ESs appeared to be related to urban land use structure and climate. For Luton synergies were higher in the south-east with higher values corresponding to urban built-up areas i.e. central business district. For the town of Milton Keynes, synergies between ESs were higher in urban areas and lower in the suburbs and on the east side of the town. The soil erosion and water supply synergies could be driven by climatic, topographical and hydrological processes which are likely to be influenced by landscape structure and habitat configuration.

2.4.3 Ecosystem Service Bundles

Each bundle consists of ecosystem services that are more alike within the bundle than between bundles. The *Potential Soil Erosion* bundle type had the highest values for potential soil erosion and distributed in areas where land cover is primarily grass. There were signs of synergies between potential soil erosion, P retention and baseflow; a fact illustrated to some extent by the third axis in the PCA. It indicated areas with high levels of surface runoff, slow release flow, nutrient retention and potential soil erosion. This bundle was dominated by potential soil erosion. The bundle could be generated by climate and land cover properties which determine the higher levels of the ESs water supply and potential soil erosion. It had the highest number of regulating services and could indicate areas for protection (Turner et al., 2014). A similar trend was found in Chen et al. (2020) for Beijing and its surrounding areas with synergies between carbon storage and erosion control and trade-offs between erosion prevention

and water supply at a coarser resolution (1 km grid cell size). A similar finding was also found by Baró et al. (2017) for the urban region of Barcelona where synergies were found between climate regulation and erosion control at 100 m resolution. Although research has found both synergic and trade-off findings for each of these ecosystem service relationships this may be related to the differences in study scales, the effects of local heterogeneity, the effects of shared ecosystem attributes (i.e. stand size, spatial configuration etc.) between ecosystem services and to the fact that urban systems are highly patchy (Wu and Li, 2019).

The *Urban Trees and Woodland* bundle had the highest levels for carbon storage and above mean values for habitat quality. It had below mean values for soil erosion, quick flow, baseflow and pollinator abundance. It indicated areas with high values in carbon storage and low values in nutrient retention. A similar trend was observed in Holt et al. (2015) for the city of Sheffield where synergies were found between carbon storage, stormwater runoff reduction and habitat provision at 500 m resolution. A comparable finding was also found in Peña et al. (2018) for the city of Bilbao covering an area of 413 km² where synergies were found between carbon storage, water flow regulation and habitat maintenance. A similar finding was found in Mexia et al. (2018) for an urban park of the city of Almada, Portugal, where synergies were found between erosion control and carbon storage at 1 m² resolution. A similar finding was also found in Dobbs et al. (2014) for the city of Melbourne's urban trees and woodland where synergies were found between habitat provision, climate mitigation and carbon storage at 30 m resolution. A higher supply of services was related to fragmented areas with one (or few) large patches of vegetation. These findings are consistent with previous studies that have analysed relations between ecosystem services (e.g. Derkzen et al., 2015). These studies suggest that urban green space structure plays a major role in determining the bundle of ESs.

Higher carbon storage occurs in wooded areas with trees where carbon is stored in above ground biomass (Davies et al., 2011) and soil (Edmondson et al., 2014). The interactions between ESs carbon storage and nutrient retention are

most likely determined by biogeochemical processes and configuration. The low values in soil erosion and surface runoff could indicate the function of trees to anchor the soil, intercept rainfall and mitigate surface runoff and soil erosion. The *Urban Grassland* bundle had higher values for pollinator abundance and nutrient retention rates showing signs of spatial trade-offs with habitat quality and carbon storage and were found in urban areas where land cover is primarily grass. The low values of habitat quality are most likely due to the proximity of grassland to paved land and buildings. The *Suburban Grassland* bundle type had high values for nutrient retention and moderate values for habitat quality and comprised suburban areas where land cover is grassland showing signs of trade-offs with carbon storage. It indicates areas with high nutrient retention and habitat quality. The *Suburban grassland* bundle could be driven by land cover (grassland) properties and the proximity of grassland to less built-up areas. The interactions between carbon storage and nutrient retention could be explained by plant ecological traits and functions, and configuration. It appeared on the map to overlap with the *Potential Soil Erosion* bundle in suburban areas and had a high supply of services.

In urban ecosystems the analysis of ecosystem service bundles allows to identify the shortcomings of ecosystem service provision and has implications in land use planning (Raudsepp-Hearne, Peterson and Bennett, 2010) and allows to identify which services are vulnerable to trade-offs (Turner et al., 2014). For example, in the correlation analysis there was a weak positive correlation between habitat quality and carbon storage. However, in the *Suburban grassland* and *Urban grassland* bundle types there were signs of trade-offs between the mean values of habitat quality and carbon storage and there might be the potential to enhance carbon storage in these areas.

Previous research has found that an increase of floral resources results in an increase in pollination supply (Davis et al., 2017). In this study higher pollinator abundance was found in urban grass patches near large contiguous habitat patches of broadleaf trees and grass. This may be due to habitat suitability and proximity to likely nesting sites. Habitat connectivity enhances pollination services

as pollinators benefit from high quality habitats in close proximity to nearby floral resources (Redhead et al., 2016). Allotments and residential gardens are important to pollinator species (Baldock et al., 2019). By contrast, built-up area resulted less favourable in pollinator abundance. Enhancing connectivity and floral richness is likely to support an increase in pollination services. Thus, potential for improvements in the design and implementation of environmental schemes.

2.4.4 Implications

Ecosystem service bundle analysis can be used in urban planning to detect and evaluate the synergic and trade-off relationships between services and the variation of ES production across an urban system. It reveals how urban green space can produce bundles of ecosystem services and how land cover influences service level and is critical to green infrastructure for delivering a broad range of services for human well-being. It can provide insights to landscape planning and management, especially in the urban landscape where the interactions between patterns and processes are complex. ES bundle analysis can assist in urban planning should a decision be required to evaluate how altering urban form may influence service production. It can identify areas of high service production. For example, in this study the suburban grassland bundle had a high supply of ESs.

ES bundle analysis can be used to detect and enhance the supply of ESs. Urban green space with low levels of an ecosystem service could be enhanced. The implications for the nutrient retention service are that green space areas with high levels of trade-offs between nutrient retention and carbon storage will be represented by grasslands. The implications for the carbon storage service are that green space areas with low levels of trade-offs between nutrient retention and carbon storage will be represented by trees and woodland habitats. This gives an indication of the type of service associated with a land cover type.

The implications for the habitat quality service are that suburban green space areas with high levels of trade-offs between habitat quality and pollinator abundance will be represented mostly by grasslands and found at a distance from built-up areas. This information can give an indication of the type of service associated with a land cover type. The implications for the pollination service are that urban green space areas with low levels of habitat quality and pollinator abundance trade-offs will be found in urban built-up areas. Providing a variety of habitats in suburban areas for pollinators for nesting and forage floral resources would enhance the pollination service in those areas.

The implications for the erosion control service are that in urban green space areas with high levels of water supply and potential soil erosion synergies the erosion control service will be lower. Therefore, these areas can be closely monitored and restored. The implications for the water supply service are that green space areas with low levels in soil erosion and water supply synergies will be less at risk from surface runoff. The green space areas with high levels of soil erosion and water supply synergies suggest that these areas will have a high supply of water supply service, baseflow and quick flow.

ES bundle analysis can be used to evaluate the supply of ESs. Landscape structure has been shown to affect the provision of multiple ecosystem services (Lamy et al., 2016). Dobbs et al. (2014) found that the provision of ESs was positively related to the amount of vegetation and negatively related to its degree of fragmentation. An urban morphology that enhances the synergies and mitigates the trade-offs of multiple ecosystem service production is important in the design of healthier and climate-resilient urban ecosystems.

Certain ecosystem services may be closely tied to specific land uses and associated land cover. For example, the urban trees and woodland bundle was associated with carbon storage, habitat quality and surface runoff reduction services. The landscape distribution of ecosystem services may correspond to predictable socio-ecological subsystems and associated land use types.

2.4.5 Limitations and Uncertainties

The InVEST models were designed to be applied at a landscape scale and in non-urban environments. Therefore, there may be some bias introduced in the assessment. The sediment delivery model applies the USLE equation to calculate soil erosion which is widely used but is limited in scope, only representing rill/inter-rill erosion processes. Like the sediment delivery model, the NDR model has a small number of parameters and outputs generally show a high sensitivity to inputs. The retention efficiency values are based on empirical studies, and factors affecting these values are averaged. The model also assumes that once nutrient reaches the stream it impacts water quality at the watershed outlet, no in-stream processes are captured. The model does not represent the details of the nutrient cycle but rather represents the long-term, steady-state flow of nutrients through empirical relationships. The Seasonal Water Yield model does not include many of the complexities that occur as water moves through a landscape as reported in the manual guide. For baseflow there are no quantitative estimates only the relative contribution of pixels. Quick flow is based on curve number, which does not take topography into account. The habitat quality model assumes that all threats are additive. However, in most cases, the collective impact of multiple threats is much greater than the sum of individuals. In addition, cultural services which were not assessed could be considered in further research.

2.5 Conclusions

This study identified ecosystem service bundles and analysed the synergies and trade-offs among ecosystem services in urban areas at a 2 m spatial resolution. There was a significant tendency for trade-offs between regulating services nutrient retention and carbon storage and for regulating services to form synergies and trade-offs. There was a significant tendency for trade-offs between supporting service habitat quality and pollinator abundance. The variation in all six ESs (i.e. the entire bundle) across the landscape and the ES gradients which

represent the trade-offs (or synergies) along which the ecosystem service bundle changed were revealed by the PCA. One gradient reflects areas with higher levels in nutrient retention and areas with higher levels in carbon storage. A second gradient reflects suburban areas with higher levels in habitat quality and urban areas with high levels in pollinator abundance. The six ecosystem services formed four ecosystem service bundle types showing distinct composition and geographic patterns. However, the spatial distributions of bundles are sensitive to the ecosystem services selected and care should be taken to select model data appropriate to the scale of inquiry. The bundles showed grassland areas with prevalent soil erosion with high levels in water supply, suburban grassland areas with high values in nutrient retention and habitat quality, urban woodland areas with high levels in carbon storage and urban grassland areas with high values in pollinator abundance and nutrient retention. The results of this study showed that ecosystem service bundle analysis can be used to identify the existence of synergies and trade-offs and evaluate the supply of ecosystem services. This could be used in sustainable ecosystem management and urban planning to improve the provision of multiple ecosystem services in urban areas and in green space design. Landscape composition and configuration affects the spatial distribution of ecosystem services and further studies that address the multiple relationships among ecosystem services and the influence of urban structure may provide insight and useful information to ecosystem management and to landscape planning and give a better understanding to mitigating the trade-offs and enhancing the synergies.

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3 UNDERSTANDING THE IMPORTANCE OF LANDSCAPE CONFIGURATION ON ECOSYSTEM SERVICE BUNDLES AT A HIGH RESOLUTION IN URBAN LANDSCAPES IN THE UK

James D. Karimi; Ron Corstanje; Jim A. Harris

Cranfield University, School of Water, Energy, and the Environment, Cranfield, Bedfordshire MK43 0AL, United Kingdom

Abstract

Context

Landscape structure is thought to affect the provision of ecosystem service bundles. However, studies of the influence of landscape configuration on ecosystem service trade-offs and synergies in urban areas are limited. This study used Bayesian Belief Networks to predict ecosystem service trade-offs and synergies in the urban area comprising the towns of Milton Keynes, Bedford and Luton, UK.

Objectives

The objectives of this study were to test (1) a Bayesian Belief Network approach for predicting ecosystem service trade-offs and synergies in urban areas and (2) assess whether landscape configuration characteristics affect ecosystem service trade-offs and synergies.

Methods

Bayesian Belief Network models were used to test the influence of landscape configuration on ecosystem service trade-offs and synergies. The outputs of a

principal component analysis (PCA) on six ecosystem services and landscape configuration metrics were used as response and explanatory variables, respectively. We employed Spearman's rank correlation and principal component analysis to identify redundancies between landscape metrics.

Results

We found that landscape configuration affects ecosystem service trade-offs and synergies. A sensitivity analysis conducted on the principal components showed that landscape configuration metrics core area (CORE) and effective mesh size (MESH) are strong influential determinants of ecosystem service trade-offs and synergies.

Conclusions

This study demonstrates that landscape configuration characteristics affect ecosystem service trade-offs and synergies and that a core set of metrics could be used to assess ecosystem service (ES) trade-offs and synergies. The findings may be relevant to planning and urban design and improved ecosystem management.

Keywords: Ecosystem service bundle, Urban, BBNs, Landscape configuration, Social-ecological systems, Trade-offs and synergies

3.1 Introduction

Landscape ecology studies the spatial relationships between functional land units, the abiotic and biotic processes between ecosystems and the change of landscape patterns over time. Human activities are considered an integral part of ecosystems and activities such as agriculture and urban development affect the landscape structure and patterns (Mitchell, Bennett and Gonzalez, 2013; Qiu and Turner, 2015). Landscape structure is the arrangement of land cover and land use across a landscape. Broadly, it includes landscape composition (how much of each land cover or land use that exists), configuration (the spatial pattern of these land cover or land use types), and connectivity (Mitchell et al., 2015). Landscapes can be analysed at four different levels depending on the desired emphasis: cell, patch, class, and landscape. Landscape metrics measure landscape pattern. Patch level refers to characteristics of an individual patch, i.e. pertaining to individual patches in a categorically-classified landscape. Class level refers to a set of patches of the same type, i.e. pertaining to a single patch type (land cover type) in a categorically classified landscape. Landscape level refers to the entire patch mosaics i.e. pertaining to the full extent of the data or, as in a hierarchy, the entire patch mosaic (in a categorically classified landscape). Landscape structure or pattern is defined by its composition and spatial configuration (Leitão et al., 2006). Changes to landscape structure affect material exchange and energy flow and impede ecosystems to provide their services. Landscape structure affects the provision of multiple ESs as landscape composition and configuration affect ecological processes (Lamy et al., 2016).

Urban ESs in towns and cities provide several benefits such as air purification, temperature regulation, noise reduction, urban cooling, runoff mitigation, recreational and cultural values (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013) which requires building a resilient supply of ESs and incorporating urban ESs in urban planning (McPhearson et al., 2015), but urban planning often entails determining trade-offs in ecosystem services and identifying where synergies occur. ES trade-offs occur when one service increases and another one decreases. Trade-offs occur when the provision of

one ES is reduced as a consequence of increased use of another ES (Rodríguez et al., 2006). This may be due to simultaneous response to the same driver or due to true interactions among services. ES synergies occur when both services either increase or decrease. This may be due to simultaneous response to the same driver or due to true interactions among services (Bennett, Peterson and Gordon, 2009). In this study, the term ES interactions refer to ES trade-offs and synergies (Turkelboom et al., 2015). Modelling tools allow to map ES bundles and detect trade-offs and synergies, and within these modeling suites, Bayesian Belief Networks (BBNs) are useful tools to assess whether landscape structure affects ES trade-offs and synergies.

Significant relationships have been found between landscape structure and the provision of ecosystem services at a landscape level (Zhang and Gao, 2016). Most studies have focused on landscape composition to explain the provision of ecosystem services. Lamy et al. (2016) found that landscape composition contributed more than landscape configuration in explaining the variation in the supply of ecosystem services. Incorporating landscape configuration into models though is thought to provide a better understanding of the provision of multiple ecosystem services.

Climate change and land cover patterns can affect the provision of ESs (Haase and Schwarz, 2012). Urban green space and green infrastructure can enhance the resilience of cities. Urban ecosystem services include air quality regulation, climate regulation, carbon storage and sequestration, noise reduction, outdoor recreation and health benefits (Elmqvist et al., 2013; Haase et al., 2014). Dobbs et al. (2014) found synergies among regulating, provisioning and supporting services in a municipality of the city of Melbourne (in an area that covers 37.6 km²). Trade-offs were found with cultural services and regulating, provisioning and supporting services. ES provision was positively related to the amount of vegetation and negatively related to its degree of fragmentation. Peña et al. (2018) found that provisioning services had trade-offs with regulating services and cultural services in Bilbao (in an area that covers 413 km²). Synergies were found between cultural services and between regulating

services. For example, synergies were found between carbon storage and water flow regulation. The trade-offs and synergies were influenced by land use type with natural land cover associated with multiple ESs.

In Rotterdam, a city that covers 326 km², more synergies between services were found than trade-offs in areas of urban green space. Synergies were found between cooling, carbon storage and air purification (Derkzen, van Teeffelen and Verburg, 2015). The green space types (i.e. tree, woodland, shrub and herbaceous) though were not all able to provide all ESs and differed in ES provision by the amount and type of green space type in the district. ES bundles were found to depend on the composition and configuration of urban green space. Regulating services have been identified as cause for concern, and thought to underlie the sustainable production of provisioning and cultural ecosystem services and are important to the resilience of social-ecological systems (Raudsepp-Hearne, Peterson and Bennett, 2010). Verhagen et al. (2016) found that landscape configuration affects the provision of ESs at the cell and watershed scale at a 25 m resolution and that different responses of ESs to configuration suggests that accounting for configuration involves trade-offs between ESs.

Landscape structure is known to affect the provision of multiple ESs (Lamy et al., 2016) with landscape composition and configuration affecting the provision of ESs. However, there is limited knowledge on whether landscape configuration affects ES trade-offs and synergies and the mechanisms and processes that create trade-offs and synergies. Landscape configuration could drive trade-offs and synergies between ESs. The landscape configuration of urban green spaces appears to affect their ecological and landscape functions (Leitão et al., 2006; Tian et al., 2014). Landscape configuration can affect ecological processes and the provision of ESs (Leitão et al., 2006). Landscape metrics (LM) are a useful tool to quantify landscape structure and pattern and allows to measure ecological attributes such as habitat heterogeneity, patch shape, isolation and context (Kim and Pauleit, 2005), and are particularly useful in urban settings. Quantifying the spatial character of vegetation and land use can be used as a proxy for assessing

the landscape's ability to perform functions such as water and nutrient retention (Inkoom et al., 2018). Thus, the landscape structure provides an understanding of the underlying impact on ecological process.

Effective mesh size (MESH) is based on the probability that two points chosen at random will be connected. This probability is then converted into the size of a patch - the effective mesh size (unit in area, e.g. ha). The smaller the effective mesh size, the more fragmented the landscape. Effective mesh size, has been used to assess landscape fragmentation as a proxy for identifying potential habitat areas (Moser et al., 2007; Inkoom et al., 2018). Habitat fragmentation has been found to affect the provision of multiple ecosystem services (Cordingley et al., 2015) and theory predicts that fragmentation could drive trade-offs and synergies among services and may create ES bundles (Mitchell et al., 2015). Landscape configuration in urban areas may be an important factor in influencing the provision of ESs (Holt et al., 2015). In spatial planning, LM are used in combination with other landscape pattern analytical approaches to evaluate landscape mosaics (Inkoom et al., 2018). Inkoom et al. (2018) advised that to interpret the metrics additional information about the land cover attributes and ecological functions be collected for ES assessment. Mouchet et al. (2014) provides guidelines and methods to model ES bundles and quantitative methods for analysing ES associations. Relationships between ESs can be understood by identifying which co-vary positively or negatively. Principal component analysis (PCA) can be used to identify trade-offs and synergies between services. Machine-learning algorithms should be used to identify drivers of ES associations when the relationships among variables are complex. In this study, a BBN approach was used. BBNs can cope effectively with incomplete information on the relationships between variables, thus facilitating modelling when data availability is insufficient to render a deterministic approach feasible (Korb and Nicholson, 2010). A major strength of Bayesian modelling is the possibility to make predictions when information on the state of input variables is partially missing (Van der Biest et al., 2013). BBNs are thus well-suited to

complexity and incomplete knowledge, which are common in ecological systems (Landuyt et al., 2013).

The aim of this study was to assess whether landscape configuration affects ecosystem service trade-offs and synergies. The objectives of this study were to test (1) a Bayesian Belief Network approach for predicting ecosystem service trade-offs and synergies in urban areas and (2) assess whether landscape configuration characteristics affect ecosystem service trade-offs and synergies. We examined the potential influence of landscape configuration on ecosystem service trade-offs and synergies by seeking answers to the following research questions: (i) does landscape configuration affect ecosystem service interactions, and (ii) can landscape configuration metrics be used to assess (and predict) ecosystem service trade-offs and synergies? We hypothesized that landscape configuration could drive ecosystem service trade-offs and synergies. A BBN modelling approach can be used to assess the influence of landscape structure on ecosystem service trade-offs and synergies. For example, we might expect that habitat quality from large patches to not be adversely affected because larger patches of green space are less likely to be affected by the surrounding built-up matrix. For example, we might expect that pollinator abundance from small patches with a low Euclidean distance between patches to not be adversely affected because small patches of green space can provide in urban areas a high variety of habitats for pollinators.

3.2 Methods

3.2.1 Overall Approach

In this study, a BBN modelling method was used for predicting ES trade-offs and synergies and to test the relationships between landscape configuration and ES trade-offs and synergies. Patch level and class level metrics were selected to assess the influence of configuration on ES trade-offs and synergies and references based on published works suggested LM (Syrbe and Walz, 2012;

Haas and Ban, 2018). The LM were based on a raster land use/land cover (LULC) map and were then used to assess the influence of landscape configuration on ES trade-offs and synergies by using BBN models. The sensitivity of the model outputs to the predictors was assessed in order to explore the influence of those drivers in determining predicted ES trade-offs and synergies. The ESs were modelled in the urban area comprising the towns of Milton Keynes, Bedford and Luton, UK. The input data was combined across the three towns to assess the influence of landscape configuration on ES trade-offs and synergies. This approach allows the results to be more widely applicable in other urban areas across the UK.

3.2.2 Land Use Land Cover, Land Structure and Ecosystem Services

The fine scale (2 m) land use/land cover map used in this study (Figure 2.1; obtained from Chapter 2) was created from colour infrared aerial photography originally at 0.5 m resolution obtained from LandMap Spatial Discovery (<http://landmap.mimas.ac.uk/>). The imagery was taken on 2 June 2009 for Bedford, 30 June 2009 and 24 April 2010 for Luton, and 8 and 15 June 2007 and 2 June 2009 for Milton Keynes, based on cloud-free image availability. Vegetated and non-vegetated surfaces were separated according to a Normalised Difference Vegetation Index (NDVI) threshold. UK Ordnance Survey MasterMap layers were used to distinguish buildings, roads and water bodies. Subsequently, airborne LiDAR was used to categorize vegetation into height classes for short grass (< 0.5 m), tall grass and shrubs (0.5–2 m), short trees (2–10 m), medium trees (10–15 m), and tall trees (>15 m) (Grafius et al., 2016, 2019). The land cover map was resampled to a 2 m spatial resolution for all modelling and analysis. The land cover map comprised vegetation cover for broadleaf trees, coniferous trees, and grass/herbaceous and vegetation types distinguished by height. Note that, although the data were gathered at two different time points (2009/2010 for aerial imagery, 2012 for LIDAR), negligible change to urban land cover took place in the study area during this time.

The mapped outputs of a principal component analysis (PCA) conducted on ES datasets (Chapter 2) were used and combined with landscape metrics of mapped land cover. The three principal components represented Nutrient retention and Carbon storage trade-offs (PC 1), Habitat quality and Pollinator abundance trade-offs (PC 2) and Potential soil erosion, Water supply synergies (PC 3). The PCA principal component maps (ES trade-offs and synergies) accounted for 73.68 % of the total variation of the ESs (Chapter 2). The ESs were chosen based on methods and as defined in MA (Millennium Ecosystem Assessment, 2005). The ecosystem services were chosen as representatives of important provisioning, supporting and regulating services. The ecosystem services were found to cluster spatially to form four ecosystem service bundle types at a 2 m spatial resolution and exhibited distinct geographic patterns.

3.2.3 Landscape Metrics Selection and Modelling Method

Fragstats 4.2 (McGarigal et al., 2012) was used to calculate the following landscape metrics for the urban green spaces at the patch level; patch area (AREA), perimeter (PERIM), radius of gyration (GYRATE), perimeter–area ratio (PARA), shape index (SHAPE), fractal dimension index (FRAC), contiguity index (CONTIG), core area (CORE), number of core areas in each patch (NCORE), core area index (CAI) and Euclidean nearest-neighbour distance (ENN) for vegetated land cover types (see Appendix B, Table B.1). At the class level, 24 class level metrics were chosen which comprised area and edge, shape, core area, and aggregation metrics (Appendix B, Table B.2 for metric abbreviations and definitions). Vegetation comprised broadleaf trees, coniferous trees, and grass/herbaceous and vegetation types distinguished by height. Non-vegetated areas were treated as the background matrix and excluded from analysis. The edge depth criterion was chosen as 5 m based on research which tested core area calculations across the same study area and determined that 5 m appeared to be an effective balance across all classes (Grafius et al., 2018). For each town, the patch ID file generated by Fragstats was converted into a polygon shapefile

and the principal component raster maps converted into a point shapefile. The two maps were intersected to obtain a point shapefile using the Intersect tool in ESRI ArcGIS Desktop 10.5.1. The file table was exported and joined with the calculated Fragstats patch-level metrics values. The tables of each town were combined and the principal components' values were averaged for each patch. The table was used for the analysis. The file table with the principal component map values for each town were summed and grouped by vegetation type and joined with the calculated class level metrics using JMP software (SAS Institute Inc., 2018). The tables were combined and used for the analysis.

