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Visions for woodland expansion in 21st Century Scotland:
alternative governance strategies and ecosystem service
implications

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Declaration

I declare that this thesis has been composed by myself, and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. My contribution and those of the other authors to this work are explicitly indicated below. I confirm that the appropriate credit has been given within this thesis where reference has been made to the work of others.

The work presented in Chapter 2 was previously published in *Forest Ecology and Management* as *Reviewing the evidence base for the effects of woodland expansion on biodiversity and ecosystem services in the United Kingdom* by Vanessa Burton (myself), Darren Moseley (co-supervisor), Marc Metzger (supervisor), Calum Brown (co-supervisor), and Paul Bellamy (RSPB). I carried out the entire research process and write-up of the manuscript with comments and guidance from supervisors. Paul Bellamy had a role in initiating the study based on a request from the RSPB.

The work presented in Chapter 3 was previously published in *Landscape Ecology* as *Green Gold to Wild Woodlands; understanding stakeholder visions for woodland expansion in Scotland* by

Vanessa Burton (myself), Marc Metzger (supervisor), Calum Brown (co-supervisor), and Darren Moseley (co-supervisor). I conceived and carried out the research and write-up of the manuscript with guidance and comments from supervisors. Further acknowledgements regarding assistance with the workshop process are given at the beginning of the chapter.

Signed

Date

Abstract

In order to tackle global challenges including climate change, biodiversity and habitat loss, deforestation and forest degradation, land system research needs to support decision making which helps to develop sustainable land use systems. In a Scottish context woodland expansion and multi-functionality in terms of ecosystem service (ES) provision are core aims of land use policy. However, there are conflicting objectives between stakeholders and research has struggled to quantify the synergies and trade-offs between these. There is a lack of understanding in terms of how to achieve ES multi-functionality, as well as considerable uncertainty with regards to the continuation of public support for different land uses after Brexit. This thesis aimed to understand the synergies and trade-offs between ES generated by woodland expansion under alternative stakeholder ‘visions’ – or ‘positive descriptions of ideal futures.’ Through exploring how these visions might be met, it also examined how governance might influence woodland expansion and ES provision. An interdisciplinary approach was adopted, combining evidence synthesis, stakeholder engagement, and agent-based modelling (ABM) to explore the effect of alternative stakeholder visions for woodland expansion on ES provision. In Chapter 2, a systematic review of evidence for the effect of woodland expansion on biodiversity and ecosystem services in a UK context found that currently the largest body of evidence exists for the effects of conifer plantations, and public benefits such as carbon sequestration and flood regulation.

Evidence gaps need to be filled in relation to a broader consideration of taxa and metrics for biodiversity, natural regeneration of native woodland, and effects on cultural and provisioning ES. Chapter 3 presents a mixed-method approach combining document analysis, a stakeholder workshop and semi-structured interviews, resulting in five distinct ‘visions’ for how woodland expansion might ideally take place. These illustrated a great deal of common ground between high-level stakeholders, but also important distinctions in terms of overall objectives, priority ES, and governance mechanisms with which visions might be achieved. In chapters 4 and 5, an established ABM framework was adapted to describe a new model, CRAFTY-Scotland. The elicited visions were represented within the model, in order to explore the ES implications and likelihood of meeting Scottish government targets for woodland expansion. Findings suggest that ABM offers a useful method for exploring normative visions, taking into account multiple ES and quantifying trade-offs between non-economic values. The results suggest that there could be largely positive effects of woodland expansion on ecosystem services, across visions. Trade-offs are quantified relating to declines in livestock and floral species diversity. However, all ecosystem services results are strongly dependent on the current data, knowledge, and modelling choices. Willingness of traditional and sporting estate managers to diversify has a strong influence on whether or not woodland cover targets are met. Key barriers to achieving targets appear to be the continued dominance of marginal agriculture and single-use management in the Highlands. Of the governance mechanisms represented within the model, the most successful include targeted annualised incentives for woodlands, diversified land management, and increased financial, human and social resources for local communities. Together, the findings suggest that more significant changes may be required to meet targets for woodland expansion, particularly in relation to highly valued ‘traditional’ Scottish landscapes. Any such changes should be debated at regional levels in participatory applications. Modelling approaches of this kind, combining spatially explicit data together with processes and governance of the land use system, are currently under-utilised and offer valuable decision support tools if built upon further. Given the urgent need to move towards sustainable land use in the face of multiple challenges, linking societal vi-

sions to models in research approaches which engage society with science and encourage futures thinking have great potential.

Lay Summary

The Scottish Government wants to increase woodland cover in Scotland for a number of reasons. Woodlands and forests are known to provide us with many benefits, including timber for furniture and buildings, places to visit and relax, as well as being beautiful habitats which enhance our landscapes. Planting more of them could also help us to tackle some of the global challenges we are facing. By storing carbon from the air as they grow, woodlands can help to slow down climate change. They also provide new varied habitats for many mammal, bird, insect, and plant species, helping to reduce and reverse biodiversity loss.

However, people that own and manage land aren't always willing or prepared to plant trees and people value land and different kinds of habitats for all kinds of reasons, and other benefits. These benefits can include supplying us with food, providing homes for species which prefer open habitats, and, in the same way as woodlands, simply for their beauty. By replacing other habitats, such as croplands, heather moorlands and grasslands, we change the benefits that we get from the land, and people have many different views on whether or not this is acceptable. So, despite the government targets and the urgent need to tackle climate change and biodiversity loss, we don't know if it is possible to meet them given past reluctance and previously missed targets.

We need to keep a balance and plant more woodlands whilst also respecting other types of land

uses and the benefits that we get from them. However, scientists don't yet know how best to achieve this balance. Computer models have been used a great deal in environmental science to tackle these kinds of problems and explore different possible futures. They help decision makers to test alternative strategies and see what the effects might be. These models have rarely included the fact that land is owned and managed by many different people, with different opinions and views which will affect what they decide to do with their land.

This research found that organisations working in forestry, conservation, and agriculture in Scotland envisaged different types of new woodlands, for different purposes, and had different ideas for how the people who own and manage the land could be encouraged to plant more trees. These views were incorporated into five 'visions' or 'ideal positive futures' which describe these various ideas, essentially providing alternative stories about the types of woodlands that should be planted, where they should be planted, what benefits they should provide, and how land managers could be encouraged to plant them. A new computer model, which represents the environment of Scotland - including the many different types of land managers and their views - was developed. By representing each of the alternative stories in the model, this research explored how each one might affect the benefits we get from the environment over the next 100 years.

The results show that increasing woodland cover in Scotland could be beneficial in many ways, providing more timber, storing carbon, reducing flood risk, and offering new opportunities for employment. However, there could be a reduction in farming for livestock, and a loss of some open moorlands and heathlands which are home to unique species of flowering plants, and highly valued by many people for traditional livelihoods (including farming, deer stalking, and grouse shooting) and recreation. The vision which described a future with a much greater variety of types of land managers and land uses, as well as more resources and funding for local communities to manage their own land, was most successful at increasing woodland cover and meeting the government targets. Visions where land managers were paid every year to plant and

maintain woodlands were also successful. Using new woodlands to provide home-grown timber could be especially important for encouraging the planting and maintenance of woodlands. In visions where similar land managers had control over large areas of land and were less prepared to plant woodlands, targets were less likely to be met.

Overall, the research has provided a new method which may help researchers and decision makers explore the effects of increasing woodland cover. By including the views of many different land managers, the model gives a more realistic idea of what may be possible in terms of where woodland should be located, and what benefits it could provide.

Introduction

1.1 FORESTS CAN PROVIDE SOLUTIONS TO A PERFECT STORM OF GRAND CHALLENGES, BUT UNCERTAINTIES REMAIN

How can society develop a more sustainable relationship with the land? Land provides the principal basis for human livelihoods, including food and freshwater, and human use directly affects more than 70% of the land surface (Arneeth et al., 2019). With multiple challenges converging and compounding one another, this question is of central importance to research, policy, and society as a whole.

1.1.1 NAVIGATING THE PERFECT STORM

There has never been a clearer picture of the impact that humankind has had, and continues to have on the environment. Climate change, in particular warming of the climate system, is unequivocal, and many of the changes observed are unprecedented over decades to millennia (IPCC, 2014). Anthropogenic factors are extremely likely to have been the dominant cause of these observed changes, and continued future changes are likely to increase the risks of pervasive and irreversible impacts for people and ecosystems across the globe (IPCC, 2014). Ecosystems and biodiversity across the globe are showing rapid declines. Key drivers including land use change, direct exploitation, climate change, pollution, and invasion of alien species are causing unprecedented rates of change (IPBES, 2019). Among the many global drivers of change, deforestation and forest degradation directly affect the livelihoods of hundreds of millions of people, and environmental degradation is not a new problem, with evidence for change over thousands of years (Ghazoul & Chazdon, 2017).

1.1.2 CALLS TO ACTION

Given these challenges, society increasingly aspires to achieve sustainability. Popularised in the late 80s and originally defined as “development which meets the needs of the current generation without compromising the ability of future generations to meet their own needs” (Giddings et al., 2002), implementation has been troubled by varied interpretations of what sustainability truly comprises based on different discourses and values (Giddings et al., 2002; McManus, 1996; Redclift, 2005). There is a wide variety of high level international and national legislation aiming to tackle the challenges outlined above, and thus move towards developing more sustainable societies. The UN Sustainable Development Goals, which have been adopted by all United Nations member states, provide urgent calls to action in order to meet a shared blueprint of peace and prosperity for people and the planet (United Nations, 2015). The UN Paris Agree-

ment (COP21), which is due to enter into force in 2020, aims to limit average global temperature increases to 1.5°C (UNFCCC, 2016). National governments around the world have pledged to restore hundreds of thousands of hectares of land under the Convention on Biological Diversity 2010 Aichi targets, 2011 Bonn Challenge, and 2019 New York Declaration on Forests (Bloomfield et al., 2019).