A BBN modelling approach was chosen for its potential to use empirical data and cope effectively with incomplete information. BBNs are semi-quantitative, probabilistic models, and are useful tools for modelling ecological predictions. BBNs are suitable in an adaptive modelling framework because of their ability to update individual causal relations as new information becomes available and their explicit treatment of uncertainties in ES research. BBNs can be used to make predictions of the provision of ecosystem services and model multiple ecosystem services (Landuyt et al., 2012). An influence diagram can be used to illustrate relevance and influence between variables. It is a graph model that consists of two components: a directed acyclic graph or DAG and conditional probability tables or CPTs. The DAG consists of a set of nodes and the dependencies between the nodes are represented by directed arrows which represent cause-effect relations between dependent and independent nodes. The strengths of the causal relations between the networks variables are stored in conditional probability tables CPTs (Landuyt et al., 2013). The diagram is converted into a Bayesian Belief Network consisting of nodes and arrows showing relevance between predictor variables and response variable (Marcot et al., 2006). Furthermore, BBNs offer a range of validation techniques such as expert-based validation and sensitivity analysis (Landuyt et al., 2013). Bayesian Belief Networks have been used to model ecosystem services and in natural resource management (Cain, 2001; McVittie et al., 2015).

3.2.4 Statistical Analyses to Data Reduction

JMP and R software (R Development Core Team, 2016) were used for statistical analysis. The reduction of landscape metrics into a limited set of metrics is necessary as redundancy between metrics can affect the outcome of the investigation. Collinearity, a high correlation between independent variables, inflates the standard errors and makes some variables less likely to be statistically significant. We used the Kolmogorov-Smirnov-Lilliefors (KSL) test and the Shapiro-Wilk test to test for data normality in JMP on the patch level and class level metrics, respectively. Further, a Spearman's rank correlation was performed in a pair-wise correlation of 11 patch-level and 24 class-level metrics as some of our variables had a non-normal distribution using the R 'Hmisc' package (Harrell, 2019).

Principal component factor analysis (PCA) was conducted in JMP on the patch level metrics to reduce redundancy that exists among the metrics (Hair et al., 2014). The PCA was based on the correlation matrix of the 11 metrics. The cumulative proportion of variance explained by each component was examined. An orthogonal varimax rotation was applied to redistribute the variance and facilitate the interpretation of the factor matrix. The first three principal components accounted for 76 % of the total variance for all metrics (see Appendix B, Table B.3 for factor analysis results). The principal components to retain was based on the Kaiser-Guttman criterion (eigenvalue > 1). After examining the output of the correlation assessment, 7 metrics with a correlation coefficient greater or equal to $|r| \geq 0.9$ were discarded by using the factor matrix derived from the PCA. The metric between the two with the lower loading was discarded. For instance, the correlation matrix revealed a high correlation between AREA and PERIM. Since AREA had a lower loading, it was excluded from further analysis. Similarly, GYRATE had a high correlation with PERIM. Since GYRATE had a lower loading it was excluded. The seven patch level metrics excluded after the preliminary assessment were AREA, GYRATE, PARA, SHAPE, PERIM, NCORE and CAI. To conclude, 4 metrics were left for subsequent analysis. These included FRAC, CONTIG, CORE and ENN. To further reduce the level of

redundancy between patch level metrics and identify the core patch level metrics which explained the patch variability in the dataset a second principal component factor analysis was conducted on the remaining variables and an orthogonal varimax rotation applied.

In the same way, a principal component factor analysis was conducted on the class level metrics to reduce redundancy between metrics and a varimax rotation applied. The PCA was based on the correlation matrix of the 24 metrics. The cumulative proportion of variance explained by each component was examined. The first three principal components accounted for 95 % of total variance for all metrics (see Appendix B, Table B.4). Similarly, after examining the output of the correlation assessment, 15 metrics with a correlation coefficient greater or equal to $|r| \geq 0.9$ were discarded by using the factor loading matrix. The metric with the lower loading was discarded. For example, the correlation matrix revealed a high correlation between CA and PLAND. Since CA had a lower loading, it was excluded. PD had a high correlation with LSI. Since PD had a lower loading, it was excluded. The 15 class level metrics excluded after the preliminary assessment were CA, PD, SHAPE_AM, ED, TE, GYRATE_MN, GYRATE_AM, FRAC_AM, FRAC_MN, TCA, PLAND, CPLAND, AI, PLADJ and LPI. To conclude, 9 metrics were left for subsequent analysis. These included LSI, AREA_MN, AREA_AM, SHAPE_MN, CORE_MN, ENN_MN, ENN_AM, COHESION and MESH. To further reduce the level of redundancy among class level metrics and to identify the core landscape metrics which explained the variability in the dataset a second principal component factor analysis was conducted on the remaining variables and a varimax rotation applied (see Appendix B, Table B.5 for factor analysis results).

3.2.5 Model Construction

BBN modelling was conducted using Netica software 6.05 (Norsys Software Corp., 2018). The BBN made predictions within vegetated areas. Separate but

comparable (i.e. showing the same network structure) BBN models were created for each of the three principal components, with each principal component as the model outcome. The influence network for each BBN included landscape configuration metrics as model predictors, and ES trade-off (or synergy) values as the response variable. Conditional probabilities define the relationships between landscape configuration metrics and ES trade-offs (or synergies), and were obtained through processing individual 'cases', where each case represented an ES trade-off (or synergy) value and landscape configuration metric values found at the same location. The model then used these conditional probabilities to predict ecosystem service trade-offs (or synergies) at every vegetated location within the study area. All the nodes were discrete or discretised continuous variables. The case dataset with the principal components and the landscape metrics predictor variable values was imported and the 'test with cases' feature was run. A sensitivity analysis was conducted on the ES trade-off (and synergy) nodes. All nodes were automatically discretised with ten states each. A simplification of this with five states for each input parameter and three for dependent variables was used for ease of visualisation of model structure (Figure 3.1) and consistency when comparing conditional probabilities (Marcot et al., 2006).

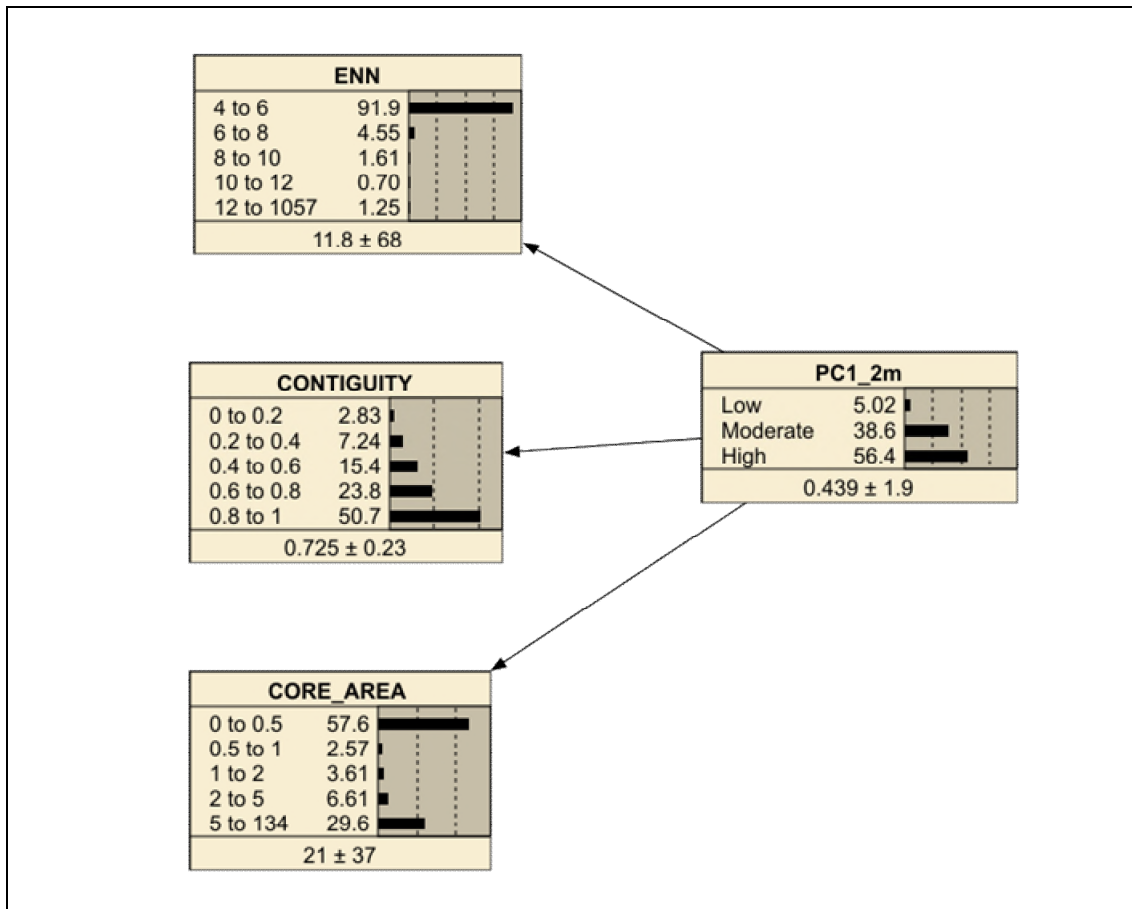


Figure 3.1 Example of Bayesian Belief Network model structure for Nutrient retention and Carbon storage trade-offs. All models used a comparable structure, with the dependent variable and the conditional probabilities changing between models. The influence diagram illustrates the relationships between the dependent variable (i.e. the ES trade-offs or synergies) and the independent variables. A similar structure was used for the class level metrics. Arrows denote the direction of probabilistic influence implemented in software rather than causal relationships between the factors

3.2.6 Model Performance and Sensitivity Testing

Model performance was assessed using error rates, a goodness-of-fit measure, that expresses the frequency with which the model's strongest prediction (most

likely outcome) is incorrect against the observed data. To assess the influence of the landscape metrics in determining principal components (trade-offs or synergies between ESs) a sensitivity analysis was conducted. Sensitivity analysis determined how much the beliefs (i.e. principal component predictions) were influenced by each new finding in the predictor nodes (i.e. change in landscape configuration characteristics). The parameter sensitivities in the models between the predicted nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies and the configuration metrics were assessed. Sensitivity was expressed as the expected reduction in variance of the expected real value due to a finding in a particular node (e.g. complete insensitivity would occur if addition of new data to the model caused no reduction in this variance). The conditional probabilities were generated by the model based on the available data and using a machine learning BBN modelling approach. The conditional probabilities for the node states were extracted and graphed as a heat map to show the predicted landscape configuration metric probability at each state level of trade-off (or synergy).

3.3 Results

3.3.1 Data Reduction

In the Spearman correlation assessment, we found that most of the metric pairs were significant (Table 3.1 and Table 3.2). The first three principal components accounted for 89 % of the total variance for all the patch-level metrics (Table 3.3). The principal components to retain was based on the percentage of variance and the Kaiser-Guttman criteria (eigenvalue > 1). Although the second and third component fell just below the threshold the first three components explained 89 % of the variance and were retained as a result of percentage of variance. The scree plot shows the relationship between the increasing principal components

of each metric and the cumulative proportion of variance explained (see Appendix B, Figure B.1).

As an approach to which metrics to choose, following Riitters et al. (1995) the metric with the highest loading was chosen as criterion that is representative of that factor. In summary, the metrics with the highest loadings obtained from each of our three factor loadings were: contiguity index (CONTIG, 0.89), Euclidean nearest-neighbour distance (ENN, 1), and core area (CORE, 1), and were chosen as surrogate variables. The metrics on the first axis had the highest loadings (suggesting correlations of $r > 0.7$) for FRAC and CONTIG. As the metrics corresponded to shape metrics, it was termed Shape Indicator component. The metrics on the second axis had the highest loadings for ENN. As the metric corresponded to a Euclidean nearest-neighbour distance metric, it was termed Patch Distribution Indicator component. The metrics on the third axis had the highest loadings for CORE. As the metric corresponded to a core area metric, it was termed Core Area Indicator component.

Thus, among the nine remaining metrics, the first two components accounted for about 85 % of the total variance of the class level metrics (see Appendix, Table B.5). The principal components to retain was based on the Kaiser-Guttman criterion (eigenvalue > 1). As an approach to which metrics to choose, following Riitters et al. (1995) the metric with the highest loading was chosen as criterion that is representative of that factor. In summary, the metrics with the highest loadings obtained from each of our two factor loadings were: effective mesh size (MESH, 0.98) and area-weighted Euclidean nearest neighbour distance (ENN_AM, -0.9), and were chosen as surrogate variables (Riitters et al., 1995). The scree plot shows the relationship between the increasing principal components of each metric and the cumulative proportion of variance explained. The metrics on the first axis had the highest loadings for AREA_MN, AREA_AM, CORE_MN and MESH (suggesting correlations of $r > 0.7$). Since the metrics corresponded to the area, core area and aggregation metrics, it was termed as Area, Core area and Aggregation Indicator component. The metrics on the second axis had the highest loadings for LSI, SHAPE_MN,

ENN_MN, ENN_AM and COHESION. As the metrics corresponded to shape, shape complexity, connectivity and Euclidean nearest-neighbour distance metrics, this axis was termed Shape, Shape Complexity, Connectivity and Nearest-Neighbour Indicator component.

Table 3.1 Correlation matrix showing Spearman's rank correlation coefficients ρ (rho) illustrating the relationships between patch level landscape metrics (Significance: * P < 0.001)**

	AREA	PERIM	GYRATE	PARA	SHAPE	FRAC	CONTIG	CORE	NCORE	CAI	ENN
AREA	1										
PERIM	0.99 ***	1									
GYRATE	0.97 ***	0.99 ***	1								
PARA	-0.93 ***	-0.87 ***	-0.85 ***	1							
SHAPE	0.86 ***	0.92 ***	0.93 ***	-0.64 ***	1						
FRAC	0.78 ***	0.86 ***	0.85 ***	-0.54 ***	0.94 ***	1					
CONTIG	0.96 ***	0.91 ***	0.89 ***	-0.99 ***	0.71 ***	0.62 ***	1				
CORE	0.31 ***	0.29 ***	0.30 ***	-0.31 ***	0.26 ***	0.17 ***	0.31 ***	1			
NCORE	0.31 ***	0.29 ***	0.30 ***	-0.31 ***	0.26 ***	0.17 ***	0.31 ***	1.00 ***	1		
CAI	0.31 ***	0.29 ***	0.30 ***	-0.31 ***	0.26 ***	0.17 ***	0.31 ***	1.00 ***	1.00 ***	1	
ENN	-0.19 ***	-0.20 ***	-0.20 ***	0.16 ***	-0.21 ***	-0.19 ***	-0.16 ***	-0.11 ***	-0.11 ***	-0.11 ***	1

Table 3.2 Correlation matrix showing Spearman's rank correlation coefficients ρ (rho) illustrating the relationships between landscape class level metrics after data reduction and elimination of variables with $|r| \geq 0.9$ based on factor loadings (Significance: * $P < 0.05$, ** $P < 0.01$ and * $P < 0.001$)**

	LSI	AREA_MN	AREA_AM	SHAPE_MN	CORE_MN	ENN_MN	ENN_AM	COHESION	MESH
LSI	1								
AREA_MN	0.64 *	1							
AREA_AM	0.55	0.77 **	1						
SHAPE_MN	0.75 *	0.81 **	0.59	1					
CORE_MN	0.40	0.87 ***	0.64 *	0.47	1				
ENN_MN	-0.79 **	-0.59	-0.59	-0.36	-0.55	1			
ENN_AM	-0.89 ***	-0.75 *	-0.49	-0.68 *	-0.58	0.84 **	1		
COHESION	0.75 *	0.94 ***	0.75 *	0.88 ***	0.76 *	-0.56	-0.81 **	1	
MESH	0.88 ***	0.81 **	0.84 **	0.73 *	0.60	-0.83 **	-0.84 **	0.84 **	1

Table 3.3 Result of the factor analysis for the first three factors after Varimax rotation. Significant values that meet $r > 0.7$ are in bold. Highest loadings per factor are italicized

	Factor Number		
	1	2	3
Eigen value	1.59	1.00	0.98
% Cumulative variance explained	39.67	64.64	89.26
	Factor loadings (after varimax rotation)		
FRAC	0.88	-0.06	-0.01
CONTIG	0.89	0.00	0.04
CORE	0.02	0.00	1.00
ENN	-0.04	1.00	0.00

3.3.2 BBN Model Performance and Sensitivity Analysis

The LM identified in the principal component analysis were used for predicting ES trade-offs and synergies and to test the relationships between landscape configuration and ES trade-offs and synergies. At the patch level, the results of the case testing with Bayesian Belief Networks showed model error rates of 51 % for PC 1, 71 % for PC 2 and 67 % for PC 3 (Table 3.4). Predicted habitat quality and pollinator abundance trade-offs and predicted potential soil erosion, water supply synergies were most sensitive to core area (CORE) and exhibited a relatively high percentage of variance reduction (respectively 20.5 and 12.8). Predicted nutrient retention and carbon storage trade-offs were most sensitive to contiguity index (CONTIG) and exhibited a high percentage in variance reduction (39.8) and had the lowest error rate (Table 3.4). The sensitivities were lower for ENN. This suggests that predicted nutrient retention and carbon storage trade-offs, habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies are least sensitive to ENN. The results indicated that CORE was the most influential predictor for two of three ES interactions at the patch level at a 2 m resolution.

At the class level, the case testing with Bayesian Belief Networks showed an error rate of 0 % for Nutrient retention and Carbon storage trade-offs, 0 % for Habitat quality and Pollinator abundance trade-offs and 0 % for Potential soil erosion, Water supply synergies (Appendix B, Table B.6). The low error rates for the class-level metrics can be explained because generally most class-level metrics (a class is a set of patches of the same type, i.e. a land cover type) can be interpreted as fragmentation indices and measure the configuration of a particular patch type (Leitão et al., 2006). Therefore, they appear to be appropriate to assess the influence of landscape fragmentation of a land cover type. As urban areas are highly patchy and fragmented, they could be appropriate for measuring the extent and fragmentation of a particular class (or classes). Class-level metrics quantify characteristics of an entire class (i.e., patch type) such as total extent, average patch size and degree of aggregation or clumping. The sensitivity to findings reflects the strength between predictors and principal components predictions. Predicted nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies were most sensitive to MESH and exhibited a high percentage in variance reduction (respectively 96.2, 70.7 and 97.5). This indicated that MESH was the most influential predictor in determining ecosystem service trade-offs and synergies in urban areas at the class level at a 2 m spatial resolution.

Table 3.4 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient retention and Carbon storage trade-offs (PC 1), Pollinator abundance and Habitat quality trade-offs (PC 2) and Potential soil erosion and Water supply synergies (PC 3) at a 2 m spatial resolution

	Error rate	Sensitivity (Percent in Variance Reduction)		
		<i>CORE</i>	<i>CONTIG</i>	<i>ENN</i>
PC1	51.33%	28.00	39.80	2.80
PC2	70.90%	20.50	12.50	0.86
PC3	66.86%	12.80	10.40	0.75

3.3.3 Probabilistic Associations between Landscape Configuration and ES Trade-offs and Synergies

Heat maps show the nature of probabilistic associations between the values of landscape configuration metrics and predicted trade-offs or synergies levels using simplified node levels (Figure 3.2; Table 3.5). Here, high conditional probabilities reflect the likelihood of an outcome given a set of parent node states; e.g. low and moderate nutrient retention and carbon storage trade-offs are expected in areas with low core area, whereas high nutrient retention and carbon storage trade-offs are expected in patches with a large core area, a low Euclidean nearest neighbour distance and a high contiguity index. In the PCA (Chapter 2), low PC1 scores represented high values in carbon storage and low values in nutrient retention, i.e. woodlands, whereas high PC 1 scores represented high values in nutrient retention. There is therefore an expectation that in areas with low core area, carbon storage will be high. Conversely, there is therefore an expectation that in areas with large core area, a low Euclidean distance and a high contiguity index, nutrient retention will be high. Core area (CORE) appeared to be a strong predictor for trade-offs of habitat quality and pollinator abundance, with the highest conditional probabilities associated with low core area at low and

moderate levels of predicted habitat quality and pollinator abundance trade-offs. In the PCA, low PC 2 scores represented low values in habitat quality and high values in pollinator abundance, whereas high PC 2 scores represented high values in habitat quality and low values in pollinator abundance. There is therefore an expectation that in areas with low core area and low Euclidean distance, pollinator abundance will be high. High levels of predicted potential soil erosion, water supply synergies were associated with low core area, low Euclidean nearest neighbour distance and a high contiguity index. In the PCA, low PC 3 scores represented low values in soil erosion and low values in water supply, whereas high PC 3 scores represented high values in soil erosion and high values in water supply services. There is therefore an expectation that in areas with low core area, low Euclidean nearest neighbour distance and a high contiguity index, soil erosion will be relatively high.

Mesh size (MESH) appeared to be a strong predictor for trade-offs of nutrient retention and carbon storage, with the highest conditional probabilities associated with low mesh size at low to moderate levels of predicted trade-offs (Appendix B, Figure B.2, Table B.7). High levels of predicted nutrient retention and carbon storage trade-offs appeared to be associated with high mesh size. In the PCA, low PC 1 scores represented low values in nutrient retention and high values in carbon storage, whereas high PC 1 scores represented high values in nutrient retention. There is therefore an expectation that in areas with a high mesh size and low area-weighted mean Euclidean nearest neighbour distance, nutrient retention will be high. Mesh size appeared to be a strong predictor for habitat quality and pollinator abundance trade-offs, with the highest conditional probabilities associated with low mesh size at low to moderate levels of predicted trade-offs. In the PCA, low PC 2 scores represented high values in pollinator abundance, but low values in habitat quality. There is therefore an expectation that in areas with a low mesh size and low area-weighted mean Euclidean nearest neighbour distance, pollinator abundance will be relatively high. High levels of predicted potential soil erosion, water supply synergies appeared to be associated with low mesh size. In the PCA, low PC 3 scores represented low

values in soil erosion and low values in water supply, whereas high PC 3 scores represented high values in soil erosion and high values in water supply. There is therefore an expectation that in areas with low mesh size and low area-weighted mean Euclidean distance, soil erosion will be relatively high. Low levels of predicted potential soil erosion, water supply synergies appeared to be associated with high mesh size.

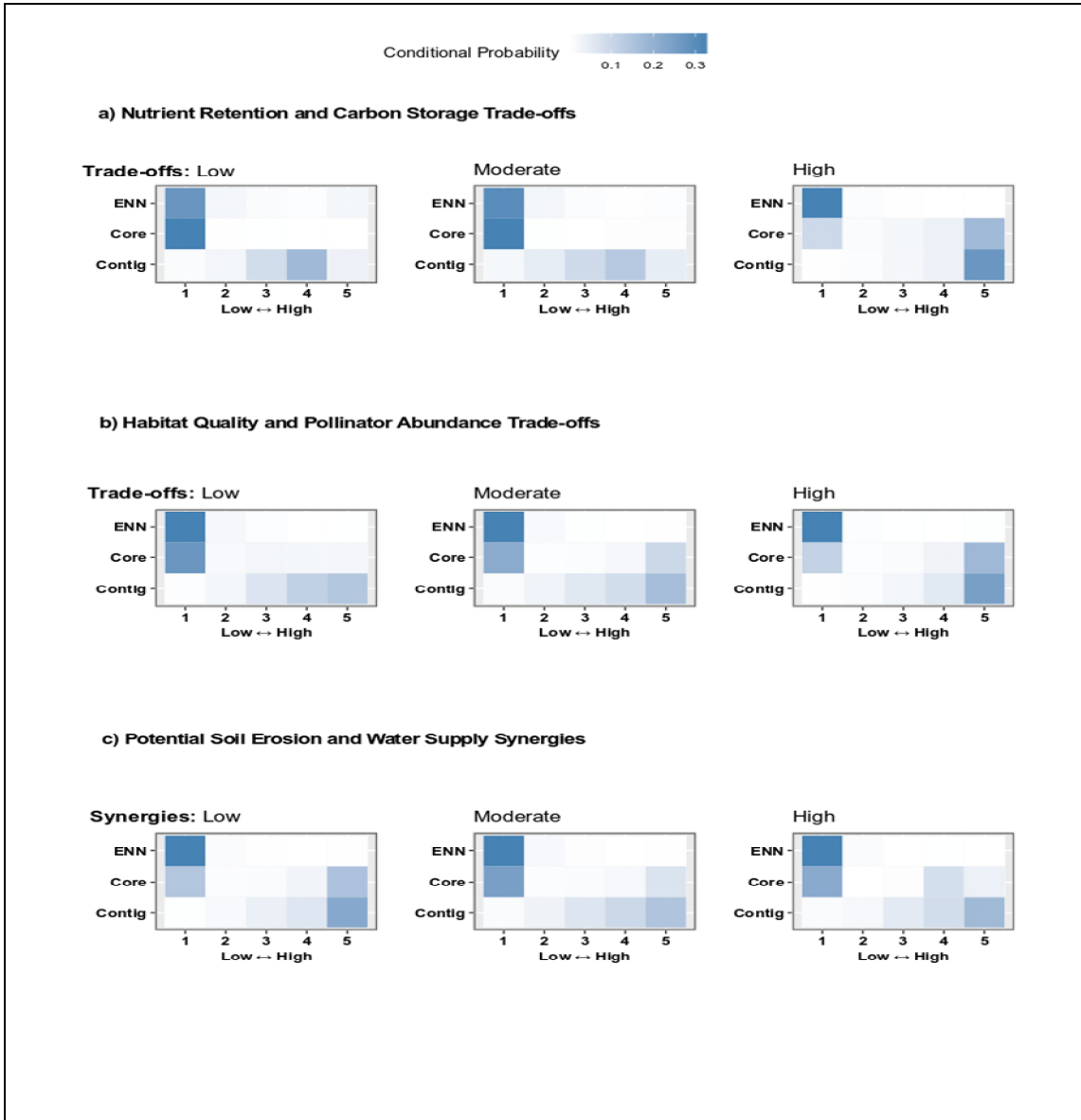


Figure 3.2 Heat maps that visually depict the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (i.e. core area, contiguity index and Euclidean nearest neighbour; values of bin ranges are shown in Table 3.5) and the predicted trade-offs (or synergies) of each ecosystem service trade-offs or synergies type. Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of input parameter values and predicted trade-offs (or synergies) represented by that cell in the heat map

Table 3.5 Bin ranges for input parameter values in Figure 3.2 heat maps of Bayesian model conditional probabilities

Bins	Low	Moderately low	Moderate	Moderately high	High
Core Area (ha)	0-0.5	0.5-1	1-2	2-5	5-134
Contiguity Index	0-0.2	0.2-0.4	0.4 - 0.6	0.6-0.8	0.8-1
Euclidean Nearest Neighbour Distance (m)	4-6	6-8	8-10	10-12	12-1057

3.4 Discussion

Using a BBN modelling approach this study aimed to test whether landscape configuration affects ES trade-offs and synergies. The levels in the sensitivity to findings of the dependent variables (ES interaction predictions) to the landscape metrics suggest that landscape configuration metrics core area and mesh size are the most influential determinants of ecosystem service trade-offs and synergies.