Land-based mitigation strategies are established as important solutions to achieve goals for sustainable development and climate change mitigation (Grassi et al., 2017) and thus tackle several major problems at once. In particular, reforestation is expected to have extremely high climate change mitigation potential (Griscom et al., 2017). Ecological restoration is defined as ‘the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed’ (SER, 2004). More recently, interest in ‘rewilding’ has rapidly grown, broadly defined as restoring natural processes and ecological dynamics. This falls within the framework of ecological restoration, but has grown out of debates around more radical change, novel forms of conservation management, and the desire to embrace progressive interdisciplinary science (Jepson, 2016). However, despite the agreements and research developments outlined above, there is ongoing deforestation and degradation, and ecological restoration is a long-term and slow process (Watts et al., 2020). The knowledge base for implementing large-scale forest and landscape restoration needs further work (Chazdon et al., 2017). In addition, time-lags are inherent in the implementation of land-based mitigation strategies, and these need to be better taken into account in order to identify truly achievable mitigation actions (Brown et al., 2019a). These lags can include the time required for: effective communication, policy developments, uptake of new policies, monitoring, and conflicts between governance levels and sectors.

1.1.3 VALUING NATURE AND NEGOTIATING CHANGE

The targets outlined above are ambitious in scope, and yet they are also non-specific and open to varied interpretation. Mace (2014) has outlined how perceptions of conservation and restoration

have evolved through time. The most recent interpretation is one which aims to truly link nature and culture, with greater emphasis on interdisciplinarity, adaptability, and linking the social and ecological sciences. The Ecosystem Approach, coined by the Convention on Biological Diversity as “a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way” recognises that “humans, with their cultural diversity, are an integral component of ecosystems” (Convention on Biological Diversity, 2000). ‘Landscape Approaches’ (Sayer et al., 2013) aim to include people in ecological restoration and encourage true participation in environmental decisions. The concepts of Ecosystem Services (ES) and Natural Capital developed from these approaches as ways to better integrate the environment into decision making. ES represent the benefits which human populations derive, directly or indirectly, from ecosystem functions - which refer to the various habitats, biological properties and processes of ecosystems (Costanza et al., 1997). Natural Capital is often defined as the ‘stock’ of natural ‘material’ from which these benefits flow.

This ideal of truly linking nature and culture is not one which is easily realised. Both ES and Natural Capital have been, and continue to be, the subject of critique and counter-arguments (McCauley, 2006; Schröter et al., 2014). Nevertheless, both concepts offer frameworks by which to both demonstrate the irreplaceable value of nature, the fact that different people want different benefits from the environment, and that there is a need to somehow quantify these in order to allow negotiations to take place. Valuation of ES has been the subject of a great deal of research and debate. It has developed from initially being focused on purely economic approaches (Costanza et al., 1997), to relational values which refocus on people’s preferences, principles and responsibilities towards the environment (Chan et al., 2012), and deliberative approaches which generate shared preferences and values through discussion and learning (Irvine et al., 2016; Kenter et al., 2014, 2016). The weaknesses of mainstream economic valuation approaches have been acknowledged, and it is argued that a fundamental change in economic theory is required to move forward in ES research (Costanza et al., 2017). Institutional and governance concerns,

along with set social norms, have been identified as the most severe obstacles to implementation of landscape approaches (Sayer et al., 2013). In response, new forms of environmental governance are emerging (Primmer et al., 2015). Due to the growth of interdisciplinary ecosystem and landscape approaches, stakeholders and their expectations are diversifying, and there is greater need to address this plurality through deliberative governance. Issues also no longer fall within just one sector, and they are happening under accelerating environmental change, meaning that multilevel and adaptive governance is required.

1.2 UNDERSTANDING FUTURE LAND USE CHANGE

Significant challenges remain in terms of ensuring a sustainable relationship between society and land into the future. As outlined above, landscape approaches are at their heart a negotiation process, and integrated landscape thinking which aims to reduce conflicts necessitates understanding the synergies and trade-offs between different ES. Methods to do this to date have primarily been economic and biophysical, treating landscape change as a predictable physical process rather than the social (or negotiation) process that it is.

1.2.1 A BRIEF INTRODUCTION TO MEASURING ECOSYSTEM SERVICES

ES can be, amongst other things, measurable indicators of the different aspects of land systems, and so they can provide appropriate means for analysing and communicating the results of quantitative land system assessments (Rounsevell et al., 2012b). The Millennium Ecosystem Assessment (MA) (Millennium Ecosystem Assessment, 2005) was the first comprehensive study to offer a new framework for analysing socio-ecological systems, and research approaches developed substantially after its release. A number of ES classification systems have been developed, including the original proposed by the MA (Millennium Ecosystem Assessment, 2005), TEEB (Groot et al., 2010), and CICES (Haines-Young & Potschin, 2010). Although detail and subcategories

vary between systems, the four broad categories of regulating (e.g. of climate, water, disease), supporting (e.g. primary production, soil formation), provisioning (e.g. food, water, fibre, fuel), and cultural (e.g. spiritual, aesthetic, recreation, education) ES remain constant. Regulating and supporting services now tend to be grouped together as a single 'Regulating and maintenance' category. The applicability of ES as indicators meant that many earlier approaches were purely biophysical and focused on development of spatial mapping tools (Haines-Young & Potschin, 2009). ES maps are acknowledged to be important tools to bring ES into practical application, by communicating complex spatial information, raising awareness and informing landscape planning (Burkhard & Maes, 2017). Regulating and maintenance services have been most commonly mapped, followed by cultural and provisioning services, with logical and empirical approaches being applied most (Englund et al., 2017). However, the proliferation of mapping approaches together with rapid development of computer based mapping programmes has led to an almost inflationary generation of ES maps, some of which have been of inferior quality (Burkhard & Maes, 2017).

Research has acknowledged challenges and aims to look for areas where further investigation could address these. In particular, issues have been identified regarding the discipline-bound nature of different sectors, and a need for further evidence for the processes and feedbacks within socio-ecological systems (Carpenter et al., 2009). Challenges have also been acknowledged in terms of integrating the ES concept into actual land use planning, management, and decision making (Groot et al., 2010). More recent approaches have aimed to address these difficulties. A vast array of place-based studies have modelled ES in contrasting landscapes, thus providing methods and tools for ES simulation and evaluation at various spatial and temporal scales (Fu & Forsius, 2015). In particular, a need to take account of societal demand for ES has led to approaches aiming to map demand. Wolff et al. (2015) found that operationalisation of ES demand in policy, planning and management requires a more consistent understanding and definition of ES demand, its drivers and how it changes over time. The impact of demands for multiple

ecosystem services on land use change also needs to be investigated (Wolff et al., 2015). The need to better understand relationships between ES has begun to be addressed. Lee & Lautenbach (2016) reviewed a large number of studies in order to quantify relationships in terms of trade-offs, synergies, or ‘no-effect’. Synergistic relationships dominated between different regulating services and between different cultural services, whereas the relationship between regulating and provisioning services was trade-off dominated (Lee & Lautenbach, 2016). Work has also aimed to identify multifunctional ‘bundles’ of services, with higher diversity found in forested areas and mosaic landscapes (Mouchet et al., 2017).

Recent approaches have reflected on the use of ES maps as tools, and whether they are actually used in decision making. Root-Bernstein & Jaksic (2017) provided a critical reflection on the use of the ES framework by ecologists, arguing that too much effort has been focused on providing decision-makers with the wrong kind of data. Recent literature suggests that, despite a number of projects and toolkits aimed at integrating ecosystem services into decision-making, assessments rarely play an instrumental role in influencing decisions (Ainscough et al., 2019). The concept does have an important role as a ‘boundary object’, by raising awareness and incorporating multiple different types of values into ecosystem assessments (Ainscough et al., 2019). With this boundary object role in mind, there is increasingly a need for a shift in focus, with research efforts aiming to understand the governance around ES rather than producing further detailed technical mapping.

1.2.2 FUTURES THINKING

Given methods to quantify and map ES, investigations have also aimed to define potential futures in terms of environmental and socio-economic change and the effect they may have on ES demand and supply. Scenario methods emerged from military strategy, were adopted and advanced by the business sector, and widely applied to environmental problems from the 1970s onwards (Rounsevell & Metzger, 2010). They have been defined as “plausible and often simpli-

fied descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships” (Millennium Ecosystem Assessment, 2005). At their heart, scenarios are tools to address uncertainty. They do not attempt to predict the future, but instead consider multiple plausible futures and assist in making better informed decisions (Cork, 2016). There are several different types including: predictive (forecasting the most likely circumstances, or ‘what-if’ approaches), explorative (exploring external factors beyond control, or approaches where certain strategies are implemented), and normative (value based ways to preserve or transform the current system). Within this final category, participatory scenario development of societal ‘visions’ of the future are thought to be particularly powerful. Visions are a way of thinking about more radical or transformative changes. By focusing more on the needs and wants of society, they are viewed as a way to narrow down many possible policy decisions to a smaller number of relevant and sustainable land management options and choices (Rounsevell et al., 2012b). Given the grand challenges faced by society, using futures thinking to imagine more positive transformations towards sustainability could have a valuable role in engaging people with science, decision making, and environmental protection and restoration.

1.2.3 MODELLING LAND USE CHANGE

Land use research has developed over time from being more focused on land cover towards approaches paying more attention to the drivers of land use practices and integrated systems science (Niewohner et al., 2016). Models have played a major role in land system science, as they allow structured analysis of complex interactions within the land system (Rounsevell et al., 2012b). They are used to describe, explore and predict changes in land use and other human systems (Brown et al., 2016). By doing so, they provide experimental settings that would otherwise be unavailable, and so can help to understand system dynamics, sensitivities, and uncertainties (Brown et al., 2016).