3.4.1 Selected Landscape Metrics

The first three principal components accounted for about 89 % of the total amount of variance observed in the data of the patch level metrics. Out of the four metrics assessed with principal component factor analysis, factor loadings on the first axis suggested strong contributions from FRAC and CONTIG. Factor loadings on the second and third factor axes had strong contributions from ENN and CORE. AREA, GYRATE, PERIM, PARA, SHAPE, NCORE and CAI were excluded due to high correlation in the Spearman correlation assessment. Our results suggest that FRAC and CONTIG could be used to assess ecosystem services and in spatial planning. Likewise, the high loadings on the second and third factor axes suggested that ENN and CORE could be used to assess ecosystem services.

However, the influence of landscape structure on ecosystem service trade-offs and synergies in urban areas can be better studied and captured using our metrics CONTIG, ENN and CORE.

FRAC and CONTIG are shape metrics. Shape metrics can be used to gain insight into the processes forming the mosaic, for example shape and shape complexity can be used for habitat services and scenic quality (Syrbe and Walz, 2012). CORE has been used to assess landscape accessibility and habitat quality (Inkoom et al., 2018). ENN can be used to measure habitat accessibility. The findings suggest the possibility of using metrics CONTIG and FRAC to assess and investigate ES trade-offs and synergies in urban areas. Likewise, ENN and CORE could be used in ES assessment.

The first two components accounted for about 85 % of the total amount of variance observed in the data of the class level metrics. Out of the nine metrics assessed with principal component factor analysis, factor loadings on the first axis suggested strong contributions from AREA_MN, AREA_AM, CORE_MN and MESH. Patch size and its derivatives (e.g. AREA_MN and AREA_AM) can be used as indicators of landscape function (Leitão et al., 2006). AREA_MN can be used in planning to identify which land cover types must be preserved in the plan to facilitate diversity. Fragmentation measures indicate scenery quality and the possibility for animals to move across the landscape. Mesh size can be used to assess scenery quality, erosion prevention and habitat value services (Syrbe and Walz, 2012).

The metrics on the second axis LSI, SHAPE_MN, ENN_MN, ENN_AM and COHESION represented shape, shape complexity, connectivity and Euclidean nearest-neighbour distance metrics. The metrics have the potential for ES assessment and land use planning. COHESION has been used to measure connectivity at the class level for pollination, pest regulation, seed dispersal, and habitat services (Haas and Ban, 2018). However, the influence of landscape configuration on ecosystem service trade-offs and synergies in urban areas can be better studied and captured by the use of our metrics MESH and ENN_AM.

3.4.2 Predicted Ecosystem Service Trade-offs and Synergies and Landscape Configuration Influence on ES Trade-offs and Synergies

Broad generalities can be established from the conditional probability heat maps about the relationships between ES trade-offs and synergies and landscape configuration (Figure 3.2). At the patch level, CORE emerged as an important factor for trade-offs (nutrient retention and carbon storage, habitat quality and pollinator abundance), with low core area and low Euclidean nearest-neighbour distance associated with low and moderate levels of predicted trade-offs. The conditional probabilities show that low nutrient retention and carbon storage trade-offs predictions are expected in areas with low core area and low Euclidean distance. Low core area and low Euclidean distance could be an indication of greenspace patches characterised by loosely connected core areas of trees, as individuals or in small stands, and vegetated road verges, wooded corridors and buffered streams. Urban trees and woodland were associated with high values in carbon storage and low values in nutrient retention, i.e. low PC 1 scores. Therefore, low core area associated with low nutrient retention and carbon storage trade-offs prediction could give an indication of fragmented woodland. The spatial distribution of the patches and relative location may matter as well (Leitão et al., 2006; Verhagen et al., 2016).

The conditional probabilities showed that high habitat quality, but low pollinator abundance is expected in areas with a large core area. Large patches of contiguous grassland in the suburbs were associated with high levels of habitat quality and low levels of pollinator abundance, i.e. high PC 2 scores. The high trade-offs between habitat quality and pollinator abundance could be driven by large core areas of grassland and distance from built-up areas. The low levels of pollinator abundance could be due to low proximity to likely nesting sites for pollinator species and lower floral resources (Gunnarsson and Federsel, 2014; Baldock et al., 2015).

High potential soil erosion and water supply synergies are expected in areas with a low core area. The higher levels in soil erosion and water supply synergies could be due to a smaller patch size to mitigate surface runoff and soil

erosion. Large patches of vegetation cover protect aquifers and soil resources (Kim and Pauleit, 2005). This could be an effect of fragmentation and shrinkage on service provision at a landscape level. The predicted soil erosion and water supply synergies could be driven by core area and by ecological processes i.e. water flow.

At the class level MESH emerged as an important factor for nutrient retention and carbon storage trade-offs, with low mesh size associated with low and moderate levels of predicted trade-offs. Mesh size can be used to measure erosion or flood prevention (Syrbe and Walz, 2012; Inkoom et al., 2018). Larger values indicate a higher capacity for vegetation land cover to mitigate soil erosion and surface runoff. High surface runoff and flood risks appeared to be associated with green space with a low mesh size.

In this study, the urban ecosystem services were influenced by landscape structure. The findings show that urban habitat configuration exerts an influence on ES trade-offs and synergies. The surrounding matrix appeared to influence habitat configuration and ES provision. Suburban green areas were mainly associated with large patches of grassland with high levels in nutrient retention and low levels in carbon storage, whereas urban green areas were mainly associated with smaller patches of grassland and isolated trees. The differences in trade-offs between suburban areas and urban areas could partly be driven by a higher degree of fragmentation in urban areas. The high levels of nutrient retention and carbon storage, and habitat quality and pollinator abundance predicted trade-offs could be due to land use configuration (i.e. fragmentation), land-use changes and ecological processes.

Climate change affects the distribution of ecosystems, species and processes and one of the best-documented anthropogenic climate modifications is the urban heat island (UHI) effect (Grimm et al., 2008). Climate change and land cover patterns can affect the provision of ESs (Haase and Schwarz, 2012). Green infrastructure and nature-based solutions can respond to environmental change and enhance the provision of ESs and the benefits they provide by

developing resilient landscapes and cities (Lafortezza et al., 2018). Urban ecological infrastructure and ecosystem services can increase the resilience of cities by enhancing their ability to cope with disturbance and climate change and adapt to climate and other global change. Green infrastructure and ecosystem services can be referred to as a form of insurance value. Enhancing green space and green infrastructure ensures a resilient supply of ESs. The results from this research could provide insights to urban planners and land managers for a better distribution of ESs.

3.4.3 Model Performance and Landscape Configuration

Landscape configuration metrics appear to be strong determinants of ES trade-offs and synergies. At the patch level, although the model error rates (Table 3.4) ranged between 50 and 71 %, the mean rate among the models (63.0%) was comparable to results found in other studies applying BBNs to environmental systems (Aalders, 2008; Grafius et al., 2019). At the class level, the principal components were found to be most sensitive to mesh size. The findings suggest that landscape configuration could drive ES interactions. Area, core area and aggregation metrics appeared to be the most influential metrics in determining ES trade-offs and synergies.

Green spaces with a large patch size and a short inter-site Euclidean distance have greater potential to support species, provide ESs and have a better ecological quality (Kim and Pauleit, 2005; Tian, Jim and Wang, 2014). CORE, CONTIG and ENN could be used to assess the influence of configuration on nutrient retention and carbon storage trade-offs at the patch level. In this study, the differences in sensitivity analysis results between ES trade-offs and synergies models could be due to the degree and pattern of fragmentation and the ES in question (Mitchell et al., 2015; Mitchell, Bennett and Gonzalez, 2015).

At the class level the ES interactions showed strong relationships with the configuration metrics suggesting that mesh size is a key driver of urban ES

interactions. The high levels in sensitivity between ES trade-offs and synergies models suggest that landscape configuration factors affect ES interactions and could be appropriate to assess the influence of landscape structure on ES trade-offs and synergies and for planning.

3.4.4 Implications

The findings show that landscape configuration affects the provision of ESs and could drive ES trade-offs and synergies. The modelling approach has potential value as a method of ES trade-offs and synergies prediction in complex landscapes and could be used to assess how ES trade-offs respond to variation of urban habitat configuration, and thereby relevant to planning considerations and landscape-scale research. The findings could have implications in landscape planning and management. The indicators could be used for structural assessment of nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and soil erosion and water supply synergies and in planning in similar urban areas in the UK.

3.4.5 Limitations

LM have been found to be sensitive to extent, land cover classes and spatial resolutions of remotely sensed data (Verhagen et al., 2016; Inkoom et al., 2018). Therefore, users of our suggested metrics must proceed with caution, since some of the metrics may be sensitive to changing spatial resolution (Inkoom et al., 2018). Further studies on spatial-temporal remote sensing data can reveal the potential of the use of LM and its contribution to the influence of landscape structure on ES provision. In addition, studies on the influence of configuration on ES bundles could provide a better understanding of the relationships between landscape configuration and ES provision, and subsequently account for landscape configuration in landscape management.

3.5 Conclusions

We have demonstrated the feasibility of using a BBN modelling approach for predicting ES trade-offs and synergies. Our approach provides useful information on the sensitivity of ES trade-offs and synergies to habitat configuration features providing ecological understanding that is relevant to planning decisions and assessment of urban development impacts. The results show that landscape configuration affects ecosystem service interactions and demonstrates that landscape configuration metrics core area and mesh size are influential determinants of ecosystem service trade-offs and synergies. The findings suggest that the core set of metrics MESH, ENN_AM, CORE, ENN and CONTIG could be used as indicators to assess ES interactions in similar urban areas. Cities will need to manage a resilient supply of ESs for an enduring supply of services in urban systems affected by global environmental change. Further research is needed to understand how climate interacts with and drives changes in urban ecosystems, and how these changes will affect the supply of ESs. Further research is needed to assess the influence of potential drivers on ES provision and green infrastructure which may provide insights into what management or policies could improve the provision of multiple ESs. Cross-scale comparative studies of the influence of landscape structure on ESs are needed in urban areas. The findings may contribute to planning and urban design and improved ecosystem management.

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4 USING BAYESIAN BELIEF NETWORKS TO ASSESS THE INFLUENCE OF LANDSCAPE CONNECTIVITY ON ECOSYSTEM SERVICE TRADE-OFFS AND SYNERGIES IN URBAN LANDSCAPES IN THE UK

James D. Karimi; Jim A. Harris; Ron Corstanje

Cranfield University, School of Water, Energy, and the Environment, Cranfield, Bedfordshire MK43 0AL, United Kingdom

Abstract

Context

Landscape connectivity is assumed to influence ecosystem service (ES) trade-offs and synergies. However, empirical studies of the effect of landscape connectivity on ES trade-offs and synergies are limited, especially in urban areas where the interactions between patterns and processes are complex.

Objectives

The objectives of this study were to use a Bayesian Belief Network approach to (1) assess whether functional connectivity drives ES trade-offs and synergies in urban areas and (2) assess the influence of connectivity on the supply of ESs.

Methods

We used circuit theory to model urban bird flows of *P. major* and *C. caeruleus* at a 2 m spatial resolution in Bedford, Luton and Milton Keynes, UK, and Bayesian Belief Networks (BBNs) to assess the sensitivity of ES trade-offs and synergies model outputs to landscape and patch structural characteristics (patch area, connectivity and bird species abundance).

Results

We found that functional connectivity was the most influential variable in determining two of three ES trade-offs and synergies. Patch area and connectivity exerted a strong influence on ES trade-offs and synergies. Low patch area and low to moderately low connectivity were associated with high levels of ES trade-offs and synergies.

Conclusions

This study demonstrates that landscape connectivity is an influential determinant of ES trade-offs and synergies and supports the conviction that larger and better-connected habitat patches increase ES provision. A BBN approach is proposed as a feasible method of ES trade-off and synergy prediction in complex landscapes. Our findings can prove to be informative for urban ES management.

Keywords: BBN; Trade-offs and synergies; Ecosystem services; Connectivity; Urban; Model; Circuit theory

4.1 Introduction

Ecosystem services indicate the benefits that humans directly or indirectly receive from the ecosystem (Costanza et al., 1997). ES trade-offs occur when one service increases and another one decreases. Trade-offs occur when the provision of one ES is reduced as a consequence of increased use of another ES (Rodríguez et al., 2006). This may be due to simultaneous response to the same driver or due to true interactions among services. ES synergies occur when both services either increase or decrease. This may be due to simultaneous response to the same driver or due to true interactions among services (Bennett et al.

2009). Human activities are modifying land cover and land use patterns, altering landscape structure and ecosystems, such as connectivity. Landscape connectivity refers to the degree to which the landscape facilitates or impedes the flow of species and materials across the landscape and results from the interaction between landscape structure and function (Leitão et al. 2006). Changes to landscape structure can affect the movement of species and materials which affect the provision of ESs.

Understanding the importance of landscape connectivity may be important for predicting how land use affects ES provision. Connectivity is relevant in land conservation plans and management. In landscape ecology, landscape connectivity includes concepts such as structural connectivity and functional connectivity. The former is related to landscape structure, the spatial configuration of land cover types or habitats and is usually measured using landscape metrics such as patch size, whereas functional connectivity is organism-orientated determined by the flow of organisms across the landscape and by the responses of organisms to landscape structure (LaPoint et al., 2015). The term connectivity includes both biotic connectivity, which refers to the movement of organisms across the landscape and abiotic connectivity, relating to the movement of matter. Landscape connectivity can affect the supply of ESs by controlling the pattern and rate of biotic and abiotic flows important for service provision (Mitchell, Bennett and Gonzalez, 2013).

Urban green space provides ecosystem services such as carbon sequestration, climate regulation, and benefits to nearby residents. Studies have shown that human interactions with green space provide psychological well-being and a sense of connectedness to nature (Cox et al., 2017). Urban features influence structural and functional connectivity (Cox et al., 2016; Grafius et al., 2019). Cox et al. (2016) found that vegetation cover increases connectivity and influences the movement of songbirds. Functional connectivity can be promoted by structural components. However, landscape connectivity is altered by changes in land cover and land use, including habitat fragmentation.

Evidence suggests that decreased landscape connectivity usually has negative effects on regulating services such as pollination, pest control, and food provision (Mitchell, Bennett and Gonzalez, 2013). Theory suggests that different ESs are likely to respond either positively or negatively to landscape connectivity change, creating and modifying trade-offs and synergies between services. Changes in connectivity, whether decreasing as a result of clearing for urban expansion, or increasing as a result of restoration and conservation, may have both positive and negative effects on ESs through complex interactions with different species and processes (Mitchell, Bennett and Gonzalez, 2013; Maguire et al., 2015). For example, retaining non-crop habitat patches near cropland areas increases both pollination and pest regulation services, which in turn increases crop production. As regards to ES provision related to the movement of matter, a decrease in the rate of water flow through riparian buffers from upland areas might increase pollutant filtration and water quality regulation, but decrease water provision downstream (Mitchell, Bennett and Gonzalez, 2013). Conversely, a decrease of water flow from a river to its surrounding riparian buffers might decrease water quality regulation and flood control but increase water provision downstream. Ecosystem services associated with water flowing in streams and rivers within a watershed (e.g. drinking water provision, erosion control and water quality regulation) can be affected by changes in landscape connectivity of riparian buffering corridors (Dakos et al., 2015). Services in which connectivity is not an important factor affecting service provision include carbon storage, carbon sequestration and the existence value of biodiversity.

ESs in urban areas provide benefits such as water flow regulation, air purification, noise reduction, pollination and seed dispersal and air temperature regulation (Gómez-Baggethun and Barton, 2013). In this research, we test the influence of landscape and patch structural characteristics (patch area and connectivity) on ES trade-off and synergy predictions to assess whether connectivity drives trade-offs and synergies between ecosystem services. Landscape connectivity may influence the magnitude and distribution of ESs. Land use and land cover change can alter landscape connectivity and may result

in changes to ecosystem services. Different ecosystem services respond differently to connectivity and may create trade-offs and synergies between services. These trade-offs and synergies may create bundles of ecosystem services that act in similar or dissimilar ways as connectivity is changed, influenced by landscape connectivity and human land use patterns. Thus, connectivity can have either positive or negative effects on service flow depending on the service in question, the process of landscape connectivity and the resulting landscape structure. Moreover, connectivity is assumed to affect the provision of ESs not only directly through the flow of species and matter, but also indirectly by altering the levels of biodiversity and ecosystem functions that contribute to ES provision (Mitchell, Bennett and Gonzalez, 2013). Increasing connectivity therefore may enhance the supply of ESs and affect biodiversity in urban areas. Landscape connectivity could act as a bridge between biodiversity and ecosystem services. Ng et al. (2013) assumed that if a habitat within a landscape has a more significant role in connecting with other habitats, it would have a higher ecosystem service value for biodiversity conservation.

Functional connectivity can be represented by depicting the movements of urban bird flows using circuit theory. In this paper, we model functional connectivity and the habitat structure of urban great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*) which represent typical woodland species adapted to UK urban environments. Land use and land cover types are providers of ecosystem services. For example, woodlands provide a high number of services such as climate regulation, pollination, habitat quality, erosion control, water supply and nutrient retention. In this study, modelled urban bird flows were used as a proxy for woodlands and associated ESs.

The development of blue-green infrastructure in cities is considered to be a suitable approach to improve the function of green space in urban areas. Maintaining and establishing connectivity between patches is essential in facilitating biodiversity conservation. Blue-green infrastructure provide goods and services and could be a solution to intensified land use and fragmentation. Connectivity refers to the structure and extent to which (strength) resources,

species and matter migrate or interact across habitats (Dakos et al., 2015). Connectivity change may create trade-offs and synergies between ecosystem services as landscape structure and human land use are altered and subsequently affect the provision of ESs in urban areas. It has been found that habitat network structure is important for biodiversity and to the resilience of a wide range of ESs and their productivity, for example provisioning and regulating services (Chisholm, Lindo and Gonzalez, 2011; Thompson, Rayfield and Gonzalez, 2017). An interconnected network of greenspaces is thought to provide associated benefits to human populations (Lafortezza et al., 2013). Meta-ecosystem and ecological network theories (spatial-insurance hypothesis) suggest that connectivity is important for maintaining biodiversity and improve ES provision. Landscapes that are structurally and functionally connected are thought to be more resilient compared to systems where components are isolated. High levels of connectivity can facilitate recovery after a disturbance. At the same time, highly connected systems increase the potential for disturbances to spread. Additionally, the structure characterizing how system components are connected appears to play a role. Therefore, moderate levels of connectivity are likely best for maintaining resilience (Dakos et al., 2015; Field and Parrott, 2017). The effect of connectivity on ES provision is context dependent.

There is little empirical evidence that connectivity affects multiple ESs. Urban form has been found to affect the provision of ESs with high-urban development density associated with poor environmental performance, as measured by green patch size and provision of ESs (Tratalos et al., 2007). Environmental quality is related to vegetation structure and the provision of ESs. This study presents a novel approach to assess the sensitivity of ES trade-offs and synergies to connectivity and urban habitat structural features.

In this study, we used a Bayesian Belief Network (BBN) modelling method for predicting ES trade-offs and synergies and used it to test the relationships between urban habitat structural features and ES trade-offs and synergies. The objectives of this study were to use a BBN modelling approach (1) to assess whether functional connectivity drives ES trade-offs and synergies in urban areas

and (2) assess the influence of connectivity on the supply of ESs. We hypothesized that connectivity affects ES trade-offs and synergies and the provision of ESs and that high landscape connectivity increases the supply of ESs. For example, we might expect that erosion control from small patches with moderately low connectivity to be adversely affected because small patches of moderately low connected green space provide less woodland vegetation cover to protect from soil erosion. For example, we might expect that water supply services from small patches with low connectivity to be adversely affected because small patches of low connected green space provide less woodland vegetation cover to mitigate surface runoff and recharge the water table.

4.2 Methods

4.2.1 Methodological framework

In this study, a BBN modelling approach was used for predicting ES trade-offs and synergies and used it to test the relationships between urban habitat structural features (patch area, connectivity and bird species abundance) and ES trade-offs and synergies. The methodological framework for testing the relationships between habitat structural features and ecosystem service trade-offs and synergies involved three steps. In the first, a cumulative current map was generated for each town based on circuit theory models. In the second, patch area, habitat connectivity and empirical abundance data were calculated for each town and used as model predictors in step three. Point count observed bird abundance survey data, point observed bird species richness survey data, data point connectivity values and data point ES trade-off and synergy values were associated with the patch area values and were combined across the three towns. The data point ecosystem service trade-off and synergy values were obtained from a principal component analysis conducted on six ecosystem services which represented Provisioning (water supply), Regulating (carbon storage, erosion control, nutrient retention, pollination) and Supporting (habitat

quality) services (Karimi, Corstanje and Harris, 2021). The ESs were modelled with Integrated Valuation of Environmental Services and Trade-offs InVEST modelling suite version 3.4.4 (Sharp et al., 2016) (Chapter 2). The principal components' raster map values represented nutrient retention and carbon storage trade-offs (PC 1), habitat quality and pollinator abundance trade-offs (PC 2) and potential soil erosion and water supply synergies (PC 3) and were each used as response variable. In the third, BBN modelling and a sensitivity analysis were conducted (Figure 4.1). The sensitivity of the model output to the predictors was assessed in order to explore the influence of those drivers in determining predicted ecosystem service trade-offs and synergies.

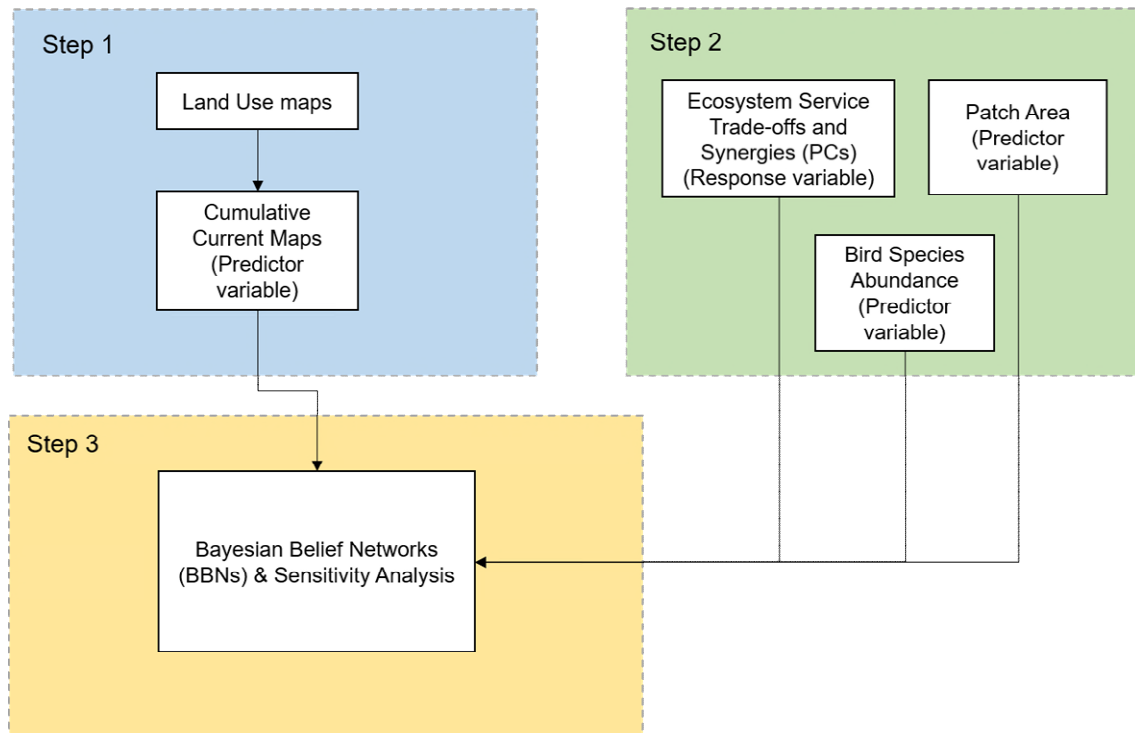


Figure 4.1 Methodological framework

4.2.2 Land Use Land Cover

The fine scale (2 m) resolution land use/land cover (LULC) map used in this study (obtained from Chapter 2) was created from colour infrared aerial photography originally at 0.5 m resolution obtained from LandMap Spatial Discovery (<http://landmap.mimas.ac.uk/>). The imagery was taken on 2 June 2009 for Bedford, 30 June 2009 and 24 April 2010 for Luton, and 8 and 15 June 2007 and 2 June 2009 for Milton Keynes, based on cloud-free image availability. Buildings and water features were identified from UK Ordnance Survey MasterMap layers, and remaining paved surfaces were separated from vegetation through the use of a Normalised Difference Vegetation Index (NDVI) threshold. An NDVI value threshold of 0.2 was used to distinguish vegetation ($\text{NDVI} \geq 0.2$) from non-vegetation ($\text{NDVI} < 0.2$). Subsequently, airborne LiDAR (Grafius et al., 2016) was used to categorize vegetation into height classes for short grass (< 0.5 m), tall grass and shrubs (0.5–2 m), short trees (2–10 m), medium trees (10–15 m), and tall trees (> 15 m) (Grafius et al., 2017, 2019). The land cover map was resampled to 2 m resolution for all modelling and analysis. GIS analysis, processing and

modelling were conducted in ArcGIS 10.6 (ESRI, 2017). A 2 m resolution provides a more accurate representation of fine-scale spatial heterogeneity and of small green space cover scattered in the urban matrix. A coarser resolution may underestimate green space cover and the supply of ESs.