Synes et al. (2016) have reviewed approaches in landscape ecological modelling to date. Approaches mainly fall into two categories: 1) pattern-based (or top-down) vs. 2) process-based (or bottom-up) (Brown et al., 2016; Synes et al., 2016). Pattern based applications include Neutral Landscape Models (NLMs), which represent pattern, with no representation of processes that created them or that might influence them in the future. They have encompassed research exploring habitat fragmentation, functional connectivity, and species distribution, as well as statistical models which derive the scenario-based climate projections developed by the Intergovernmental Panel on Climate Change (IPCC) (Synes et al., 2016). Predictive pattern based models focus on supply and predict land use patterns based on spatial data representing land suitability and on external assumptions about demand (Rounsevell et al., 2012b). There are a variety of more integrated approaches, such as land allocation models, which use demand or price information from economic models to update land-use patterns in detailed environmental models (Rounsevell et al., 2012b). Process based approaches are increasingly used, aiming to better represent the behaviours and dynamics that drive landscape patterns. In ecology, these have included population-based approaches and Individual Based Models (IBMs). At the landscape scale, Agent-Based Models (ABM) explore alternative accounts of human decision-making under socio-economic or environmental pressures (Synes et al., 2016).

Modelling approaches to date have sometimes been limited by a sectoral focus, honing in on single aspects of the land use system. Furthermore, approaches have tended to be either top-down or bottom-up, with few capturing the complexity of human-environment interactions across different scales (Rounsevell et al., 2012b). Economic models are limited in that they rarely account for non-economic resource constraints, don't take account of societal demand, and only represent human behaviour through rational price mechanisms (Rounsevell et al., 2012b). Recent analysis has also highlighted the mismatches between quantitative/metric based approaches and what policy makers are actually interested in - i.e. social variables such as health and air quality. Integrated land systems research which addresses both social and ecological aspects are

sparse, and it is argued that research needs to better integrate the social domain (whilst also acknowledging that this is often limited by data availability) (Winkler et al., 2018).

As a result, many modelling approaches to date appear to be failing to capture the issue of value discussed in Section 1.1.3. Land use decisions are fundamentally determined by individuals, driven by social norms including language, culture and institutions (Brown et al., 2016). With this in mind, ABMs are increasingly seen as a potential promising method, especially as they become more complex and empirically grounded. They are viewed as a ‘new generation of land use models’, which can embrace diverse human agency, and help to envision and design sustainable futures (Verburg et al., 2019). A recent theoretical study which explored how land manager behaviour affected the likelihood of reaching societal visions concluded that assessments of the translation of the effects identified there into real-world contexts is a valuable area for future research (Brown et al., 2018). More generally, improving ABMs for land system science is acknowledged as an area for progress, and scaling them up to land management/policy scales is expected to be particularly useful (Rounsevell et al., 2012b).

1.3 SCOTLAND AS A STAGE FOR UNDERSTANDING WOODLAND EXPANSION

Given the global challenges to achieving sustainable land use and the research methods developed to try and understand and tackle them better, this thesis brings these issues to focus on the topic of woodland expansion in Scotland. Scotland has been among the first nations to adopt an Ecosystem Approach, with a suite of progressive environmental policies coming into force since the devolution of the Scottish Government in 1999. Among these are two targets for woodland expansion. The first, outlined in the 2006 Forestry Strategy (Scottish Executive, 2006) and Rationale for Woodland Expansion (Forestry Commission, 2009) aimed to reach 25% cover by 2050. The second more recent target is aligned strongly with the Climate Change Plan (Scottish Government, 2018) and aims to reach 21% by 2032, with this integrated into the updated Forestry Strategy (Scottish Government, 2019). However, many factors have stood in the way

of achieving these targets.

1.3.1 LAND USE HISTORY, CONFLICTS, AND CURRENT CONTEXT

The context for woodland expansion cannot be considered in isolation from its history. There has been much debate over woodland history in Scotland, as it is thought that an improved understanding of the ecological baseline will provide an appropriate reference for current aims. The concept of a great ‘Caledonian Forest’ covering a large proportion of Scotland up until the last thousand years has been advocated by many (Fraser Darling, 1947; Miles & Jackman, 1991). However, palaeoenvironmental evidence suggests that there has been a dynamic balance of both agriculture and woodland throughout the Holocene, with woodland loss occurring gradually since prehistoric times (Davies & Watson, 2007; Holl & Smith, 2007; Tipping et al., 1999, 2008). The current consensus is that cover was at a maximum of 50-60% in the Neolithic (Birks, 1975), declining to around 4% at the beginning of the 20th Century due to a complex combination of human impact and climate change (Brown et al., 2011; Thomas et al., 2015). Multiple causes of forest loss are cited, including climatic decline, use of timber for overwintering fodder, cyclical ‘wandering settlements’ in the Bronze Age, and more rapid clearance for farming in the Iron Age (Tipping, 2015). The synchronicity of human and climatic impact makes it difficult to decide on the main cause of woodland decline, but there is no doubt that woodland retreat occurred at the same time as human settlement expanded (Wilson, 2015). A minority view argues that the current landscape would prevail regardless of human impact (Fenton, 2008), but most research concludes that there is no reason that more woodland should not have persisted to the present, had it not been cleared for farming, timber, and areas maintained artificially for sporting estates (Wilson, 2015).