4.2.3 Connectivity and Circuit Theory

Connectivity metrics have been developed to measure landscape connectivity based on graph theory and network analysis (Saura and Torné, 2009). Connectivity can be measured with network analysis. To depict habitats and corridors as networks, graph theory considers nodes as suitable habitat and links between nodes as the dispersal ability of a species. However, graph theory approaches are limited in their ability to consider spatial patterns of the landscape between habitat nodes. Least-cost path analysis applied in least-cost models provides a valuable method for conservation planning and corridor design. Least-cost paths calculates the shortest cumulative cost-weighted distance between a source and destination across a surface representing landscape resistance to movement (McClure, Hansen and Inman, 2016).

A relatively recent approach for modelling functional connectivity has been to use circuit-theory connectivity models. In the circuit model, landscapes are represented as conductive surfaces, and low resistances are assigned to land cover types best facilitating species flow, and high resistances for land cover types impeding species movement (McRae et al., 2008). Using an electrical analogy, effective resistances, current flow and voltages calculated across the landscape are related to ecological processes, such as movement of species and gene flow. In this study, a circuit theory approach was used to model functional connectivity for great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*).

In physics, Ohm's law states that the current through a conductor between two points is directly proportional to the voltage between the two points.

$$I = \frac{V}{R_{eff}} \quad (4-1)$$

where I is the current through the conductor, V is the voltage measured across the conductor and R_{eff} is the effective resistance of the conductor. The total amount of current that flows across the circuit depends on the voltage applied and the configuration of the circuit.

To represent landscapes as circuits, a resistance map is used to represent willingness by species to traverse the landscape and core habitat nodes the source and destination of species flow. Kirchoff's circuit laws are then used to calculate current and voltage. The circuit model calculates the current between pairs of user-defined nodes (areas with zero resistance). When each pairwise result is summed, a cumulative current map is produced. Corridors with high current values and narrow widths can be identified which represent areas important for connectivity.

In the context of ecosystem services, circuit theory has been used to examine the landscape genetic structure and movements of pollinators, especially bees, in response to habitat and land-use changes (Dickson et al. 2019). Circuit theory is suitable for characterizing relative frequency of routine movements along multiple potential paths through urban and other fragmented landscapes and the method is considered to reflect ecological reality more accurately (McRae et al., 2008). In circuit theory, circuits are defined as networks of nodes connected by resistors (electrical components that conduct current) and are used to represent and analyse graphs (McRae et al., 2008). Circuit theory has been used to model landscape connectivity (Hanks and Hooten, 2013).

Current models use Euclidean distance, least-cost path analysis, connectivity indices, least-cost distance and landscape resistance using circuit theory to model connectivity (McGarigal et al. 2012; McRae and Beier 2007; Saura and Pascual-Hortal 2007; McRae et al. 2008). A review revealed that an

understanding of ecological connectivity within urban areas appears limited (LaPoint et al., 2015). Least-cost path models, connectivity analysis and circuit theory can be combined to identify and develop ecological corridors. The combined models allow to identify priority corridors and 'pinch points'.

4.2.4 Landscape Resistance and Core Area Parameterisation

Habitat suitability and resistance maps were conceptualised to model the connectedness of the urban environment for the various types and distances of dispersal that can be expected of great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*) and treating the species as indicators of the urban landscape's ability to facilitate wildlife movement. The resistance values were assigned to mapped pixels based on LULC class and, subsequently, modified by additional relevant factors and features. Highly suitable woodland patches within the study area were assigned a low resistance value of 1 if they were larger than 5 ha in size and 2 if they were smaller than this but consisted of tall trees (>15 m), as these represent relatively ideal habitats, being old and structurally complex and less impacted by edge effects. Woodlands and shrublands outside of core habitat patches were assigned slightly higher resistance values (respectively 5 and 10) to model their use as favourable to connectivity. Low grassland was parameterised not to count as favourable habitat and assigned a resistance value of 25. Paved land was parameterised as less suitable and assigned a resistance value of 30, and water was selected as more extremely unsuitable and assigned a resistance value of 45. Buildings were the least suitable and assigned a resistance value of 50 given their lack of habitat amenities and their presence as physical barriers to movement. Modifiers to the above base values were then applied. Land cover pixels greater than 45 m from woodland had 50 added to their initial resistance value due to the reluctance of woodland species to cross gaps wider than this (implemented as a modifying effect, so land cover still plays a role; for example, a wide gap over water will have a resistance value of $45 + 50 = 95$). The land cover types and modifiers were assigned resistance values according to Grafius

et al. (2017). The resistance values ranged between 1 and 100. Higher values were related to built-up areas. Selection of core habitat nodes was based on predicted habitat suitability patch size, contiguity and structure. All woodlands greater than 10 ha were initially included, after which some were excluded on the basis of irregular shape, one core habitat node for each town.

Circuitscape software 4.0 (McRae et al., 2013) was used in this study to calculate circuit-based connectivity and generate a cumulative current density map. The landscape resistance and core habitat node areas had to be converted to an ASCII format using 'Export to Circuitscape' extension for ArcGIS for use in the software. The short-circuit regions file was used to represent the same areas as the core habitat nodes. Short-circuit regions represent areas with zero resistance that the species under study can traverse freely with no cost. Circuitscape requires three input datasets: i) input resistance data ii) focal node location files and iii) short-circuit regions file. Circuit models were generated using the pairwise mode in order to model connectivity between all pairs of 'focal nodes' (i.e. core habitat patches). A cumulative current density map was produced that combined the results of all pairwise current density maps. The cumulative current maps were used as model predictor.

Since the values of the cumulative current maps are influenced by the number of node pairs, and each town contained a different number of core habitats (Bedford 7; Luton 14; Milton Keynes 11), the maps exhibited different data ranges and were rescaled to values between zero and one to facilitate comparison between maps.

4.2.5 Input Data: Patch Area, Connectivity and Empirical Abundance Data

Point count survey data was used to estimate bird abundance and bird species richness (Plummer and Siriwardena, 2018). The survey data was collected positioning observation points (n=454) within 116 tiles (grid squares of 500 m x

500 m) which had been randomly selected for bird surveying using a stratified sampling design. Abundance estimates were calculated at each observation point by summing up the maximum counts of singing and non-singing *P. major* and *C. caeruleus* individuals within a radius of 200 m. The maximum value across all points within each tile was taken as indicator of that year's abundance (2013). This produced an estimate of overall abundance at that survey point. Bird species richness was calculated at each observation point by summing up the total of bird species recorded within a radius of 200 m (Grafius et al., 2019). Overall bird species richness values for modelling input were based on the maximum observed richness across all points within a tile and taken as indicator of that year's richness (2013). This produced an estimate of overall richness at each point.

Patch area and connectivity data were based on a raster LULC map (Chapter 2). Patch area (ha) was calculated using Fragstats software (McGarigal et al., 2012). Corridor-based metrics of habitat connectivity have been identified as strong predictors of biodiversity in urban areas (Beninde, Veith and Hochkirch, 2015). Cumulative current maps were produced following Grafius et al. (2017) who used data on great tits (*P. major*) and blue tits (*C. caeruleus*) movements to model functional connectivity. These woodland species have adapted to life in UK suburban environments, but their movements within urban environments are constrained by habitat fragmentation (Cox et al., 2016) making them suitable species for corridor-based metrics of habitat connectivity. They have similar habitat preference, habit and behaviour and their suitable habitats are represented by large woodlands (Grafius et al., 2017). Larger habitats with fewer gaps will increase forage efficiency and decrease breeding costs in both *P. major* and *C. caeruleus*. *P. major* is thought to act as indicator for balanced urban food webs due to its sensitivity to green space connectivity. Land use and land cover types are providers of ecosystem services. Woodlands provide a number of services such as carbon storage, nutrient retention, waters supply, pollination, habitat quality and erosion control. And so, functional connectivity can be represented by depicting the movements of urban bird flows using circuit theory.

In this study, functional connectivity was used as a proxy of woodlands and associated ESs and as an indicator of ES provision. Urban landscapes with high functional connectivity (i.e. with a high tree cover) can supply multiple ESs.

4.2.6 Ecosystem Service Trade-offs and Synergies Input Data

The data outputs of a principal component analysis conducted on six ES spatial datasets were used for GIS processing and subsequently as response variable for BBN modelling. The ESs analysed represented Provisioning (water supply) Regulating (carbon storage, erosion control, nutrient retention, and pollination) and Supporting (habitat quality) services (Karimi, Corstanje and Harris, 2021; Chapter 2). The three principal components represented nutrient retention and carbon storage trade-offs (PC 1), habitat quality and pollinator abundance trade-offs (PC 2) and potential soil erosion and water supply synergies (PC 3).

For each town a dataset where each observation represented a point observation of counts of bird abundance (within a radius of 200 m), a point observation of bird species richness (within a radius of 200 m), data point cumulative current raster map values, data point principal components raster map values and patch area values found at the same location was data processed using the Extract Multi-Values to Points tool in ArcGIS Desktop 10.6. The datasets of each town were combined using JMP software (SAS Institute Inc., 2018) to generate a dataset of 116 'cases' (observations) and used for Bayesian modelling.

4.2.7 Bayesian Belief Networks

Bayesian Belief Networks (BBNs) are multivariate statistical models, acknowledged for their unique probabilistic modelling approach and their high model transparency (Landuyt et al., 2013). Bayesian belief techniques have several model related advantages, e.g. the possibility of taking into account

uncertainties and combine expert knowledge with empirical data (Van der Biest et al., 2013). As networks, they can cope effectively with incomplete information on the relationships between variables. BBNs are well-suited to complexity and incomplete knowledge, which are common in ecological systems (Landuyt et al., 2013). BBNs are useful tools for modelling ecological predictions and used for assessing the influence of environmental predictor variables on ecological response variables (Marcot et al., 2006).

4.2.8 Model construction

BBN modelling was conducted using Netica software (Norsys Software Corp., 2018). The BBN made predictions within vegetated areas. Bird surveys were centred on vegetated areas, but encompassed mixed areas containing both vegetated and non-vegetated areas. Separate but comparable (i.e. possessing the same network structure) BBN models were created for each of the three principal components (representing trade-offs and synergies among services) with each ES trade-off or synergy as the model outcome. Each BBN model included patch area, connectivity and bird species abundance as model predictors, and ES trade-off (or synergy) as the response variable. A separate influence network was created with bird species richness as predictor variable in place of bird abundance preserving the other variables in the model. The predictor variables were chosen for their theorised influence on ES trade-offs and synergies. Bird species abundance and species richness were each included in the model as an indicator of biodiversity than as drivers of ES trade-offs and synergies to test whether there is concordance with the provision of ESs (i.e. biodiversity is increasingly important as the number of services considered increases). Conditional probabilities define the relationships between the habitat structural features and the ES trade-offs, and were obtained by processing individual 'cases', where each case represented an ES trade-off (or synergy) value and habitat structural feature values found at the same location. The model then used these conditional probabilities to predict ES trade-offs (or synergies) at every vegetated location (116 points). All nodes were automatically discretised

with ten states each. A simplification of this with five states for each input parameter and three for dependent variables was used for ease of visualisation of model structure (Figure 4.2).

Model performance was assessed using a goodness-of-fit measure, reported as the model's error rate, that expresses the frequency with which the model's strongest predictions is incorrect against the observed data. It supplies an analogous measure of confidence in the model predictions (Aalders, 2008). A sensitivity analysis was conducted on the BBN models. Sensitivity analysis determined how much the beliefs (i.e. ES trade-off and synergy predictions) were influenced by each new finding in the predictor nodes (i.e. changes in patch area, connectivity and bird species abundance). Sensitivity was expressed as the expected reduction in variance of the expected real value due to a finding in a particular node (e.g. complete insensitivity would occur if the addition of new data records to the model caused no reduction in the variance). The conditional probabilities for the node states were extracted from the models and graphed as a heat map to show the predicted factor probability at each state level of trade-off (or synergy).

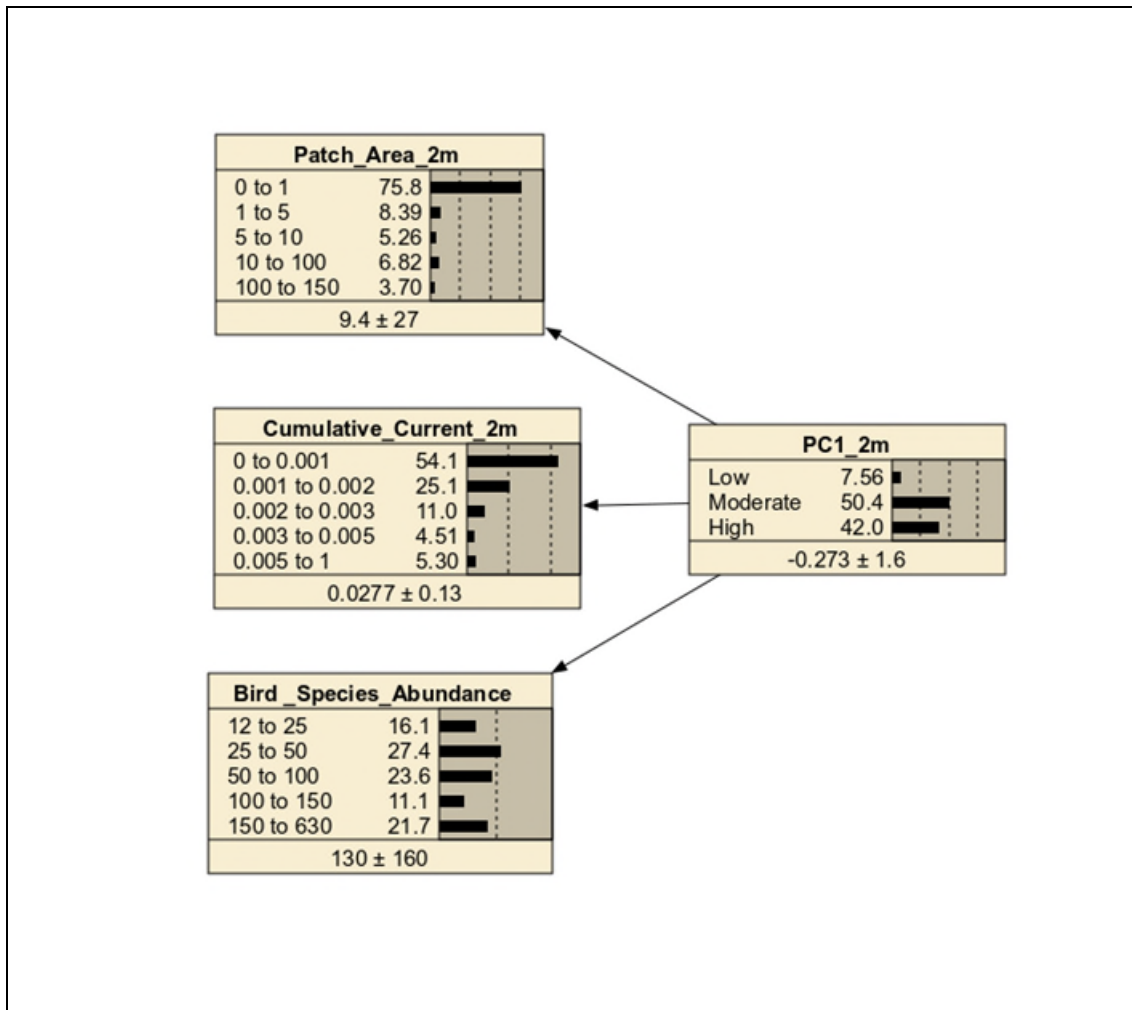


Figure 4.2 Example of Bayesian Belief Network model structure for Nutrient retention and Carbon storage trade-offs. All models used a comparable structure, with the dependent variable and the conditional probabilities changing between models. The influence diagram illustrates the relationships between the dependent variable (i.e. ES trade-offs or synergies) and the independent variables. Arrows denote the direction of probabilistic influence implemented in software rather than causal relationships between the factors

4.3 Results

4.3.1 The Cumulative Current Maps

The modelling of landscape connectivity for *P. major* and *C. caeruleus* resulted in a cumulative current map for each town (Figure 4.3). The intensity of the current was used as a proxy for wildlife movement and was calculated between each pair of core habitats. For Bedford, the cumulative current was affected by the distribution of core habitat areas with the south-western region exhibiting a decrease in modelled flow values due to the presence of only one major habitat patch in that region. The proximity of habitat nodes to one another in other areas of the town appeared to generate an increase in current values. For Luton, modelled current flows were greater in the south-eastern region due to the proximity of the habitat nodes to one another. Modelled movement patterns appeared to be similar but had a greater emphasis on wooded corridors and mixed habitats, such as through residential gardens between rows of terraced housing and vegetated corridors along major transport arteries. In Milton Keynes, modelled current flows were higher along wooded corridors and vegetated road verges. Current flows appeared to follow the major vegetated grid road network and were higher on the western side of the region where the core habitat nodes were distributed. Modelled current flows along wooded corridors in residential districts also suggest the importance of these features. Conversely, modelled current flows in the city centre and industrial estates had a sparser flow network.

The circuit model of flow through a network is relevant to nutrient retention, carbon storage, habitat quality, pollination, erosion control and water supply services as the supply of the services are each associated with either a specific land cover type provider (e.g. carbon storage for woodland) or multiple land cover types providers (e.g. pollination for grassland and woodland). The provision of ESs changes as a result of changes in land use patterns or changes in the composition and structure of different ecosystems. An extensive modification to blue-green infrastructure and land cover affects the supply of ecosystem services. The cumulative current maps showed that the network structure and

how the core habitat areas are distributed influence landscape connectivity. The circuit model of flow through the network can influence the provision of ESs and is influenced by the surrounding built-up matrix. Woodland areas (i.e. suitable habitat for bird flow) provide carbon storage, nutrient retention, habitat quality, erosion control, pollination and water supply (surface runoff reduction and baseflow) services.

In the initial cumulative current maps, Bedford contained lower overall modelled current values (maximum 4.99, mean 0.03) than Milton Keynes (maximum of 8.38, mean 0.04) and Luton (maximum 21.63, mean 0.24) due to a lower number of core habitat nodes. After rescaling, Luton had the highest mean connectivity but also the highest variability (mean 0.0111, SD 0.0873). Milton Keynes (mean 0.0046, SD 0.0555) and Bedford (mean 0.0059, SD 0.0598) had lower values.

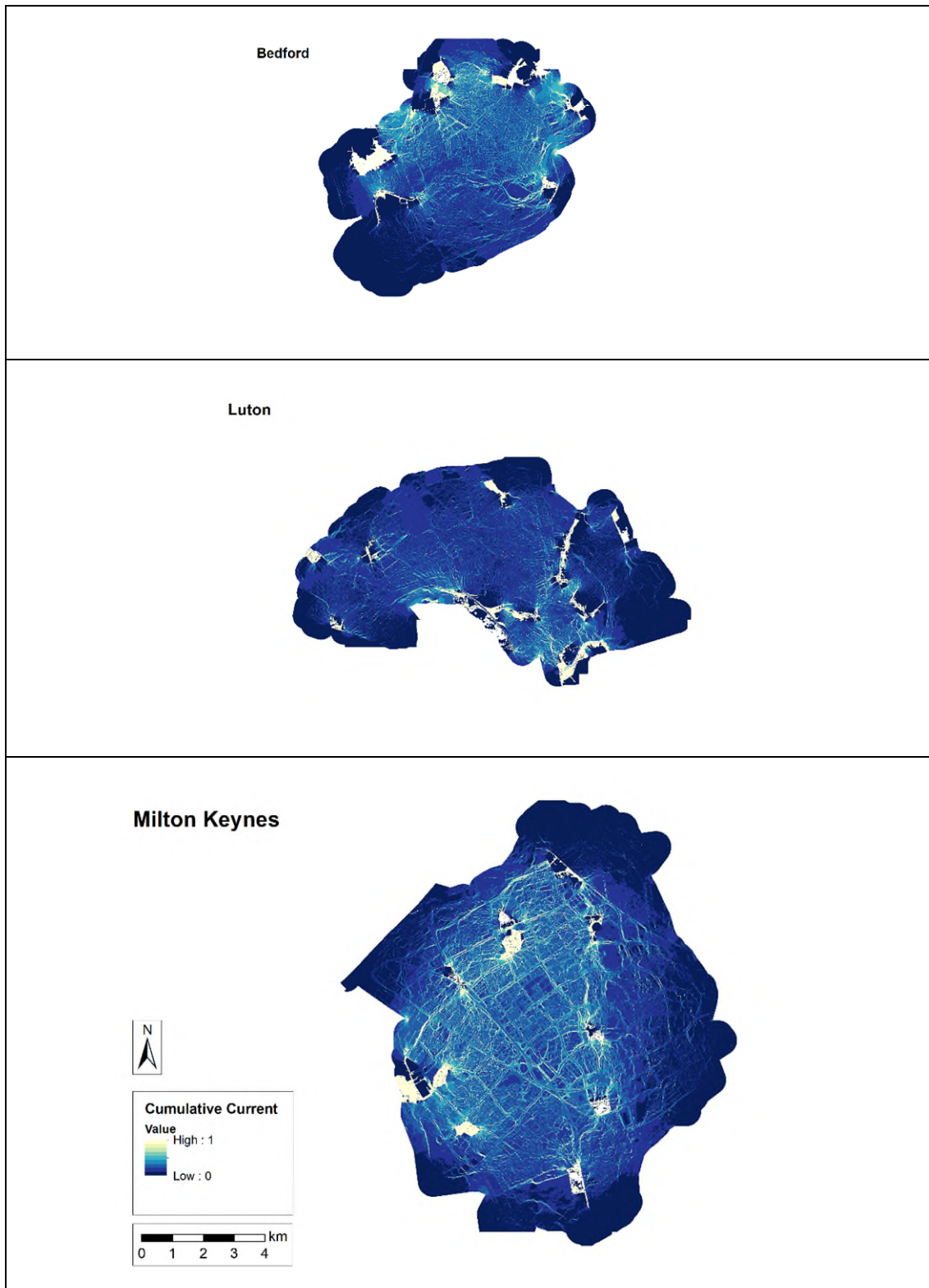


Figure 4.3 Modelled cumulative current maps (rescaled to facilitate comparison between towns) at a 2 m spatial resolution for Bedford, Luton and Milton Keynes, UK

4.3.2 Model Performance and Predictor Sensitivity

Error rates for the models ranged between 41 % for the PC describing habitat quality and pollinator abundance trade-offs and 45 % for the PC describing nutrient retention and carbon storage trade-offs (Table 4.1). The model error rates for the influence network with bird species richness ranged between 41 % for the PC describing nutrient retention and carbon storage trade-offs and 48% for the PC describing habitat quality and pollinator abundance trade-offs (Appendix C, Table C.1).

Parameter sensitivities in the models reflect the strength of the relationships between predictors and ES trade-off and synergy predictions. Connectivity exhibited the greatest sensitivity for two of three ES trade-offs and synergies. Predicted trade-offs of nutrient retention and carbon storage and habitat quality and pollinator abundance were most sensitive to connectivity and exhibited relatively high percentage of variance reduction (respectively, 7.3 and 3.6). Habitat quality and pollinator abundance trade-off predictions were least sensitive to bird abundance (1.0). Potential soil erosion, water supply synergies predictions were most sensitive to bird abundance (3.0). Potential soil erosion, water supply synergies predictions were most sensitive to bird species richness (2.6).

Table 4.1 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient retention and Carbon storage Trade-offs (PC1), Habitat quality and Pollinator abundance Trade-offs (PC2) and Soil erosion and Water supply Synergies (PC 3) at 2 m resolution

	Error rate	Sensitivity (Percent in Variance Reduction)		
		<i>Connectivity</i>	<i>Bird Sp. Abundance</i>	<i>Patch Area</i>
PC1	44.83%	7.34	4.99	4.42
PC2	40.52%	3.63	1.00	3.07
PC3	43.10%	2.01	3.05	1.74

4.3.3 Probabilistic Associations between Landscape Factors and ES Trade-offs and Synergies

Heat maps show the probabilistic associations between the values of predictor variables and the predicted ES trade-offs or synergies levels (Figure 4.4; Table 4.2). High conditional probabilities reflect the likelihood of an outcome given a set of parent node states. For example, low and moderate nutrient retention and carbon storage trade-offs are expected in areas with low patch area, whereas high nutrient retention and carbon storage trade-offs are expected in areas with low patch area and low connectivity. In the PCA (Chapter 2), low PC1 scores represented low values in nutrient retention and high values in carbon storage, whereas high PC 1 scores represented high values in nutrient retention and low values in carbon storage. There is therefore an expectation that in areas with small patch area and low connectivity, nutrient retention will be relatively high. Patch area and connectivity appeared to be strong predictors of ES trade-offs and synergies. Predicted habitat quality and pollinator abundance trade-offs exhibited strong associations with patch area and connectivity, with the highest conditional probabilities associated with low patch area and low connectivity at moderate and high levels of habitat quality and pollinator abundance trade-offs.

In the PCA, low PC 2 scores represented high values in pollinator abundance and low values in habitat quality, whereas high PC 2 scores represented high values in habitat quality and low values in pollinator abundance. There is therefore an expectation that in areas with small patch area and low connectivity, habitat quality will be relatively high.

Low levels of predicted potential soil erosion and water supply synergies appeared to be associated with low patch area. High levels of potential soil erosion and water supply synergies predictions were associated with low patch area and moderately low connectivity. In the PCA, low PC 3 scores represented low values in soil erosion and low values in water supply, whereas high PC 3 scores represented areas with high values in soil erosion and high values in water supply. There is therefore an expectation that in areas with small patch area and moderately low connectivity, soil erosion will be relatively high. Predicted ES trade-offs and synergies exhibited weak associations with bird species abundance. Conversely, predicted ES trade-offs and synergies exhibited strong associations with bird species richness (see Appendix C, Figure C.1).

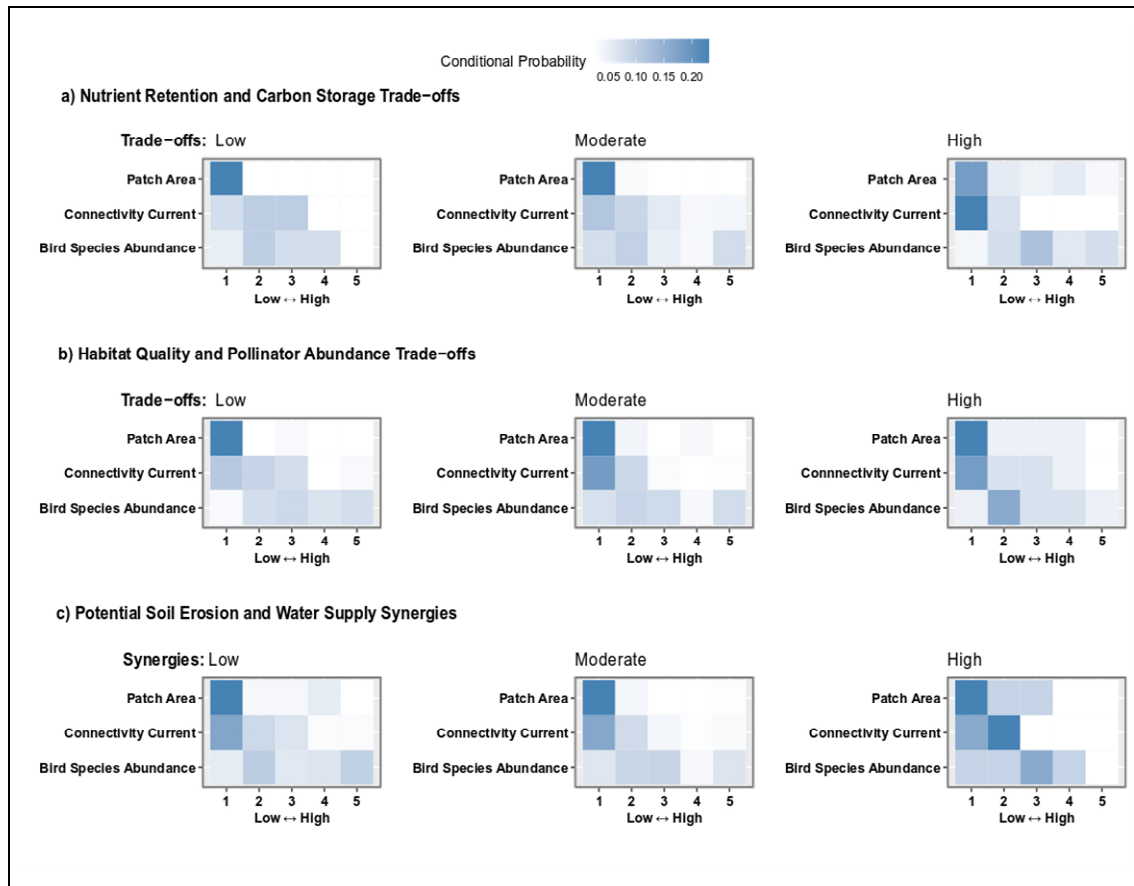


Figure 4.4 The heat maps show the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (patch area, connectivity and bird species abundance; values of bin ranges are shown in Table 4.2) and the predicted trade-offs (or synergies). Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of input value and predicted trade-offs (or synergies) represented by that cell in the heat map

Table 4.2 Bin ranges for input parameter values in Fig. 4.4 heat maps of Bayesian model conditional probabilities

Bins	Low	Moderately low	Moderate	Moderately high	High
Patch Area (ha)	0-1	1-5	5-10	10-100	100-150
Connectivity Current	0-0.001	0.001-0.002	0.002-0.003	0.003-0.005	0.005-1
Bird Sp. Abundance	12-25	25-50	50-100	100-150	150-630

4.4 Discussion

The modelling approach described represents a method for assessing the factors that influence ES trade-offs and synergies and was used to test whether connectivity drives ES trade-offs and synergies. Our study showed that connectivity influences ES trade-offs and synergies and the supply of ESs and that the modelling framework can be used to test the factors that influence ES trade-offs and synergies in complex landscapes.

4.4.1 Predicted ES Trade-offs and Synergies and Key Drivers of ES Trade-offs and Synergies

The model error rates did not vary widely (Table 4.1), the mean rate among all models (43.0%) was comparable to results found in other studies applying BBNs to environmental systems (Aalders, 2008; Grafius et al., 2019). The finding of comparable error rates supports the assertion that the predictors habitat connectivity and patch area we consider here are strong determinants of ecosystem service trade-offs in urban areas.

The conditional probability heat maps show the relationships between the ES trade-offs and synergies and habitat structure (Figure 4.4). Connectivity emerged as an important factor for multiple ES trade-offs and synergies, with low

connectivity associated with high values in nutrient retention and high values in habitat quality. There is therefore an expectation that in areas dominated by low connectivity, nutrient retention and habitat quality will be relatively high. Importantly, low patch area was associated with ES trade-off and synergy predictions. Large patches of vegetation are more likely to possess a greater variety of habitats and heterogeneity than smaller patches, with a higher supply of ESs and biodiversity (Leitão et al., 2006). Conditional probabilities (Figure 4.4) further support the expectation that nutrient retention, habitat quality and water supply will be greater in patches with low patch area and with low to moderately low connectivity. This is consistent with past research that a decrease in patch area and connectivity reduces the supply of ESs (Cordingley et al., 2015; Eigenbrod, 2016; Mitchell et al., 2013). In this study, connectivity exerted a strong influence on two of three ES trade-offs as shown in the results of the sensitivity analysis. Fragmentation is assumed to reduce the provision of multiple ESs and alter landscape connectivity. Modelling and conceptual work by Mitchell et al. (2015) have found that the highest levels of ES provision is predicted to peak at intermediate levels of natural land cover loss and of habitat fragmentation (Mitchell, Bennett and Gonzalez, 2015). Patch area and patch isolation have been found to have both positive and negative effects on ESs with changes to patch area affecting the strength of trade-offs between services (Mitchell, Bennett and Gonzalez, 2014). Landscape connectivity change is assumed to have contrasting effects on ESs. Studies suggest that decreased connectivity will reduce ES provision. In a literature review, provisioning and regulating services were found to be the most widely studied services affected by biotic and abiotic connectivity (Mitchell, Bennett and Gonzalez, 2013). The findings of this study show that in areas with low to moderately low connectivity trade-offs and synergies will be high for the considered ESs. Low to moderately low connectivity is expected in areas to support high trade-offs between services, and thus decrease the provision of ESs.

Patch area and connectivity have been found to be important for enhanced bird species abundance (Shanahan et al., 2011; Kang et al., 2015). Connectivity

has been found to have an important influence on bird species richness as it increases the number of patches from which species can arrive (Chisholm, Lindo and Gonzalez, 2011; Shanahan et al., 2011). High levels of potential soil erosion and water supply synergy predictions appeared to be associated with low patch area, moderately low connectivity and moderate bird species abundance, suggesting that in areas with low patch area, moderately low connectivity and moderate bird species abundance soil erosion and water supply synergies will be relatively high. The conditional probabilities for bird species richness were more marked compared to bird species abundance suggesting a stronger relationship with ES trade-offs and synergies (see Appendix C, Figure C.1).

Conditional probabilities show that low to moderately low connectivity is an important driver of trade-off and synergy predictions for nutrient retention and carbon storage, habitat quality and pollinator abundance and for potential soil erosion and water supply. The probabilistic associations between predicted ES trade-offs and synergies and landscape structural factors, patch area and connectivity, may be consistent with the fact that low patch area and low connectivity affect trade-offs and synergies between ecosystem services (Mitchell et al., 2013; Mitchell et al., 2015). Predicted nutrient retention and carbon storage trade-offs were most sensitive to connectivity. This suggests that connectivity may be a key driver of nutrient retention and carbon storage trade-offs. The mechanisms by which nutrient retention and carbon storage trade-offs are created may be driven by functional connectivity (Bennett, Peterson and Gordon, 2009). Nutrient retention and carbon storage trade-offs may be driven by connectivity as a result of extensive modification to land cover and arrangement of land cover types in urban areas. Low levels of nutrient retention and high levels of carbon storage were associated with woodlands, whereas high levels of nutrient retention and low levels of carbon storage with grasslands (i.e. unsuitable habitat for bird flow). High levels of predicted nutrient retention were associated with low connectivity. Conditional probabilities support the expectation that nutrient retention and carbon storage trade-offs will be greater in patches with low connectivity, suggesting that low connectivity supports high values in

nutrient retention. An increase in connectivity through the extensive modification of land cover would correspond to an increase in woodland vegetation cover (i.e. suitable habitat for bird flow), and subsequently lower nutrient retention and carbon storage trade-offs. This would result in an increase in carbon storage and a higher supply of ESs. Conversely, a decrease in connectivity through the extensive modification of land cover would correspond to an increase in grasslands (i.e. unsuitable habitat for bird flow), and in an increase in nutrient retention.

Predicted habitat quality and pollinator abundance trade-offs were most sensitive to connectivity. This suggests that connectivity may be a key driver of habitat quality and pollinator abundance trade-offs. Connectivity depends on the physical and functional connection between patches and the arrangement of land cover types. Habitat quality depends on the habitat's proximity to human land uses and the intensity of these land uses. In urban areas, it has been found that pollinator abundance was prevalent due to the presence of a variety of habitats for nesting and foraging for pollinators (Baldock et al., 2019). The mechanisms by which habitat quality and pollinator abundance trade-offs are created may be driven by patch area and connectivity which affect the supply of habitat quality and pollinator abundance services. The spatial arrangement and connectedness of land cover types influence the provision of ESs which will have either positive or negative effects on service flow depending on the service in question. Human activities that alter landscape connectivity such as habitat fragmentation can affect habitat quality and pollinator abundance. Along a suburban-urban gradient, habitat quality would be reduced whereas pollinator abundance enhanced. Habitat quality is enhanced by natural and semi-natural land cover, whereas pollinator abundance is enhanced by the availability of a variety of habitats. Habitat quality and pollinator abundance trade-offs may be driven by patch area and connectivity and by the influence of the surrounding built-up areas. High levels of habitat quality and low levels of pollinator abundance predictions were associated with low connectivity. Conditional probabilities support the expectation that habitat quality and pollinator abundance trade-offs will be greater in areas

with low connectivity and low patch area, suggesting that low connectivity and low patch area support high values in habitat quality. High levels in habitat quality and low levels in pollinator abundance were associated with suburban grasslands. Low connectivity which represented unsuitable habitat for bird flow was associated with grasslands. An increase in connectivity through the extensive modification of land cover would correspond to an increase in woodland (i.e. suitable habitat for bird flow). This would correspond to an increase in habitats for pollinators, and as a result lower habitat quality and pollinator abundance trade-offs. This would result in an increase of habitat quality and pollinator abundance, and subsequently a higher supply of ESs. The habitat quality and pollinator abundance trade-offs appeared to be driven by connectivity, land use patterns and ecological processes.

Predicted potential soil erosion and water supply synergies were most sensitive to bird abundance. Bird species abundance and species richness were each included in the model as an indicator of biodiversity than as drivers of ES trade-offs and synergies to test whether there is concordance with the provision of ESs (i.e. biodiversity is increasingly important as the number of services considered increases). Conditional probabilities support the expectation that soil erosion and water supply synergies will be greater in patches with moderately low connectivity, low patch area and moderate bird abundance. High levels of potential soil erosion and water supply synergy predictions were associated with moderately low connectivity (i.e. suitable habitat for bird flow) and moderate bird abundance. A possible explanation is that patch area in combination with connectivity increases bird abundance (Shanahan et al., 2011; Kang et al., 2015). An increase in patch area and connectivity through the extensive modification of land cover would correspond to an increase in woodland areas (i.e. suitable habitat for bird flow), and subsequently an increase in bird abundance. An increase in woodland vegetation increases carbon storage, habitat quality, erosion control, pollination and water supply services, and the supply of ESs.

Potential soil erosion, water supply synergies were sensitive to patch area and connectivity. High levels of predicted potential soil erosion and water supply

synergies appeared to be associated with moderately low connectivity and low patch area. There is therefore an expectation that in patches with low patch area and moderately low connectivity, the soil erosion and water supply synergies will be high and would result in vegetation-field edge effects (Mitchell et al., 2015). Erosion regulation is dependent on the flow of water and vegetation cover and a decrease in habitat connectivity (i.e. vegetation cover) as described here would result in an increase in surface runoff and soil erosion. The mechanisms by which soil erosion and water supply synergies are created may be driven by connectivity and by an interaction between services (Bennett, Peterson and Gordon, 2009). Impervious land increases surface runoff and decreases water infiltration. Conditional probabilities support the expectation that soil erosion and water supply synergies will be greater in patches with low patch area and moderately low connectivity. High levels of soil erosion and high levels of water supply were associated with urban grassland and urban trees and woodland areas. An increase in connectivity through the extensive modification of land cover would correspond to an increase of woodland areas (i.e. suitable habitat for bird flow). This would correspond to a decrease in soil erosion and water supply synergies as woodland areas mitigate surface runoff and protect from soil erosion. Large patches of vegetation protect larger areas from soil erosion and allows the recharge of the water table (Leitão et al., 2006). This would result in an increase in erosion control and a decrease in surface runoff, and thus a higher supply of ESs. High levels in potential soil erosion and water supply may be driven by landscape structure, connectivity, topography and ecological processes. The combined effect of low patch area and moderately low connectivity may create potential soil erosion and water supply synergies.

4.4.2 Implications, Further Research and BBN Modelling

The findings show that connectivity influences ES trade-offs and synergies with implications in the design of green space, ecological networks and sustainable ecosystem management. The cumulative current maps represented modelled

current values of bird flow in urban areas based on habitat suitability (i.e. large woodlands) and land cover resistance. After rescaling, Luton exhibited a higher mean current value than Milton Keynes and Bedford. The higher mean values for Luton are an effect of a higher number of core habitats, its high tree cover and the positive influence of patterns and forms favourable to connectivity (e.g. its lower water cover). The findings show that extensive modification to land cover affects the circuit model of flow through the network and the supply of ESs. Green space structure and connectivity affect the supply of ESs creating trade-offs and synergies between services and form bundles of ESs. Each service responds differently to the variation of landscape structure even if the services do not interact strongly. Connectivity is important in the design of ecological networks in urban areas. Blue and green infrastructure and associated ESs can provide insurance by helping to buffer from disturbances such as flooding, heat stress, landslides and storms. Human activities which alter connectivity such as fragmentation and ES use can affect the provision of ESs. The structure of an ecological network and how the system components are connected is important. The identification of areas with multiple ESs as components of an ecological network and ES bundles could help in orienting management strategies to sustainability in urban areas. Large and better-connected habitat patches of tall and mature vegetation may confer resilience to a bundle of ESs.

The modelling approach and ES bundle analysis can be used to analyse green infrastructure and associated ESs. Analyses of synergies and trade-offs and identification of multifunctional key areas enable policymakers to maximize ESs. A blue-green infrastructure provides a number of benefits and services, but different green areas will have different ecological functions and provide different ecosystem services. To ensure the flow and access to ecosystem services is not interrupted, representative successional stages and different kinds of green areas in different urban contexts should be planned and managed for (Andersson, 2006). As ESs interact and are affected by connectivity, which create trade-offs and synergies between services and form bundles, an understanding of the possible effects of connectivity on green space is vital to build a resilient

supply of ESs (McPhearson et al., 2015) and enhance a multifunctional blue-green infrastructure so as to counteract climate change and land use. An understanding of the delivery of multiple ESs of an ecological network allows to identify the areas where managers can focus conservation planning objectives and develop sustainable development schemes.

Further studies on the effects of landscape structure on ES provision are needed to test and develop a better understanding of the effects of drivers on the provision of ESs. ESs are the co-products of socio-ecological systems and depend not only on ecosystem functions and ecological processes but also on social and biophysical variables (Eigenbrod, 2016). Therefore, the amount and configuration of social variables such as land management systems, the distribution of wealth and human populations should be considered as possible drivers which affect the demand for ESs. Conceptual frameworks built on meta-ecosystem and ecological network theories are needed to develop a better understanding of the effects of connectivity on ESs (Thompson, Rayfield and Gonzalez, 2017).

The findings of the conditional probability heat maps showed that for the considered ESs high levels of predicted trade-offs appeared to be associated with low patch area and low to moderately low connectivity. There is therefore an expectation that in areas with low patch area and low to moderately low connectivity, for the considered ESs, trade-offs between services will be high and thus result in a decrease in ES provision. This implies that large habitat patches and high landscape connectivity provide more synergies. Patch type (i.e. natural or semi-natural habitats) is also important as not all patches are (natural) habitats and habitat quality influences the supply of ESs and species. Our findings may be relevant in the design of increased connectivity through blue-green infrastructure.

An additional consideration is that the implications of connectivity for the resilience of ESs are complicated by the fact that socio-ecological processes operate simultaneously at different scales. Drivers may operate at local, regional

and global scale. Connectivity may safeguard ecosystem services against a disturbance either by facilitating recovery or by constraining locally the spread of a disturbance (Dakos et al., 2015). At the same time, highly connected systems increase the potential for disturbances to spread. Changes to landscape connectivity and the provision of services can depend on the scale at which ESs are altered. An understanding of the possible effects of disturbances and hazards in urban areas on multiple ESs is vital in sustainable cities for building and ensuring a resilient supply of ESs.

The BBN modelling approach offers an advantage to other modelling methods as it combines the possibility to use empirical data and expert knowledge (Landuyt et al., 2013; Van der Biest et al., 2013). The general framework can be applied to other potential drivers that influence ES trade-offs and synergies. This may provide a better understanding of the effects of drivers on ES trade-offs and synergies, through complex interactions with different species and processes, and an understanding of the relationships among ESs and the mechanisms behind these relationships, whether the services are responding to a shared driver or interacting (Bennett, Peterson and Gordon, 2009).

4.5 Conclusions

The present study assessed the influence of connectivity on ES trade-offs and synergies at a fine (2 m) spatial resolution, at a landscape scale ($> 100 \text{ km}^2$). We demonstrated that by applying a BBN modelling approach the influence of landscape and habitat structural features on ES trade-offs and synergies can be tested. Our models performed with error rates similar to BBN models used in other environmental contexts. The approach provides useful information on the sensitivity of ES trade-offs and synergies to different landscape structural features.

Our findings showed that patch area and connectivity exerted a strong influence on ES trade-offs and synergies and support the principle that, broadly, large and better-connected patches of vegetation increase ES provision and bird abundance in urban areas. Connectivity was found to be the most influential variable in determining two of three ES trade-offs and synergies. Low patch area and low to moderately low connectivity were associated with high levels of ES trade-offs and synergies predictions. In this study landscape connectivity affected multiple ESs and may form bundles.

Landscape management requires an understanding of how landscape connectivity affects ESs and their interactions. A BBN modelling approach may provide an effective solution to test the potential factors that drive ES trade-offs and assess how ES trade-offs respond to the variation of urban landscape structural features, and thereby relevant to landscape-scale research and ES management. BBNs are important tools for assisting in decision-making and scenario testing, and for urban planning. Further research is needed to understand how ecological networks enhance the resilience of urban ESs.

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5 OVERALL DISCUSSION: IMPLEMENTATION OF THE WORK

This chapter contains a synthesis and reviews the questions, objectives and hypotheses of the research. The main findings, research limitations and suggestions for future work are summarised according to the research objectives. Subsequently, the general contribution and the implications of the research are presented.

5.1 Objective 1: To Identify and Analyse the Composition of Ecosystem Service Bundles and the Spatial Variation of all Ecosystem Services (i.e. the Bundle)

The first objective addresses the first question, “Do multiple ecosystem services coexist and form spatial ecosystem bundles at 2 m spatial resolution and at a landscape scale in urban areas?” The ecosystem services clustered spatially to form four ecosystem service bundles showing signs of trade-offs and synergies between ES as explained in Chapter 2. Bundle 1 (*Potential soil erosion*) had high above mean values in potential soil erosion and moderate values in nutrient retention and water supply and comprised suburban areas where land cover is primarily grassland, although it also occurred in urban areas with a scattered distribution. It indicated areas with prevalent soil erosion (Figure 2.2; Table 2.5). Bundle 2 (*Urban trees and woodland*) had high above mean values in carbon storage and moderate above mean values in habitat quality and comprised urban areas where land cover is primarily broadleaf and coniferous trees. Bundle 3 (*Urban grassland*) had high above mean values in pollinator abundance, nutrient retention, and comprised mainly urban areas with grassland. It had above mean values for baseflow. Bundle 4 (*Suburban grassland*) had the highest above mean values in nutrient retention and habitat quality with moderate above mean values for quick flow. It comprised suburban areas with grassland. It indicated areas with relatively high habitat quality. Bundle 2 (Urban trees and woodland) had the highest spatial coverage for Bedford (40 %). Bundle 3 (Urban grassland) was the

most widespread with regard to areal coverage for Luton and Milton Keynes (respectively, 36 % and 42 %). The results show that ES bundles clustered and exhibited distinct geographic patterns. This study shows how ES bundles mapped across the landscape.

This study also illustrates the trade-offs and synergies between ecosystem services using principal component analysis. The principal component analysis revealed the trade-offs and synergies between ES as shown in the loading plot graph (Appendix A, Figure A.4c). Trade-offs and synergies correspond to the actual delivery of ES (Berry et al., 2015). Trade-offs and synergies occur if ES interact. This may be due to simultaneous responses to a same driver or to true interactions among ES (Bennett, Peterson and Gordon, 2009). A spatial trade-off was found between nutrient retention and carbon storage (Appendix A, Figure A.4c; Table 2.4). This appeared to give a separation between areas with grassland with high values in nutrient retention from areas with trees with high values in carbon storage and indicated a gradient of nutrient retention and carbon storage spatial trade-offs between grasslands with higher values in nutrient retention and woodland areas with higher values in carbon storage. These trade-offs could be due to plant ecological traits and land cover type. Some herbaceous species are better equipped to utilise nitrate than woody species, whereas woody species are better equipped to store carbon. Grasslands and woodlands have different ecological traits which affect the allocation of nutrients and carbon (Groffman et al., 2004, 2009). In this study, carbon storage included carbon storage in plants (above ground biomass and root biomass) and carbon storage in the soil.

A second spatial trade-off was shown between habitat quality and pollination. This appeared to separate suburban areas with higher values in habitat quality from urban areas with higher values in pollinator abundance, describing a gradient of increasing habitat quality and pollinator abundance spatial trade-offs from urban to suburban areas. The increasing trade-offs could be due to land use and proximity of cover types to built-up areas and a higher variety of habitats, grassland and trees, in urban areas which favours forage floral

resources and nesting sites for pollinator species. A third gradient represented synergies between water supply (baseflow and quick flow) and potential soil erosion and described a gradient of increasing water supply and soil erosion synergies with higher values between ES from less built-up to more built-up areas and occurred in areas with grassland and woodland. The spatial water supply and soil erosion synergies appeared to be related to climate and hydrological factors and the type of land cover. The results help to understand how the services are distributed across the landscape, how the distributions of different services compare and where trade-offs and synergies among ecosystem services might occur. This empirical evidence shows that ES interact with each other which could be due to responses to the same driver or due to true interactions between services. Therefore, an analysis of the trade-offs and synergies gives us the ability to examine the mechanisms and processes for trade-offs and synergies (Raudsepp-Hearne et al., 2010; Turkelboom et al., 2015).

Ecosystem service bundles give an indication of potential delivery of ES (Berry et al., 2015). Ecosystem service bundles capture how ecosystem services interact. Ecosystem service-bundle analysis allows to identify areas where ecosystem service provision falls below known thresholds and identifies which services are vulnerable to trade-offs and has implications in land planning (Raudsepp-Hearne, Peterson and Bennett, 2010; Turner et al., 2014). For example, in the correlation analysis there was a weak positive correlation between habitat quality and carbon storage (Table 2.3). However, this pattern was not evident in the suburban and urban grassland bundle types where the mean values of carbon storage were not reflected in the average values of habitat quality and there might be the potential to enhance carbon storage in these areas. In the potential soil erosion bundle type, there were trade-offs between habitat quality and carbon storage, and likewise there may be the potential to enhance carbon storage in these areas (Figure 2.3a). Research that examines the causes of these differences may yield insights into management policies to improve the provision of ES. Ecosystem service-bundle analysis can identify areas on a

landscape where ecosystem management has produced exceptionally desirable or undesirable sets of ecosystem services (Raudsepp-Hearne, Peterson and Bennett, 2010). Spatial bundle analyses capture how naturally co-occurring ecosystem services are linked with human controlled land uses and their linked services (Turner et al., 2014). The landscape distribution of ecosystem services may correspond to predictable socio-ecological subsystems and associated land-use types, e.g. agriculture, wetlands and multifunctional land uses (Raudsepp-Hearne, Peterson and Bennett, 2010; Turner et al., 2014).

The pairwise correlation analysis revealed the interactions between services (Table 2.3). There were high negative correlations between nutrient retention and carbon storage and between habitat quality and pollinator abundance, indicating a trade-off. There were weak positive correlations between potential soil erosion and water supply indicating a synergy.