The last hundred years of woodland history are well documented, with a concerted effort to enhance the woodland resource post World-War-I supported through the establishment of the Forestry Commission, with an initial focus on conifer plantations for timber. More recently, a

succession of Woodland Grant Schemes supported planting of native woodlands, and conversion of Plantation on Ancient Woodland Sites (PAWS) back to native species, as well as more sensitively located and managed conifer plantations. Despite this afforestation, at 19% (Forest Research, 2019) woodland cover in Scotland remains low in both a historical and European context (Thomas et al., 2015), with the European average sitting at around 37%. The theory of ‘forest transition’ postulates that there is a change from net deforestation to net reforestation as economic development proceeds, agricultural efficiency improves, and rural to urban migration takes place (Mather, 2004). Scotland is argued to be unique, as although all of the above have occurred, ‘surplus’ land has been amalgamated into large estates managed predominantly as open habitats for deer stalking and grouse shooting, rather than reverting to forest (Mather, 2004). This structure means that Scotland has one of the most concentrated patterns of landownership in the world (Wightman, 1999). Reed et al. (2009b) argue that Highland Scotland is an exception to the UK trend for a shift from production to consumption in the uplands primarily due to the estate structure of land ownership.

In addition to the estate model, Scotland has also been highlighted as having a unique approach within its two national parks. Unlike elsewhere in the world, where the predominant aim of national parks is purely conservation, Scotland has combined environmental management with local rural development (Stockdale & Barker, 2009). This has much to do with the social and political context. The Highland Clearances refer to a period in the late 1700s where Highlanders were forcibly evicted from the land and replaced with large estates managing for sheep and deer (Holl & Smith, 2007). These events caused a rift in Scottish culture, with many authors arguing that Highlanders were dispossessed of their indigenous relationship to nature and the land (Hunter, 2014). Remaining sensitivities concerning these Clearances are combined with the fact that a large proportion of Scotland is classified as ‘Less Favoured Area’, an agricultural designation which highlights the sensitivity, and therefore vulnerability, of upland and marginal farming. At the same time, although little, if any of the Scottish landscape remains unmodi-

fied by humans, contemporary discourses view the predominantly open landscape as ‘wild’ and this view has considerable popular and political resonance in Scotland (McMorran et al., 2008). This conflict between rural livelihoods and a desire to conserve the Highland landscape has been described as a “dichotomy between threatened nature and threatened communities” (Warren, 2002). Thus there is a consistent desire to balance improving rural livelihoods with nature conservation in Scottish policy.

1.3.2 PROGRESSIVE POLICIES, BUT UNCERTAINTY REGARDING IMPLEMENTATION

Since devolution, the Scottish Government has produced a range of progressive policies including the Biodiversity Strategy (Scottish Executive, 2004), Climate Change Act (Scottish Parliament, 2009), two iterations of a Land Use Strategy (Scottish Government, 2011, 2016), and more recently the Land Reform Act (Scottish Parliament, 2016) and Community Empowerment Act (Scottish Parliament, 2015a). Together aspects of these policies advocate afforestation as a strategy to both mitigate and adapt to climate change, restore biodiversity, and link people to the land. Multi-functionality is also consistently mentioned as a primary objective for Scottish land use. Despite these objectives, environmental problems continue, with pressures from agriculture, upland management, land use change, habitat fragmentation, pollution, invasive species, and climate change having caused a 24% decline in average species abundance and 49% decrease in species abundance, with 11% of species threatened with further decline (Hayhow et al., 2019). Conflicting objectives between stakeholders and a lack of understanding of exactly how to achieve multi-functionality are cited as among the reasons for failure to meet these policies.

These issues are compounded by future uncertainties. Given the departure of the UK from the European Union, there is debate over what might replace the Common Agricultural Policy (CAP) (Bateman & Balmford, 2018). Furthermore, regardless of the political context, uncertainty in terms of the likely severity and impacts of climate change means that there is a need

to explore possible scenarios of socio-economic and climatic change. Although Scotland has been found to be ‘ES/Natural Capital literate’ with a proactive stance regarding global and European norms and requirements for nature conservation and the sustainable use of resources, the concepts are yet to be fully operationalised due to a lack of proactive policy interventions or concrete measures (Claret et al., 2018). Therefore, there is a need for research to explore how these uncertainties can be tackled.