This study is significant as it investigated the mechanisms and causes of ES provision within a bundle and analysed the trade-offs and synergies between services using principal component analysis. An understanding of the ecological processes and drivers that determine ES interactions and the mechanisms of their grouping (i.e. are they responding to the same driver or are the ES interacting) can help us learn when we can attempt to mitigate trade-offs and enhance synergies (Bennett, Peterson and Gordon, 2009). The findings may provide insights to ES management. The Potential soil erosion bundle indicated areas with high levels of soil erosion, nutrient retention and water supply (surface runoff and baseflow). The bundle could be generated by climate and land cover properties which determine the higher levels of the ES water supply and potential soil erosion. It had the highest number of regulating services and could indicate areas for protection (Turner et al., 2014). The process underpinning the bundle could be water supply. There were signs of spatial synergies between potential soil erosion and water supply.

The Urban trees and woodland bundle indicated areas with high values in carbon storage, above mean values for habitat quality and low values in nutrient

retention. It was characterised by urban trees and woodland. The low values in soil erosion and surface runoff could indicate the function of trees to anchor the soil, intercept rainfall and mitigate surface runoff and soil erosion (Leitão et al., 2006). These areas may be important for other services. There were signs of spatial trade-offs between carbon storage and nutrient retention; a fact to some extent revealed by the first axis in the PCA. A similar trend was observed in Holt et al. (2015) for the city of Sheffield where synergies were found between carbon storage, stormwater runoff reduction and habitat provision. A comparable finding was also found by Chen et al. (2020) for Beijing and its surrounding areas where strong synergies were found between carbon storage and habitat quality.

The Urban grassland bundle had high values for pollinator abundance and nutrient retention rates showing signs of spatial trade-offs with habitat quality and carbon storage and found in urban areas where land cover is primarily grass. The low values of habitat quality are most likely due to the proximity of grassland to paved land and buildings. The high values for pollinator abundance are most likely due to habitat suitability and proximity to nesting sites for pollinator species.

The Suburban grassland bundle type had high values for nutrient retention and moderate values for habitat quality, and it indicated areas with high levels of nutrient retention and habitat quality. It occurred in suburban areas where land cover is grassland showing signs of spatial trade-offs with carbon storage. The bundle could be driven by land cover (grass) properties and the proximity of grassland to less built-up areas. There were spatial trade-offs between habitat quality and pollinator abundance. The high values of habitat quality are most likely due to increasing distance from built up areas. This study shows that ES bundles appear to be determined by green space spatial patterns and ecological processes.

This study mapped the four ES bundles for the study region which was the combined built-up areas of the three large towns and analysed the trade-offs and synergies between services (Figure 2.2). The evidence supports the hypothesis that ES cluster showing signs of trade-offs and synergies between ES. The

bundles exhibited distinct geographic patterns. For the town of Bedford and Luton, the Potential soil erosion bundle clustered mainly in the suburbs. Conversely, in Milton Keynes the bundle appeared less prevalent. The Urban trees and woodland bundle clustered in large woodland areas such as parks and in urban areas with street trees and wooded verges to major roads, railways and streams and corresponded to areas which enhance ES provision. The distribution of large woodland patches affected the distribution of the bundle. The Urban grassland bundle occurred in patches in urban areas where land cover is primarily grass. The Suburban grassland bundle occurred in the suburbs where land cover is primarily grass. Therefore, this study shows the different geographic patterns of the ES bundles between the three towns. The distribution of the ES bundles is assumed to be determined by socio-ecological influences.

The principal component maps illustrated the spatial trade-offs and synergies between ES (Appendix A, Figure A.1, Figure A.2 and Figure A.3). The spatial trade-offs and synergies between ES appear to be driven by land cover properties, ecological processes and the influence of the urban matrix. The nutrient retention and carbon storage trade-offs appeared to be driven by plant ecological traits and land cover type. The habitat quality and pollination trade-offs appeared to be driven by habitat suitability for pollinator species and by distance of greenspace from built-up areas. The soil erosion and water supply synergies appeared to be driven by climatic, topographical and hydrological processes which are more likely to be influenced by landscape structure and habitat configuration. This study shows that ES bundles appear to be determined by socio-ecological dynamics.

For the towns of Bedford, Luton and Milton Keynes the principal component maps showed increasing habitat quality and pollinator abundance trade-offs from urban to suburban areas. For the three towns, the potential soil erosion and water supply synergies, for the considered ES appeared to increase from less built-up suburban areas to the urban areas. For Bedford, the synergies appeared to increase from the south-eastern region of the town to the built-up urban areas. For Luton, the soil erosion and water supply synergies were lower

in the suburban areas increasing in level towards the more built-up areas. For the town of Milton Keynes, synergies between soil erosion and water supply were higher in urban areas and lower on the eastern side of the town. The synergies could be driven by climatic and topographical (e.g. elevation) factors. Higher levels of potential soil erosion, water supply synergies were found in urban areas with grass and woodland indicating that it could be an edge effect. The findings may have implications in flood regulation.

Overall, the findings confirm the hypothesis that ecosystem services form bundles showing signs of spatial trade-offs and synergies between services. The bundles exhibited distinct geographic patterns and composition. Furthermore, land use land cover patterns and ecological processes appear to determine ES interactions leading to spatial trade-offs and synergies between services and affect ES provision. The composition of the bundles and the spatial variation of the ES gradients appeared to be determined by the cover type, topographical and structural patterns of green space and ecological processes. Principal component analysis allows to identify trade-offs and synergies between ecosystem services. Ecosystem service bundles are the spatial coincidence of ecosystem services. Ecosystem service bundles may correspond to predictable social-ecological subsystems and associated land use types. Understanding spatial bundle analyses may capture how naturally occurring ecosystem services are linked with human modified land uses. Understanding the mechanisms, the trade-offs and synergies between services can provide useful information to ecosystem management and to landscape planning and help to reduce the trade-offs and enhance the synergies. Understanding ecosystem service bundles may allow for the modelling and prediction of ES bundles.

5.2 Objective 2: The Influence of Landscape Configuration on Ecosystem Service Trade-offs and Synergies

In the second objective that is presented in Chapter 3, the question addressed is, “Is it possible to model and predict ecosystem service trade-offs and synergies and does landscape configuration influence ecosystem service trade-offs and

synergies and the provision of ES?” This study shows that landscape configuration characteristics affect ecosystem service trade-offs and synergies, and that landscape configuration metrics can be used to assess the influence of landscape structure on ecosystem service trade-offs and synergies. This study shows that a Bayesian Belief Network approach is suitable for predicting ecosystem service trade-offs. This study advances the BBN modelling approach for predicting ES trade-offs and synergies (Landuyt et al., 2013). This study used a BBN modelling approach (Figure 3.1) for predicting urban ecosystem service trade-offs and synergies and used it to test relationships between urban habitat configuration and ecosystem service trade-offs and synergies at a 2 m spatial resolution. The sensitivity of the model output to the predictors was assessed in order to explore the relative influence of those predictors in determining predicted ES trade-offs and synergies. Bayesian Belief Networks (BBNs) are useful tools to assess whether landscape structure affects ES trade-offs and synergies and the provision of ES.

Landscape structure affects the provision of multiple ES as landscape composition and configuration affect ecological processes (Lamy et al., 2016). Landscape composition was found to be more important than landscape configuration. However, incorporating specific aspects of landscape configuration into models of ES is thought to provide a better understanding of the role of landscape structure on multiple ecosystem services.

Theory and conceptual work predict that landscape structure affects the provision of ecosystem services and could drive trade-offs and synergies between services and may form ES bundles (Mitchell, Bennett and Gonzalez, 2013; Mitchell et al., 2015; Eigenbrod, 2016; Verhagen et al., 2016). Landscape structure is altered by changes in land use and land cover, including habitat fragmentation. A conceptual framework by Mitchell et al. (2015) predicts that fragmentation, a configuration measure, could drive trade-offs and synergies between ES. Verhagen et al. (2016) found that landscape configuration affects the provision of ES at the cell and watershed scale at a 25 m resolution and that different responses of ES to configuration suggests and involves trade-offs

between ES. The aspects of configuration considered were structure of a single patch (i.e. patch size or edge effects), use and structure of multiple patches, linear elements and location of land cover types.

This study also illustrates that quantification of spatial characteristics (McGarigal et al., 2012) of urban green space using landscape metrics is useful in understanding the influence of landscape structure on ecological processes and the relationships between landscape structure and ES provision (Kupfer, 2012). Landscape metrics can be used to assess ES and have been applied to indicate cultural ES and regulating ES (Frank and Walz, 2013; Inkoom et al., 2018). Landscape metrics are used to measure ecological functioning and land use processes. In this study landscape metrics used in ES assessment and land use planning at the patch and class level were selected (Syrbe and Walz, 2012; Haas and Ban, 2018). A Spearman's rank correlation and Principal Component Analysis (PCA) were conducted to identify redundancies between metrics.

This study used principal component analysis to identify a core set of metrics which could be used as indicators in ES trade-offs and synergies assessment (Table 3.3; Appendix B, Table B.5). Contiguity index (CONTIG), core area (CORE) and Euclidean distance (ENN) emerged as potential indicators of ES trade-offs and synergies at the patch level. Effective mesh size (MESH) and area-weighted mean Euclidean distance (ENN_AM) emerged as potential indicators of ES trade-offs and synergies at the class level.

Bayesian Belief Networks (BBNs) were chosen for their potential to use empirical data and cope effectively with incomplete information (Landuyt et al., 2013). BBNs are semi-quantitative, probabilistic models, and are useful tools for modelling ecological predictions. BBN modelling approach has the advantages to take into account uncertainties and to complement empirical data with expert knowledge (Van der Biest et al., 2013). The limited availability of data, high complexity of natural processes and related uncertainties favour the use of Bayesian networks for the assessment of ecosystem services. A recent advance has been the possibility to link BBNs with spatial data allowing to incorporate

spatial relationships into the model structure and to generate mapped model outcomes (Gonzalez-Redin et al., 2016). This study shows that a BBN approach can be used for predicting ES trade-offs of changing urban land use. This model is useful for modelling ecological predictions. The study shows that green space configuration affects ES trade-offs.

In this research, BBN models were used to assess the sensitivity of the model output to the predictors. For the models, the parameter sensitivities of the dependent variables (ES trade-offs and synergies) to the landscape metrics suggest that landscape configuration metrics core area (CORE) and effective mesh size (MESH) are the most influential determinants of the ecosystem service trade-offs and synergies in urban areas. The results indicated that core area was the most influential predictor for two of three ES trade-offs and synergies at the patch level at a 2 m resolution (Table 3.4). Habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies were most sensitive to core area (CORE) and exhibited a relatively high percentage of variance reduction (respectively 20.5 and 12.8). At the class level the results indicated that mesh size was the most influential predictor for the considered ES trade-offs and synergies and exhibited a high percentage in variance reduction. Therefore, this study shows that green space configuration exerts a strong influence on ES trade-offs and synergies.

Broad generalities can be established from the conditional probabilities about the relationships between habitat configuration and ES trade-offs and synergies. The high levels of nutrient retention and carbon storage, and habitat quality and pollinator abundance predicted trade-offs could be driven by green space configuration, land-use changes and ecological processes. This study shows that landscape configuration metrics can be used to examine the relationships between landscape structure and ecological processes (Kupfer, 2012).

The conditional probabilities (Figure 3.2) show that low levels in nutrient retention, but high levels in carbon storage are expected in areas with low core

area and low Euclidean distance. The principal component maps showed that low levels in nutrient retention and high levels in carbon storage were associated with urban trees and woodlands. Low core area and low Euclidean distance could be an indication of green space patches characterised by loosely connected core areas of trees, as individuals or in small stands, and vegetated road verges, wooded corridors and buffered streams. Therefore, the metric gives an indication of fragmented woodland and land use. The levels of nutrient retention and carbon storage trade-offs could be driven by plant ecological traits. Some herbaceous species are better equipped to utilise nitrate than woody species. Conversely, woody species are better equipped to store carbon (Groffman et al., 2009; Davies et al., 2011; de Vries et al., 2012).

The conditional probabilities showed that high levels of habitat quality and low levels of pollinator abundance are expected in areas with a large core area. The principal component maps showed that suburban areas had higher levels of habitat quality and pollinator abundance trade-offs. Large patches of contiguous grassland in the suburbs were associated with high levels of habitat quality and low levels of pollinator abundance. The high trade-offs between habitat quality and pollinator abundance could be driven by large core areas of grassland and distance from built-up areas. The lower levels of pollinator abundance could be due to a lower proximity to likely nesting sites for pollinator species and lower floral resources (Gunnarsson and Federsel, 2014; Baldock et al., 2015).

The conditional probabilities (Figure 3.2) show that high levels in potential soil erosion and water supply synergies are expected in areas with a low core area. The high levels of soil erosion and water supply could be due to a smaller patch size to mitigate surface runoff and soil erosion. Larger patches of vegetation protect aquifers and soil resources (Kim and Pauleit, 2005). The predicted potential soil erosion and water supply synergies could be driven by core area and by ecological processes, i.e. water flow. This study shows that green space configuration affects ES trade-offs. The models help to understand how greenspace configuration affects trade-offs and synergies between services. BBN models can be used to model ES trade-offs of changing urban land use.

This study is able to predict the ES trade-offs consequence of the changes in landscape configuration. The model is able to predict where ES trade-offs might occur.

This study strengthens the research by Dobbs et al. (2014) who found that the provision of ES is negatively related to its degree of fragmentation. The findings of this study are consistent with similar studies (Mitchell et al., 2015; Verhagen et al., 2016) that assume configuration could drive ES trade-offs and synergies. This model is a useful tool for predicting ES trade-offs and synergies and to assess whether habitat configuration affects ES trade-offs and synergies. This study applied principal component analysis to identify a set of landscape configuration metrics and a BBN modelling framework to assess the influence of habitat configuration on predicted ecosystem service trade-offs and synergies. This study further advances the BBN approach to test the influence of landscape configuration on ES trade-offs and synergies. This study shows that a BBN modelling approach is an effective method for predicting ES trade-offs and synergies. The study suggests that habitat configuration could drive predicted ES trade-offs and synergies. The study shows that ES trade-offs could be driven by green space configuration and ecological processes. This study shows that an integration of a BBN approach, GIS, and landscape ecology analytics can be used to assess the influence of green space configuration on ES trade-offs and synergies.

Overall, the result from this study suggests that landscape configuration characteristics affect ecosystem service trade-offs and synergies and the provision of ES and that a core set of landscape metrics could be used to assess the influence of landscape configuration on ecosystem service trade-offs and synergies. A BBN modelling approach might be an efficient method to assess the influence of potential drivers on ES trade-offs and synergies in complex urban landscapes. The approach allows to assess the sensitivity of ecosystem service trade-offs to different landscape structural features, thus providing ecological understanding that is relevant to planning decisions and landscape-scale

research. This study provides an understanding of the influence of habitat configuration characteristics on ES trade-offs.

5.3 Objective 3: The Influence of Landscape Connectivity on Ecosystem Service Trade-offs and Synergies

Chapter 4 explains the third objective and addresses the question, “What decision support tools might help in the urban planning process for predicting ES trade-offs and synergies and does landscape connectivity affect ES trade-offs and synergies?” This research uses a BBN modelling approach to assess whether connectivity drives ecosystem service trade-offs and synergies. Connectivity refers to the degree to which the landscape facilitates or impedes movement across resource patches (Taylor et al., 1993). In landscape ecology, landscape connectivity includes structural connectivity and functional connectivity. Structural connectivity is a physical attribute of the landscape (e.g. the configuration of land cover types or habitats) and is usually measured using landscape metrics such as patch size and patch isolation. Functional connectivity is organism-orientated, where behavioural responses are interpreted to suggest whether landscape patches function as connected from the perspective of the organism (LaPoint et al., 2015).

In this research, to represent connectivity a land use land cover map was used with circuit theory to produce a cumulative current map (Figure 4.3). Habitat suitability and resistance maps to represent connectivity were based on great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*) movements and taken as indicators of the urban landscape’s ability to facilitate wildlife movement. This research applied circuit theory to model functional connectivity. The landscape resistance map was based on its relative unsuitability of land cover for use by species to traverse the landscape (i.e. more suitable habitat is assigned a lower resistance value and vice versa) and the resistance values assigned based on LULC class.

It is theorised that landscape connectivity change affects the provision of ecosystem services and could drive trade-offs and synergies between services

and may form ES bundles that act in similar or dissimilar ways as connectivity changes (Mitchell, Bennett and Gonzalez, 2013). Studies suggest that decreased connectivity will have negative effects on ES provision.

This study used a BBN modelling approach to assess the influence of habitat structural features (patch area, connectivity and bird species abundance) on ES trade-offs and synergies and ES provision (Figure 4.2). The sensitivity of the model output to the predictors was assessed in order to explore the relative influence of those predictors in determining predicted ES trade-offs and synergies. This study used empirical abundance data to assess the sensitivity of ES trade-offs to bird species abundance. Conditional probability heat maps showed that bird species richness had stronger relationships with ES trade-offs predictions compared to bird abundance. This study is significant as it highlights the importance of functional connectivity of green space.

The findings demonstrate that patch area and connectivity affect ES trade-offs and synergies and the provision of ES. Connectivity was found to be the most influential variable in determining two of three ES trade-offs and synergies (Table 4.1). Low patch area and low to moderately low connectivity were associated with high levels of ES trade-offs and synergies predictions. Therefore, this study shows that connectivity exerts a particularly strong influence on ES trade-offs and synergies.

Conditional probabilities (Figure 4.4) support the expectation that nutrient retention and carbon storage trade-offs, habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies will be greater in patches with low patch area and with low to moderately low connectivity. The mechanisms by which ES trade-offs are created may be driven by a shared driver, i.e. connectivity (Bennett et al., 2009). Nutrient retention and carbon storage trade-offs were most sensitive to connectivity (Table 4.1). Nutrient retention and carbon storage trade-offs may be driven by connectivity as a result of land use and land cover changes to the structure and arrangement of land cover types, as most likely land cover types in urban areas have been modified.

Low levels of nutrient retention and high levels in carbon storage were associated with woodlands, whereas high levels of nutrient retention and low levels of carbon storage with grasslands. High levels in nutrient retention were greater on grasslands areas than woodlands. Conditional probabilities support the expectation that high levels of nutrient retention and low levels of carbon storage will be greater with low connectivity, suggesting that low connectivity supports high levels of nutrient retention (Figure 4.4). An increase in connectivity through the extensive modification of land cover would correspond to an increase in vegetation cover (woodland), and subsequently lower nutrient retention and carbon storage trade-offs. This study shows that habitat connectivity affects ES trade-offs. The BBN modelling approach proved to be an efficient method for predicting ES trade-offs and synergies. The model is able to predict where trade-offs among ecosystem services might occur. This study shows that habitat connectivity affects ES trade-offs and synergies.

Habitat quality and pollinator abundance trade-offs were most sensitive to connectivity. This suggests that connectivity may be a key driver of habitat quality and pollinator abundance trade-offs. Connectivity depends on the physical and functional connection between patches and the arrangement of land cover types. Habitat quality depends on the habitat's proximity to land uses. In urban areas, it has been found that pollinator abundance was prevalent due to the presence of a variety of habitats for nesting and foraging for pollinators (Baldock et al., 2019). The mechanisms by which habitat quality and pollinator abundance trade-offs are created may be driven by patch area and connectivity which affect habitat quality and pollinator abundance. The spatial arrangement of land cover types influences the provision of ES, which will either have positive or negative effects on service flow depending on the service in question. Human activities that alter landscape connectivity such as habitat fragmentation can affect habitat quality and pollinator abundance. Habitat quality is enhanced by natural and semi-natural land cover, whereas pollinator abundance is enhanced by the availability of a variety of habitats. Conditional probabilities support the expectation that in areas with low connectivity and low patch area, habitat quality will be high. The habitat quality

and pollinator abundance trade-offs appeared to be driven by connectivity, landscape structure and land use patterns. An increase in connectivity through the extensive modification of land cover would correspond to an increase in woodland areas (i.e. suitable habitat for bird flow), and subsequently lower habitat quality and pollinator abundance trade-offs. This study shows that connectivity affects ES trade-offs.

Potential soil erosion, water supply synergies were sensitive to patch area and connectivity. High levels of potential soil erosion and water supply synergies predictions were associated with moderately low connectivity and low patch area (Figure 4.4). A reduction in patch area and connectivity would result in a decrease of erosion regulation and an increase in vegetation-field edge effects (Mitchell et al., 2015). Erosion regulation is dependent on the flow of water and a decrease in habitat connectivity of vegetation cover as described here would result in an increase in water flow and soil erosion. These synergies may be driven by a simultaneous response to the same driver of change i.e. connectivity and by an interaction between services (Bennett et al., 2009). Impervious land increases surface runoff and decreases water infiltration. Large patches of vegetation protect larger areas from soil erosion and allows the recharge of the water table (Leitão et al., 2006). Conditional probabilities support the expectation that in areas with low patch area and moderately low connectivity, soil erosion and water supply synergies will be high. An increase in connectivity through the extensive modification of land cover would correspond to an increase of woodland areas (i.e. suitable habitat for bird flow), and as a result a decrease in the levels of soil erosion and water supply services as woodland areas mitigate surface runoff and protect from soil erosion. This study shows that ES trade-offs and synergies are affected by green space patterns, connectivity and ecological processes.

This study emphasises the importance of patch area and connectivity of urban green space in the provision of ES. The evidence suggests that patch area and connectivity affect ES trade-offs and synergies. This research supports the assertion that connectivity affects the provision of ES (Mitchell, Bennett and Gonzalez, 2013). This study contributes to the effective mapping of habitat

connectivity as a cumulative current map using circuit theory for *P. major* and *C. caeruleus* (Grafius et al., 2017). This research shows that an integrated BBN modelling approach provides a method for predicting ES trade-offs and synergies. The study shows that habitat connectivity enhances ES provision. The BBN modelling approach can be used to assess the influence of connectivity on ES trade-offs. This study shows that BBN models can be used to model ES trade-offs of changing urban land use.

Overall, the results suggest that landscape connectivity exerts a strong influence on nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and soil erosion and water supply synergies. The BBN modelling approach has potential value as a method of ES trade-offs and synergies prediction in complex landscapes. The general framework can be used to test the influence of potential drivers on ES trade-offs and synergies. The BBN approach can be used to assess the sensitivity of ES trade-offs and synergies to habitat structural features, thus providing ecological understanding that is relevant to planning decisions and landscape sustainability.

5.4 Contribution to Landscape Ecology Science in Urban Ecosystems

This research is among the first comparative studies to analyse how ecosystem services bundle at a fine scale (2 m) in the combined urban area of three large towns. The trade-offs and synergies between ecosystem services were identified and analysed. Trade-offs were found between nutrient retention and carbon storage, habitat quality and pollinator abundance, whereas synergies were found between soil erosion and water supply services. The ES clustered in ES bundles and exhibited distinct geographic patterns. This empirical information contributes to further advancement of theory and method in the study of ES provision in urban areas and the formation ES bundles. This study helps us understand how ES interact to form ES bundles and determines the ES gradients along which the entire bundle of ecosystem services changed. Subsequently, this study provides

a BBN modelling approach for predicting ES trade-offs and synergies and used it to test the relationships between landscape configuration and ES trade-offs and synergies. A sensitivity analysis was conducted to explore the relative influence of habitat configuration features in determining predicted ES trade-offs and synergies. This study has contributed to the development of a core set of landscape metrics as potential indicators for ES trade-offs and synergies assessment. This study helps us understand how habitat configuration influences ES trade-offs and synergies and ES provision. This study used a BBN modelling approach to assess whether habitat connectivity affects ES trade-offs and synergies. Circuit theory was used to model landscape connectivity. The evidence presented supports the application of theory and methods to analyse, predict and develop BBN models as decision support tools for the use of landscape planning and ES management and ES provision in complex urban landscapes. This study has contributed to the development of ecosystem service modelling, prediction and demonstrated the feasibility of using a BBN approach to assess the influence of potential drivers on ES trade-offs and synergies. This work helps us understand how landscape configuration and connectivity affect ES trade-offs and synergies. The modelling approach has potential value as a method of ES trade-offs prediction in complex urban landscapes. This is particularly important in order to understand the influence of potential drivers on ES provision.

5.5 Implications

The findings of this study have a number of important implications for future practice as follows:

5.5.1 Social

The study showed that ecosystem services cluster to form ecosystem service bundles with distinct geographic patterns and composition. Ecosystem service-

bundle analysis can identify areas on a landscape where ecosystem management has produced exceptionally desirable or undesirable sets of ecosystem services (Raudsepp-Hearne, Peterson and Bennett, 2010). The landscape distribution of ecosystem services may correspond to predictable socio-ecological subsystems and associated land-use types. Bundles capture how different services interact. The ES within the bundles can interact with each other, potentially leading to synergies and trade-offs, although there may be limits on the extent of realisation of the synergies due to constraints on the ability of the ecosystem to deliver each service to the desired level and/or management practices and/or the negative interactions between certain ES. ES trade-offs or synergies only occur if the considered ES interact with each other (Felipe-Lucia, Comín and Bennett, 2014; Turkelboom et al., 2015). ES synergies and trade-offs are causally linked. This may be due to simultaneous responses to the same driver or to true interactions among ES (Bennett, Peterson and Gordon, 2009). ES bundle analysis may provide insights into management practices or policies to improve the provision of ES. For example, in the correlation analysis there was a weak positive correlation between habitat quality and carbon storage (Table 2.3). However, this pattern was not evident in the potential soil erosion bundle type where the mean values of carbon storage were not reflected in the average values of habitat quality and there might be the potential to enhance carbon storage in these areas (Figure 2.3; Chapter 2). The findings of this research may assist in ES management and landscape planning. Ecosystem service-bundle analysis allows to identify areas where ecosystem service provision falls below known thresholds and reveals which ES are vulnerable to trade-offs (Figure 2.3). An understanding of ES bundles, including the important social and ecological drivers, feedbacks, and management schemes, may allow for the prediction and modelling of ES bundles, predict where and when ES trade-offs might take place, and help reduce undesirable trade-offs and enhance desirable synergies.

5.5.2 Urban Planning and Policies

The findings of this study show that landscape configuration affects the provision of ES and could drive ES trade-offs and synergies. This study emphasises how the use of GIS, landscape ecology methods and a BBN modelling approach can be used to assess the influence of habitat configuration on ES trade-offs and synergies (Chapter 3). The model allows to test whether habitat configuration features drive ES trade-offs (or synergies) and assess the relative importance of those variables that influence trade-offs (or synergies) between services.

The results of the sensitivity analysis indicated that core area was the most influential predictor for two of three ES trade-offs and synergies at the patch level at a 2 m resolution (Table 3.4). At the patch level, low levels of predicted nutrient retention and high levels of carbon storage were associated with low core area and low Euclidean distance (Figure 3.2; Chapter 3). Suburban green areas were mainly associated with large patches of grassland, whereas urban areas were associated with small patches of grassland and trees. The conditional probability heat maps showed that high levels of habitat quality and pollinator abundance trade-offs are expected in areas with a large core area. Large patches of contiguous grassland in the suburbs were associated with high levels of habitat quality and low levels of pollinator abundance. The high levels of trade-offs between habitat quality and pollinator abundance could be driven by large core areas of grassland and distance from built-up areas. The low levels of pollinator abundance could be due to a lower proximity to likely nesting sites for pollinator species and lower abundance of floral resources (Gunnarsson and Federsel, 2014; Baldock et al., 2015). This study provides an effective and practical application of how habitat configuration affects ES trade-offs. It provides information to predict ES trade-offs and how ES trade-offs predictions respond to the variation of urban landscape configuration features.

The findings demonstrate that landscape configuration characteristics affect the provision of ES. Predicted nutrient retention and carbon storage trade-offs were most sensitive to contiguity index. Habitat quality and pollinator

abundance trade-offs and soil erosion and water supply synergies predictions were most sensitive to core area (Table 3.4; Chapter 3). The ES trade-off and synergy predictions could be due to green space configuration (i.e. the spatial arrangement of cover types), land-use changes and ecological processes.

This study emphasises the use of a BBN modelling approach to assess the influence of landscape configuration on ES trade-offs (Landuyt et al., 2013). The approach provides useful information to assess the sensitivity of ES trade-offs and synergies to different habitat configuration features. It allows to test the influence of potential drivers on ES trade-offs and ES provision. This could provide insights into policies or management approaches to mitigate trade-offs and enhance synergies. This study shows that landscape configuration and ecological processes affect ES trade-offs. This could be used by planners and land managers to improve green space design.

This study used principal component analysis to identify a core set of landscape metrics as potential indicators for ES trade-offs and synergies assessment in urban areas (Table 3.3; Appendix B, Table B.5). The core set of metrics could be used as potential indicators for assessment of nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and water supply and potential soil erosion synergies in similar urban areas. The findings have implications in urban planning. The results from this research could provide insights to planners and managers for a better distribution of ES, guide urban planning and how landscape structure can be modified to plan for sustainable cities.

This study used a BBN modelling approach to assess the influence of landscape configuration characteristics in determining predicted ES trade-offs and synergies. The findings of this research might assist in green space planning and management. The model allows to predict ES trade-offs and synergies and model ES trade-offs predictions of changing urban land use. The modelling approach has potential value as a method of ES trade-offs and synergies prediction in complex landscapes and could be used to assess how ES trade-offs

respond to the variation of urban landscape configuration features, and thereby relevant to planning considerations and landscape-scale research.

5.5.3 Green Space Conservation

This study highlights the importance of landscape connectivity and ecological networks. The BBN modelling approach allows to test the relationships between connectivity and ES trade-offs and synergies. The approach allows to assess the sensitivity of ES trade-offs and synergies to landscape connectivity. The sensitivity of model output to the predictors (i.e. connectivity, patch area and bird species abundance) is assessed in order to explore the relative influence of those drivers in determining predicted ES trade-offs and synergies. The model allows to test whether landscape and patch structural features drive ES trade-offs (or synergies).

This study highlights the importance of landscape connectivity and ecological networks. The BBN modelling approach allows to test the relationships between connectivity and ES trade-offs and synergies. The approach allows to assess the sensitivity of ES trade-offs and synergies predictions to landscape connectivity. Studies suggest that decreased connectivity will have negative effects on ES provision (Mitchell, Bennett and Gonzalez, 2013). The findings suggest that habitat connectivity and patch area influence ES trade-offs and synergies. High levels of nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and potential soil erosion, water supply synergies predictions were associated with low to moderately low connectivity (Figure 4.4).

This study provides guidelines to produce a cumulative current map to represent landscape connectivity of urban green space using circuit theory (Figure 4.3). The method is generally applicable to other target species. The findings demonstrate that connectivity affects ES trade-offs and synergies and the provision of ES. Connectivity was found to be the most influential variable in

determining two of three ES trade-offs and synergies (Table 4.1; Chapter 4). The ES trade-offs and synergies predictions could be due to habitat configuration (i.e. the spatial arrangement of cover types), connectivity and ecological processes.

The findings have implications in green space design, ecological networks and sustainable ecosystem management. Green space can mitigate from climate change risks and enhance ES provision. The findings demonstrate that connectivity is an influential determinant of nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs. Connectivity is important in the design of ecological networks in urban areas. The structure of an ecological network and how the system components are connected is important (Dakos et al., 2015). The findings suggest that for the considered ES, high levels of trade-offs and synergies predictions are expected in areas with low patch area and with low to moderately low connectivity. This implies that large and better-connected patches of vegetation increase ES provision. Enhancing connectivity and green space can mitigate climate risks and build a resilient supply of ES. ES buffer against climate change, flood risk and landslides. Enhancing connectivity is believed to improve the ability of an urban ecological infrastructure to provide ES and in turn enhance its ability to mitigate and adapt to climate change (Lafortezza et al., 2013). Green infrastructure and nature-based solutions can respond to environmental change and enhance the provision of ES (Lafortezza et al., 2018). Cities will need to plan and manage urban ecosystems for enduring supply of services in dynamic urban systems affected by global environmental change. Improving green infrastructure and ES through urban planning and management can increase resilience (McPhearson, Hamstead and Kremer, 2014).

This study highlights the importance of connectivity in urban areas. Patch area and connectivity affect ES trade-offs (and synergies) and ES provision. This research might provide insights in the planning of green space and green infrastructure (Derkzen, van Teeffelen and Verburg, 2015; Peña et al., 2018). Enhancing green infrastructure and connectivity may enhance the provision of ES. Improving green infrastructure and connectivity is a prerequisite to its ability to mitigate climate change and in turn increase ES provision (Lafortezza et al.,

2013). Including ecological networks in green infrastructure planning can confer resilience to ES. Green infrastructure and nature-based solutions can respond to environmental change and enhance the provision of ES and the benefits they provide by developing resilient landscapes and cities (Lafortezza et al., 2018). Understanding how connectivity affects the provision of ES would provide valuable information for the design, management and restoration of landscapes (Mitchell, Bennett and Gonzalez, 2013). Managing multiple ES requires an understanding of the underlying mechanisms and motivations for trade-offs and synergies.

This study proposes a BBN modelling approach to test the relationships between landscape connectivity and ES trade-offs and synergies. The approach allows to assess the sensitivity of ES trade-offs and synergies to landscape connectivity. This study addresses the important topic of connectivity and how models can be appropriately used for this topic. The BBN modelling approach could be used to assess how ES trade-offs respond to the variation of habitat structural features and potential drivers, and thereby relevant to planning considerations and landscape-scale research.

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6 CONCLUSIONS AND FURTHER RESEARCH

This chapter summarises the project as a whole. Additionally, investigations for future understanding of ES bundle analysis and the influence of landscape configuration and connectivity of urban green space are presented in the Further Research section. The aims of this research are to i) assess whether ecosystem services form ecosystem service bundles at a 2 m spatial resolution in urban areas and identify and analyse the composition of ecosystem service bundles and assess whether there are specific spatial trade-offs and synergies between ecosystem services, ii) test a BBN modelling approach to assess whether habitat configuration characteristics affect ES trade-offs and synergies, and iii) assess whether landscape connectivity affects ES trade-offs and synergies.

Firstly, this study emphasises the use of ES modelling tools, Geographical Information Systems (GIS) and spatial analysis to assess whether ecosystem services form bundles and describes their geographical distributions and interactions in urban landscapes at a 2 m spatial resolution. The research results contribute to a better understanding of the interactions between multiple ecosystem services across urban landscapes. This research demonstrates the application of multivariate techniques to map ES bundles and analyses the trade-offs and synergies between ES. Consequently, this facilitates the understanding of their distinct geographic patterns and associated socio-ecological subsystems.

Secondly, a BBN modelling method was used to assess the sensitivity of ES trade-offs and synergies to landscape configuration metrics. This study demonstrates that landscape configuration of urban green space drives nutrient retention and carbon storage, habitat quality and pollinator abundance trade-offs and soil erosion and water supply synergies and affects ES provision. Evidence suggests that the trade-offs and synergies are driven by landscape configuration (i.e. fragmentation), land-use changes and ecological processes. The modelling approach provides a method for assessing the influence of configuration on ES trade-off predictions in complex urban landscapes. This can provide policies or

management approaches to mitigate trade-offs and enhance synergies and improve the provision of multiple ecosystem service across the landscape.

Thirdly, circuit theory was used to model functional connectivity and a BBN modelling framework was used to assess the sensitivity of predicted ES trade-offs and synergies to landscape connectivity. The research results demonstrate that two of three ES trade-offs and synergies were influenced by connectivity. The findings suggest that connectivity exerts a particularly strong influence on ES trade-offs and synergies. The trade-offs and synergies could be driven by habitat configuration (i.e. fragmentation), connectivity and ecological processes. The development of prediction models for predicting ES trade-offs of urban green space provide valuable information for the design, management and restoration of landscapes.

ES modelling tools, spatial analysis, connectivity modelling tools, and BBN modelling approach contribute to a better understanding of ES provision in complex urban landscapes. This study uses a modelling framework for predicting ES trade-offs and synergies in complex urban landscapes. This study is important and timely as it emphasises the influence of landscape and patch structural characteristics, configuration and connectivity, on ES trade-offs and synergies and the provision of ES. Furthermore, this research proposes a BBN modelling approach for predicting ES trade-offs and synergies. The models have a potential as a planning approach and decision support tools to help in maintaining a supply of ES and to assess where and when ES trade-offs might take place across the urban landscape.

Recommendations for Future Research:

The concept, framework, methods and practical demonstration of the integrated models in this research are documented for three large towns in the UK. Nevertheless, several recommendations below address the development of the integrated model in a global aspect. The recommendations are interrelated,

recommending specific actions to researchers and are sequential for future studies on ES in urban areas.

- i. Analyse ES bundles at different scales and identify spatial trade-offs and synergies among ecosystem services across the landscape.
- ii. Identify the other driving forces and assess factors such as ecological, socio-economic, cultural, physical, land use activities and urban plans which could drive ES trade-offs and synergies.
- iii. The modelling approach could be used for predicting ES bundles in urban areas and assess how habitat structural features affect ES bundles.
- iv. The modelling approach could be used for predicting ES trade-offs in urban areas.
- v. A spatiotemporal analyses of ES bundles and scenario analysis of ecosystem services.
- vi. Compare BBN modelling with other prediction models such as Random Forests (RF), Boosted Regression Trees (BRT), Artificial Neural Networks (ANN).
- vii. Investigate how climate interacts with and drives changes in urban ES and how these changes affect the supply of ES.
- viii. Investigate how land use patterns and climate change affect ES bundles.
- ix. Develop ecological networks for other target species and identify green space priority areas for conservation and landscape restoration.
- x. Investigate the influence of land use changes on ES provision of urban green infrastructure.
- xi. Development of green infrastructure and ecosystem services concepts for green space planning and biodiversity conservation.

APPENDICES

Appendix A Bundling Ecosystem Services at a High Resolution in the UK



Figure A.1 The maps show at 2 m resolution the Nutrient retention and Carbon storage trade-offs for the towns of Bedford, Luton and Milton Keynes.

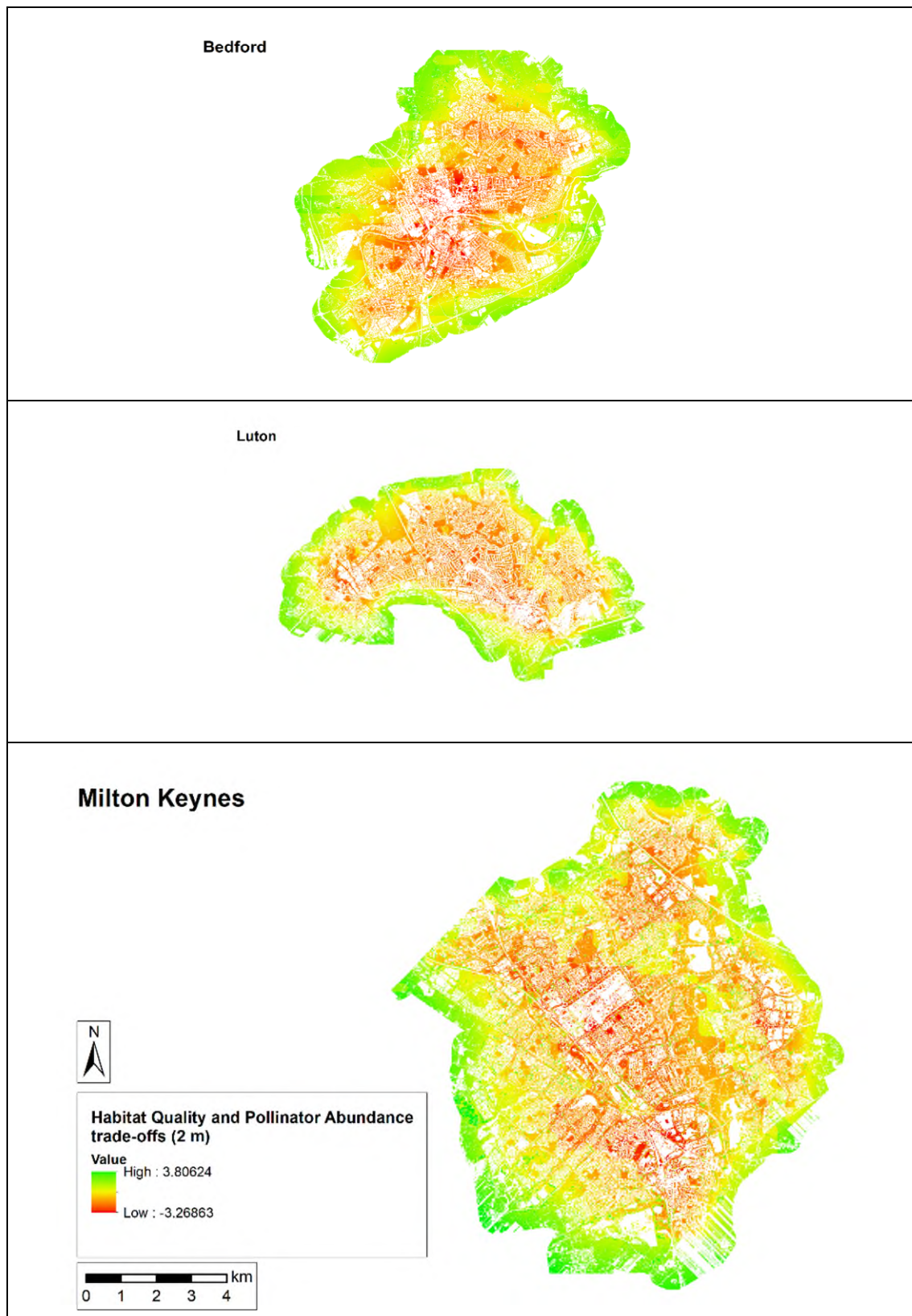


Figure A.2 The maps show at 2 m resolution the Habitat quality and Pollinator abundance trade-offs for the towns of Bedford, Luton and Milton Keynes.

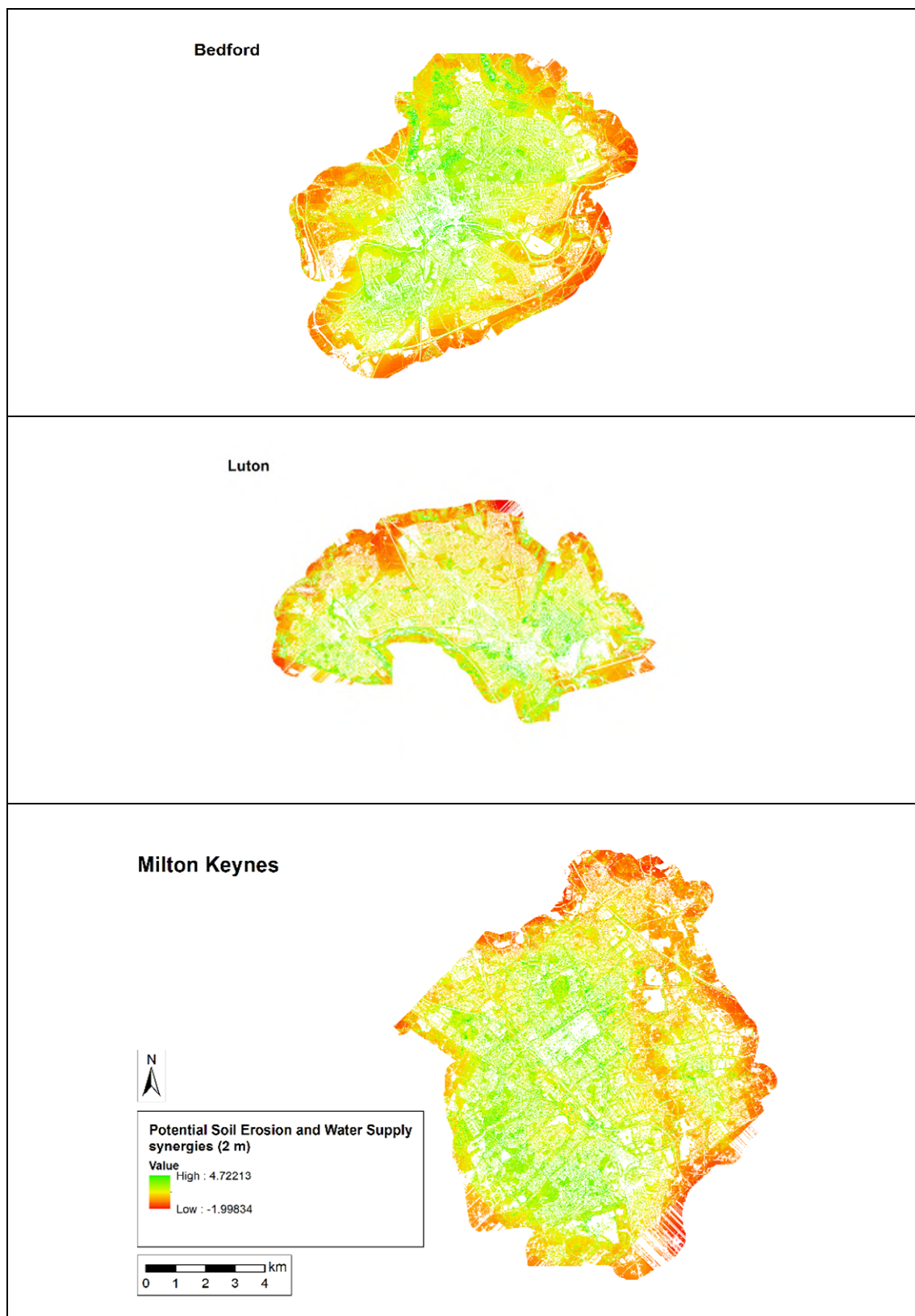


Figure A.3 The maps show at 2 m resolution the Potential soil erosion, Quick flow and Baseflow synergies for the towns of Bedford, Luton and Milton Keynes.

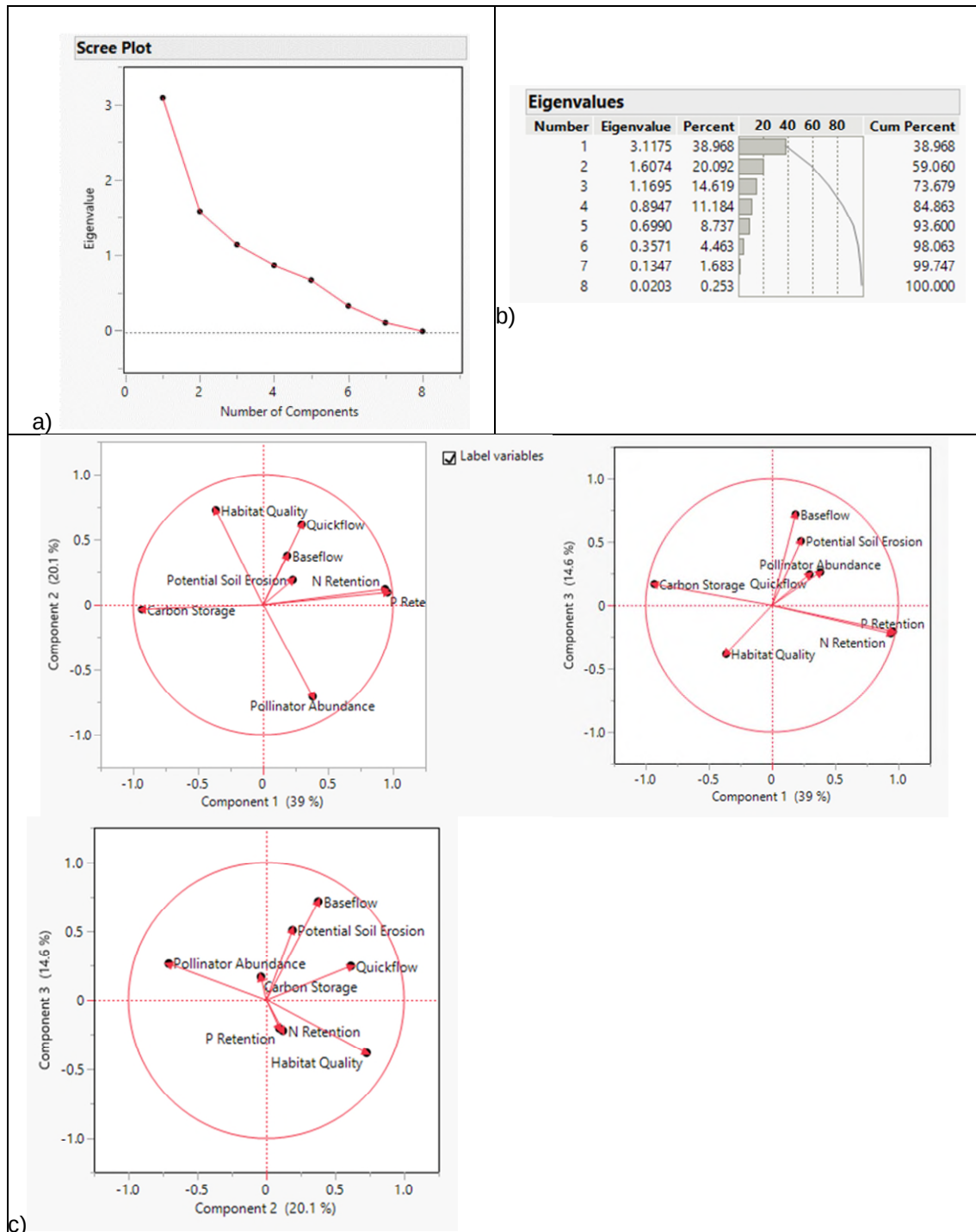


Figure A.4 Scree plot (a) showing principal components with eigenvalues > 1 according to the Kaiser-Guttman criterion (Legendre and Legendre, 1998). Principal component eigenvalues and cumulative percentage table (b) of variation explained by each principal component. PCA loading plot graphs for principal components 1 and 2, principal components 1 and 3, and principal components 2 and 3 (c). The first three principal components were used in analysis.