1.3.3 KNOWLEDGE GAPS FOR ACHIEVING WOODLAND EXPANSION

An internationally important question for ecological research is: ‘under what circumstances can afforestation... benefit biodiversity conservation, reduce emissions, and provide sustainable livelihoods’ (Sutherland et al., 2009, 2013). In order to uncover these circumstances, we need to better understand the synergies and trade-offs between ES and biodiversity conservation goals during landscape restoration, and how they can be reconciled (Ockendon et al., 2018). It is clear that these questions have particular relevance to Scotland. Regardless of the many stated benefits from woodland expansion, woodland creation in Scotland is not progressing at a rate sufficient to meet the current aspirations (see section 2.1 for more detail), and more research is required to understand why, and how this can be addressed (Thomas et al., 2015). Despite the ‘theoretically compelling’ idea of multifunctional landscapes (Reyers et al., 2012), it is argued that objectives for achieving multiple benefits will not be achieved without prior understanding of the trade-offs and synergies that might arise in specific locations (Muñoz-Rojas et al., 2015). Understanding societal demand is also essential, with research needed to uncover how we can plan restoration programs to help meet expected future ecosystem services demand (Ockendon et al., 2018). Exploring changes to agricultural policies and subsidies, including the CAP, and the likely political, social, financial and ecological outcomes is also of high priority (Ockendon et al., 2018).

1.4 THESIS AIMS, OBJECTIVES AND RESEARCH QUESTIONS

This chapter has aimed to outline the current context, initially globally and then focussing in on Scotland, and the challenges which remain in terms of ensuring a sustainable relationship between society and Scotland's land into the future. It has highlighted the need to take account of diverse values, understand ES synergies and trade-offs, and the potential for developing models of future scenarios. This thesis aims to tackle these challenges by addressing the knowledge gaps outlined above. It will assess the potential routes forward in terms of both targeting woodland expansion for multiple benefits and using effective governance models which promote sustainable environmental management for the 21st Century.

The overarching objectives are to:

1. Understand the synergies and trade-offs generated by woodland expansion under alternative visions
2. Understand how governance influences woodland expansion and ES provision

Guided by these overall objectives, the specific research questions to be addressed are:

1. What do we currently know about the impact of woodland expansion on biodiversity and ES in a UK context?
2. What visions do national level Scottish stakeholders have for woodland expansion and how do they envisage them being achieved?
3. How could these visions for woodland expansion affect future ES provision?
 - a. Are the visions feasible i.e. can they be achieved?
 - b. What are the ES relationships under alternative visions (i.e. synergies, trade-offs)?

- c. Can novel governance mechanisms influence land manager behaviour to promote pathways to visions?

1.5 RESEARCH APPROACH AND THESIS STRUCTURE

The thesis takes an interdisciplinary and mixed-methods approach, which is outlined visually in Figure 1.1. Chapter 2 undertakes a systematic review of current knowledge regarding the effect of woodland expansion on ES. Chapter 3 presents the methodology and results of a process used to elicit visions, or normative scenarios, for how woodland expansion might ideally take place in Scotland from different stakeholder perspectives. Chapters 4 and 5 apply the results of the first two research chapters within an established modelling framework, describing the development and results of CRAFTY-Scotland, an agent-based model of future land use change. Chapters 2 and 3 are published as peer-reviewed papers in the journals *Forest Ecology and Management* and *Landscape Ecology* respectively. It is intended that chapters 4 and 5 will be combined and submitted as a final paper after thesis submission.

1.5.1 A NOTE ON THE TERMS AND DEFINITIONS USED

Many different terms are used to describe different approaches to woodland creation, and this can result in some confusion or misconceptions (Mansourian et al., 2005). ‘Woodland expansion’ is used throughout this thesis to encompass afforestation, reforestation, woodland creation, and forest landscape restoration. Afforestation and reforestation both involve the artificial establishment of trees, in the former case where no trees existed before (for at least 50 years), while the latter refers to planting or seeding on land that was recently forested but that has been converted to non-forested land (Mansourian et al., 2005). Natural regeneration is considered a process of woodland expansion and can either be assisted (Chazdon, 2008) or can occur unaided if there are seed sources and browsing pressure is low (Forestry Commission, 2009). Increasingly,