Table A.1 Spatial coverage of bundles for the town of Bedford

	Number of grid cells *	Land cover (percentage)
1	1667465	20.77
2	3215743	40.06
3	2805131	34.94
4	339934	4.23

* Grid cell size was 2 m

Table A.2 Spatial coverage of bundles for the town of Luton

	Number of grid cells *	Land cover (percentage)
1	2125905	20.74
2	3234973	31.56
3	3727644	36.37
4	1161991	11.34

* Grid cell size was 2 m

Table A.3 Spatial coverage of bundles for the town of Milton Keynes

	Number of grid cells *	Land cover (percentage)
1	4217326	25.47
2	4357437	26.32
3	7009850	42.34
4	971799	5.87

* Grid cell size was 2 m

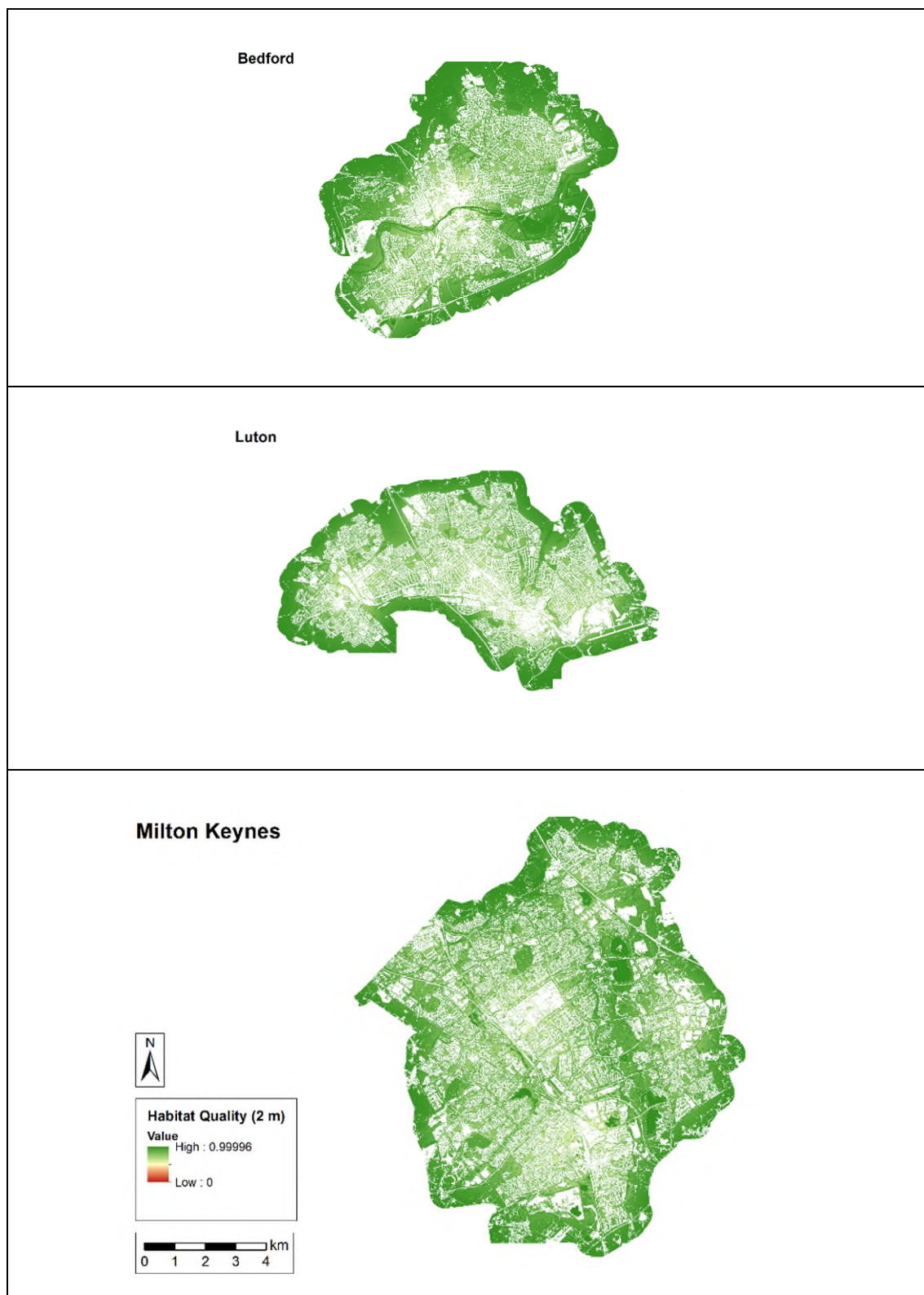


Figure A.5 The maps show the distribution of the ecosystem service indicator Habitat Quality for the towns of Bedford, Luton and Milton Keynes at 2 m resolution

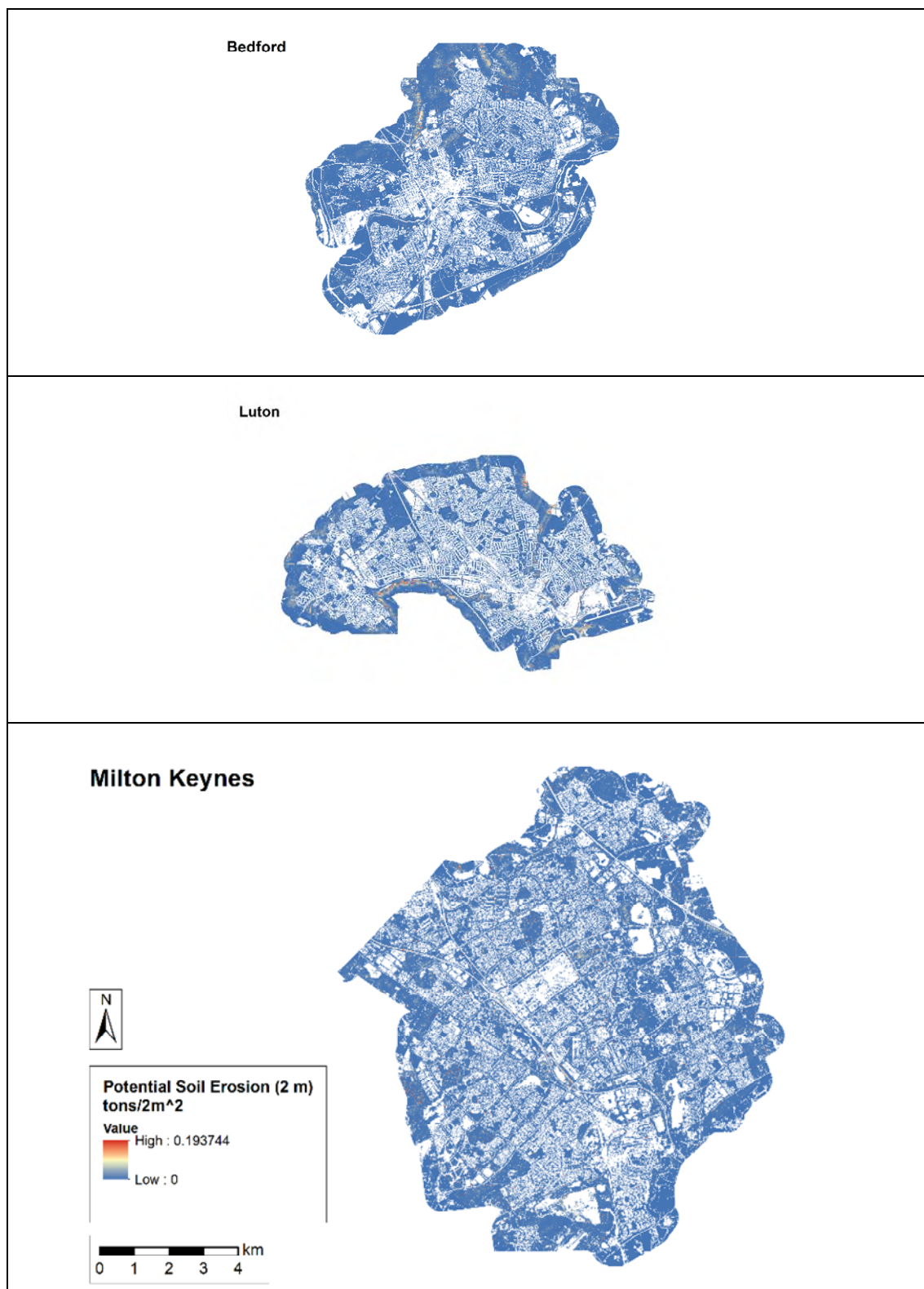


Figure A.6 The maps show the distribution of ecosystem service indicator Potential soil erosion for the towns of Bedford, Luton and Milton Keynes at 2 m resolution

Appendix B The Influence of Landscape Configuration on Ecosystem Service Trade-offs and Synergies

Table B.1 Landscape metrics at the patch level used in the analysis with acronyms, units and notes on interpretation.

Acronyms	Metric (units)	Notes
AREA	Patch area (ha)	
PERIM	Patch perimeter (m)	The perimeter of a patch is treated as an edge
GYRATE	Radius of Gyration (m)	A measure of patch extent. Sensitive to patch area.
PARA	Perimeter area ratio	A measure of shape complexity
SHAPE	Shape index	A measure of shape complexity
FRAC	Fractal dimension index	A measure of shape complexity
CONTIG	Contiguity index	Assesses the spatial connectedness of cells within a grid-cell. Favours large, contiguous patches.
CORE	Core area (ha)	The area in the patch greater than the specified depth-of-edge distance from the perimeter. In this case area < 5 m from patch edge.
NCORE	Number of core areas	Number of disjunct core areas contained within the patch boundary.
CAI	Core area index (%)	Patch core area divided by total patch area.
ENN	Euclidean nearest neighbour distance (m)	Distance to nearest patch of the same type.

Table B.2 Landscape metrics at the class level used in the analysis with acronyms, units and notes on interpretation.

Acronyms	Metric (units)	Notes
PLAND	Percentage of landscape (%)	A measure of the proportional abundance of each patch type in the landscape
LPI	Largest Patch index (%)	It is a measure of dominance of the largest patches.
AREA_MN	Mean patch size (ha)	It is a measure of mean patch size
AREA_AM	Area-weighted mean patch size (ha)	It is a weighted form of mean patch size
GYRATE_MN	Mean patch radius of gyration (m)	It is the mean patch radius of gyration
GYRATE_AM	Area-weighted Mean patch radius of gyration (m)	It is the mean patch radius of gyration where each patch is weighted by its area. It is a measure of landscape continuity (correlation length).
CA	Total (Class) area (ha)	It is a measure of the amount of a particular patch type within the landscape.
CPLAND	Core area percentage of landscape (%)	Sum of core areas of each patch of corresponding patch type as a percentage of total landscape
TCA	Total core area (ha)	Total core area of corresponding patch type
CORE_MN	Mean Core area (ha)	Mean core area m
SHAPE_MN	Mean Shape index	A measure of shape complexity
SHAPE_AM	Area-weighted mean shape index	A measure of shape complexity.

FRAC_MN	Mean patch fractal dimension	It reflects shape complexity
FRAC_AM	Area-weighted mean patch fractal dimension	Area-weighted mean patch fractal dimension. It is used to verify SHAPE_AM
LSI	Landscape shape index	A measure of shape complexity
ENN_MN	Mean Euclidean nearest neighbour distance (m)	It indicates mean patch distance between nearest neighbours of corresponding type.
ENN_AM	Area-weighted mean Euclidean nearest neighbour distance (m)	It is a weighted form of patch distance between nearest neighbours
TE	Total edge (m)	It is a measure of total edge length of a particular patch type.
ED	Edge density	It indicates fragmentation and edge effects. Meters per hectare.
PD	Patch density	It indicates spatial heterogeneity. Number of patches per 100 hectares.
MESH	Effective Mesh Size (ha)	It indicates fragmentation. It provides a relative measure of patch structure.
PLADJ	Percentage of like adjacencies (%)	It measures the degree of aggregation of the focal patch type.
AI	Aggregation index (%)	Measures the frequency that patch pairs of different class types are next to each other.
COHESION	Patch cohesion index	It is a measure of habitat connectivity. Measures the physical connectedness of the corresponding patch type.

Table B.3 Result of the factor analysis for the first three factors after Varimax rotation for the patch-level metrics. Significant values that meet $r > 0.7$ are in bold.

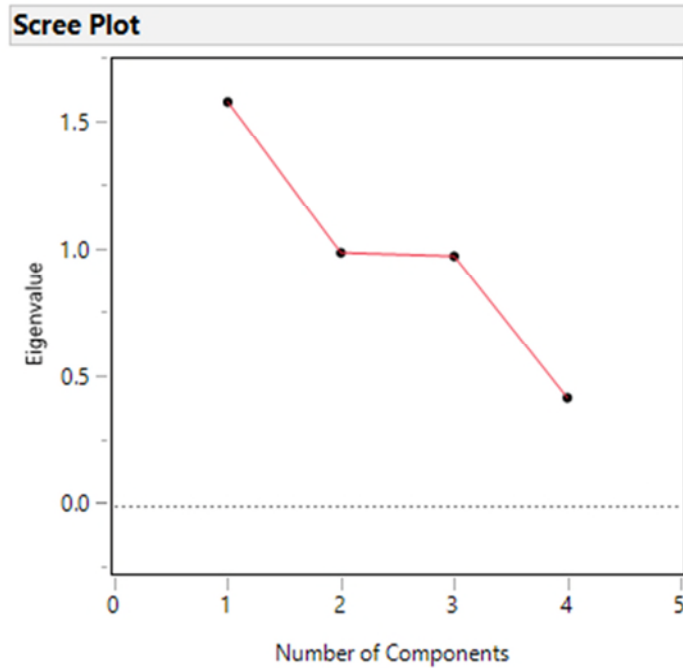
	Factor Number		
	1	2	3
Eigen value	4.86	2.50	1.00
% Cumulative variance explained	44.18	66.92	76.05
	Factor loadings (after varimax rotation)		
AREA	0.916	-0.080	0.010
PERIM	0.928	0.172	-0.057
GYRATE	0.785	0.494	-0.052
PARA	-0.053	-0.888	-0.103
SHAPE	0.376	0.760	-0.164
FRAC	0.031	0.773	-0.169
CONTIG	0.066	0.917	0.088
CORE	0.862	-0.120	0.021
NCORE	0.810	0.193	-0.052
CAI	0.528	0.256	0.097
ENN	0.008	-0.048	0.961

Table B.4 Result of the factor analysis for the first three factors after Varimax rotation for the class level metrics. Significant values that meet $r > 0.7$ are in bold.

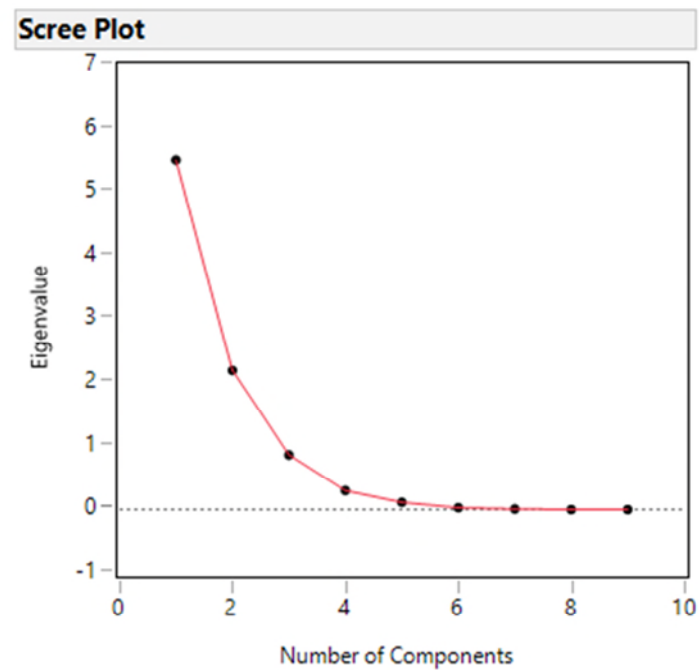
	Factor Number		
	1	2	3
Eigen value	15.86	4.61	2.22
% Cumulative variance explained	66.07	85.27	94.52
	Factor loadings (after varimax rotation)		
CA	0.8699	0.2478	0.4124
PLAND	0.8738	0.2478	0.4044
PD	0.2388	0.1859	0.9204
LPI	0.9653	0.1789	0.1797
TE	0.3379	0.3208	0.8644
ED	0.3414	0.3274	0.8579
LSI	0.0086	0.3578	0.9231
AREA_MN	0.8673	0.4435	0.1802
AREA_AM	0.9744	0.1435	0.1436
GYRATE_MN	0.2429	0.8728	0.2879
GYRATE_AM	0.9536	0.2364	0.1855
SHAPE_MN	0.0929	0.9226	0.3484
SHAPE_AM	0.6045	0.6488	0.1508
FRAC_MN	0.0962	0.8911	0.3585
FRAC_AM	0.0699	0.9075	0.3602
TCA	0.9718	0.1499	0.1633
CPLAND	0.9721	0.1493	0.1614
CORE_MN	0.9727	0.1542	0.1541
ENN_MN	-0.2033	-0.1896	-0.6964
ENN_AM	-0.2410	-0.5211	-0.7119
PLADJ	0.5646	0.7944	0.1635
COHESION	0.2480	0.9306	0.2551
MESH	0.9739	0.1386	0.1436
AI	0.5677	0.7929	0.1570

Table B.5 Result of the factor analysis for the first two factors after Varimax rotation for the class level metrics. Significant values that meet $r > 0.7$ are in bold. Highest loadings per factor are italicized.

	Factor Number	
	1	2
Eigen value	5.5015	2.9131
% Cumulative variance explained	61.128	85.496
	Factor loadings (after varimax rotation)	
LSI	0.02209	0.87640
AREA_MN	0.89260	0.40740
AREA_AM	0.98298	0.15935
SHAPE_MN	0.16684	0.87662
CORE_MN	0.98165	0.17478
ENN_MN	-0.19169	-0.71128
ENN_AM	-0.27409	-0.90116
COHESION	0.31694	0.81251
MESH	0.98302	0.15627



a)



b)

Figure B.1 Cumulative scree plots of the principal component analysis for the (a) patch level and (b) class level metrics.

Table B.6 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient retention and Carbon storage trade-offs (PC 1), Habitat quality and Pollinator abundance trade-offs (PC 2) and Potential soil erosion and Water supply synergies (PC 3) at a 2 m spatial resolution

	Error rate	Sensitivity (Percent in Variance Reduction)	
		<i>MESH</i>	<i>ENN_AM</i>
PC1	0.00%	96.20	17.40
PC2	0.00%	70.70	1.37
PC3	0.00%	97.50	27.30

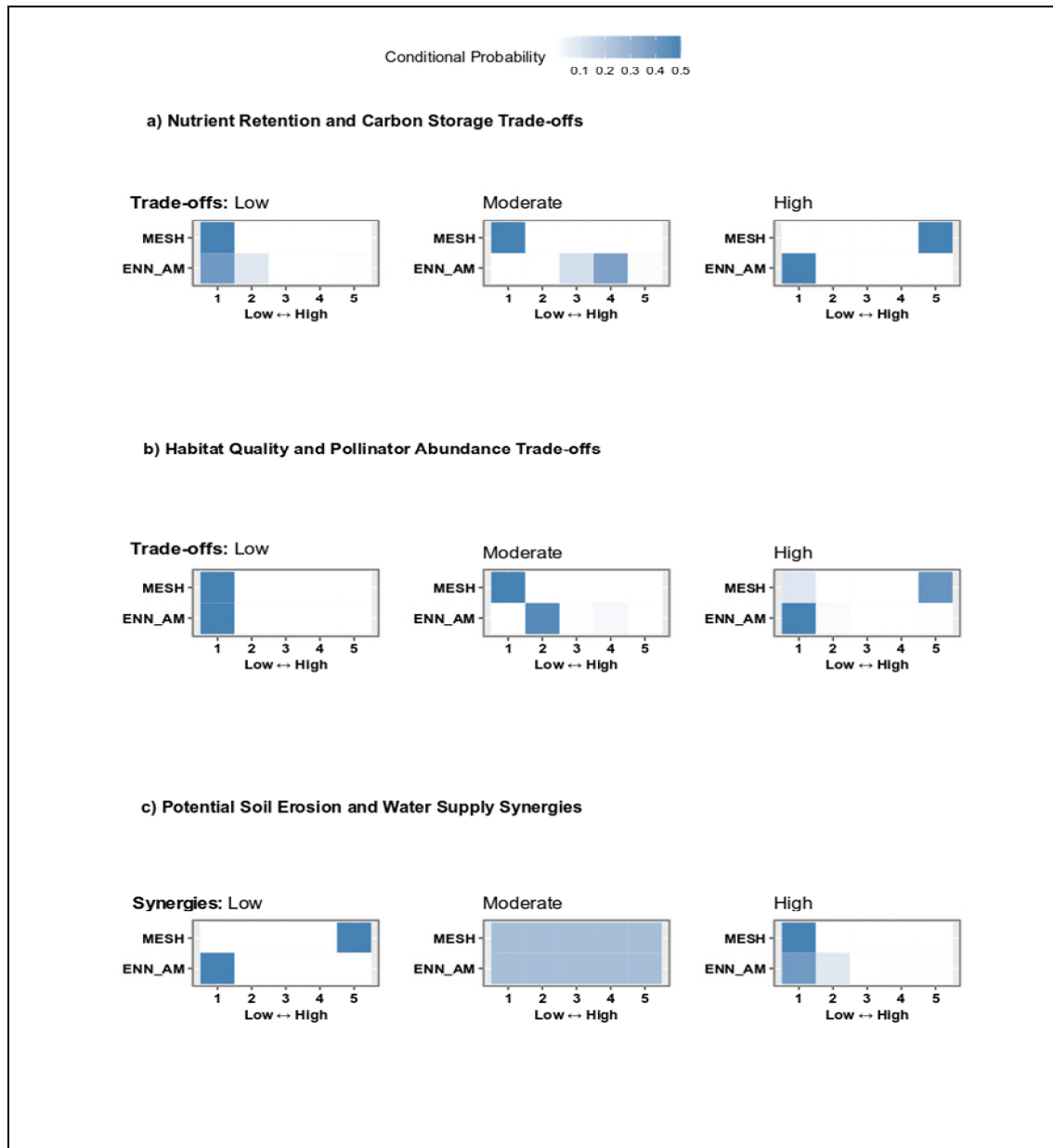


Figure B.2 Heat maps that visually depict the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (mesh size and ENN_AM; values of bin ranges are shown in Table B.7) and the predicted trade-offs (or synergies) of each ecosystem service trade-offs or synergies type. Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of spatial configuration values and predicted trade-offs (or synergies) represented by that cell in the heat map

Table B.7 Bin ranges for input parameter values in Figure B.2 heat maps of Bayesian model conditional probabilities

Bins	Low	Moderately low	Moderate	Moderately high	High
Effective Mesh Size (ha)	0-0.5	0.5-1	1-2	2-5	5-34.2
ENN_AM (m)	12-15	15-25	25-30	30-40	40-50

Appendix C The Influence of Landscape Connectivity on Ecosystem Service Trade-offs and Synergies

Table C.1 Results of case testing (error rate) and sensitivity analysis (percent in variance reduction as a metric of the relative importance of each input variable) on Bayesian Belief Network models for Nutrient Retention and Carbon storage Trade-offs (PC1), Habitat Quality and Pollinator Abundance Trade-offs (PC 2) and Soil erosion and Water Supply Synergies (PC 3).

	Error rate	Sensitivity (Percent in Variance Reduction)		
		<i>Connectivity</i>	<i>Bird Sp. Richness</i>	<i>Patch Area</i>
PC1	41.38%	7.34	3.34	4.42
PC2	48.28%	3.63	3.32	3.07
PC3	43.97%	2.01	2.56	1.74

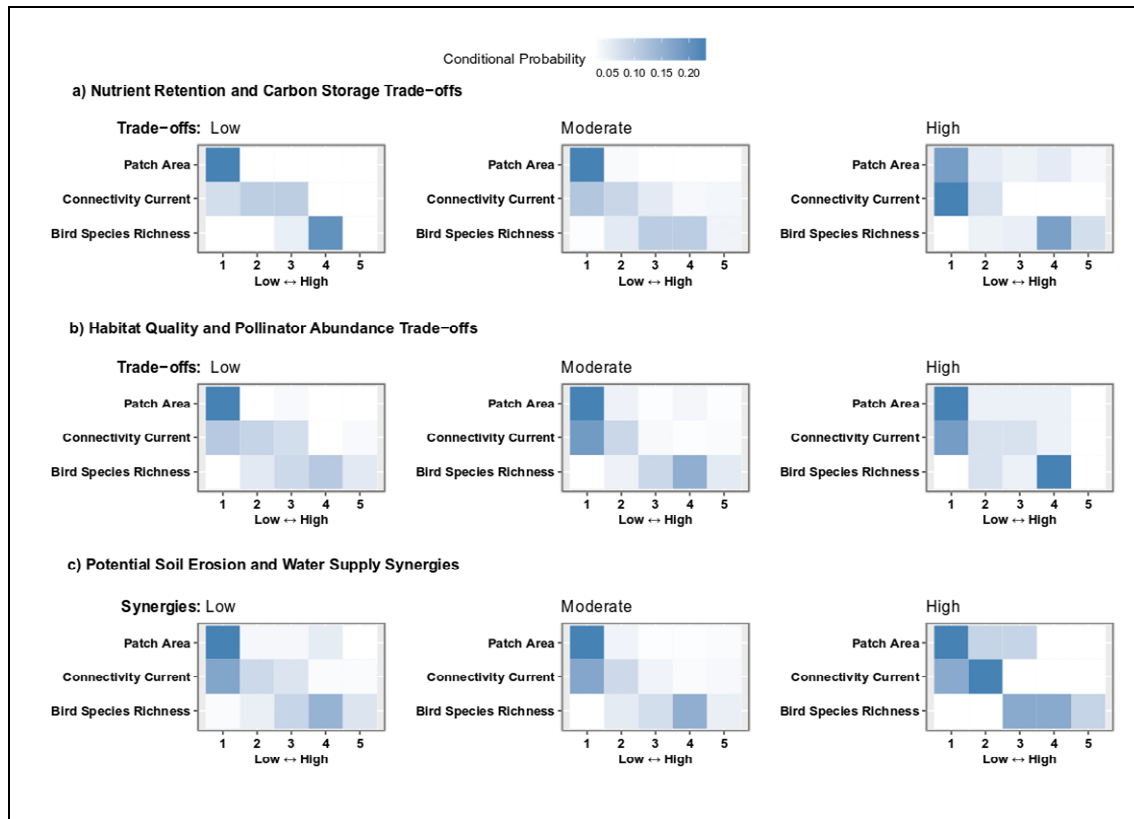


Figure C.1 The heat maps show the conditional probabilities driving each model. These represent the strength of the relationships between the input parameters (patch area, connectivity and bird species richness; values of bin ranges are shown in Table C.2) and the predicted trade-offs (or synergies) of each ecosystem service trade-offs or synergies type. Darker cells denote higher conditional probabilities, i.e. a higher likelihood of an outcome given that set of conditions, or a stronger relationship between the combination of input value and predicted trade-offs (or synergies) represented by that cell in the heat map

Table C.2 Bin ranges for input parameters in Figure C.1 heat maps of Bayesian model conditional probabilities.

Bins	Low	Moderately low	Moderate	Moderately high	High
Patch Area (ha)	0-1	1-5	5-10	10-100	100-150
Connectivity Current	0-0.001	0.001-0.002	0.002-0.003	0.003-0.005	0.005-1
Bird Sp. Richness	7-10	10-12	12-14	14-18	18-23