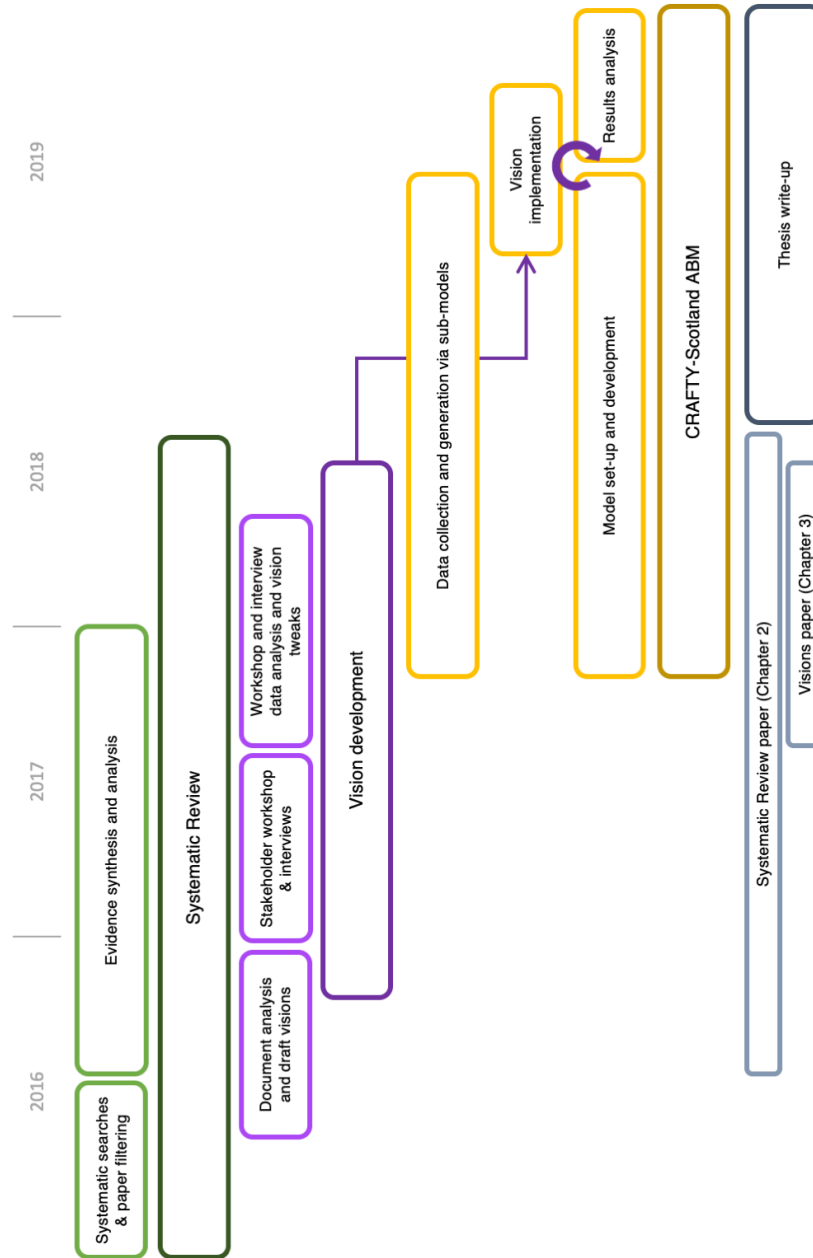


Figure 1.1: An overview of the PhD timeline and mixed-methodological approaches taken. A systematic review was undertaken to characterise the evidence base relating to the effect of woodland expansion on ecosystem services in the UK. Alongside this, visions were outlined first using a document analysis, with these being developed further through stakeholder engagement. These visions were then implemented within a spatial agent-based model which collated a wide range of data. This implementation was an iterative process, with model tweaks required to improve the representation of each vision.

Forest Landscape Restoration (FLR) is advocated on the basis that restoration has to address multiple and sometimes competing needs (Chazdon et al., 2017). It is defined as ‘a planned process that aims to regain ecological functionality and enhance human well-being across deforested or degraded landscapes’ (Lamb, 2014) . Although every effort is made to use woodland expansion as a catch-all, these terms are occasionally used interchangeably.

2

Reviewing the evidence base for the effects of woodland expansion on biodiversity and ecosystem services in the United Kingdom

The following chapter is largely based on a published paper (Burton et al., 2018b). VB carried out the research and wrote the manuscript with comments and guidance from supervisors (co-authors), and is grateful for comments from two anonymous reviewers.

2.1 INTRODUCTION

Woodland cover in the United Kingdom (UK) as a whole is currently 13%, and 19% in Scotland (Forest Research, 2019), with both these figures less than half the European and global averages of 37% and 30% respectively (FAO, 2015). As outlined in Section 1.3.1, this relative lack of woodland is attributed to a complex history of exploitation by society and natural climate changes throughout the Holocene (Holl & Smith, 2007; Tipping et al., 2008). Since the end of WW1, woodland cover in the UK increased via the expansion of the public Forestry Commission estate, and a succession of grant schemes supporting private woodland planting. This increase was characterised by an initial dominance of conifer investment forestry planted mainly for timber, shifting towards increasing emphasis on broadleaved woodlands for multiple, predominantly environmental and recreational, purposes (Wong et al., 2015). Woodland types favoured for woodland expansion vary geographically across the UK. Welsh and Scottish forests are predominantly coniferous, while almost 90% of private and other woodlands in England comprises broadleaved species (Wong et al., 2015). In the UK and elsewhere, aims for afforestation are complicated by the fact that forest planting takes place on different land use types, owned by different people with a diverse range of objectives and values (Thomas et al., 2015; Chapter 3; Burton et al., 2018a).

Globally, forest loss and degradation have led to dramatic losses of biodiversity, carbon stores and ecosystem services (ES) (Ciccarese et al., 2012). As a result, as outlined in section 1.1.2 numerous national and international policies aim for afforestation and reforestation. In the UK, these high-level goals are incorporated into specific targets for woodland creation (DEFRA, 2013; Forestry Commission, 2009). It is internationally recognised that progress towards achieving these goals is uncertain, and that multiple challenges and barriers remain (Chazdon et al., 2017). Woodland expansion aims sit within wider land use challenges, including the need to ensure sufficiency and security of food supplies and the desire for ES multi-functionality, and there remains a lack of synergies between policies in these areas. Thus, at the UK level, there is a consistent gap

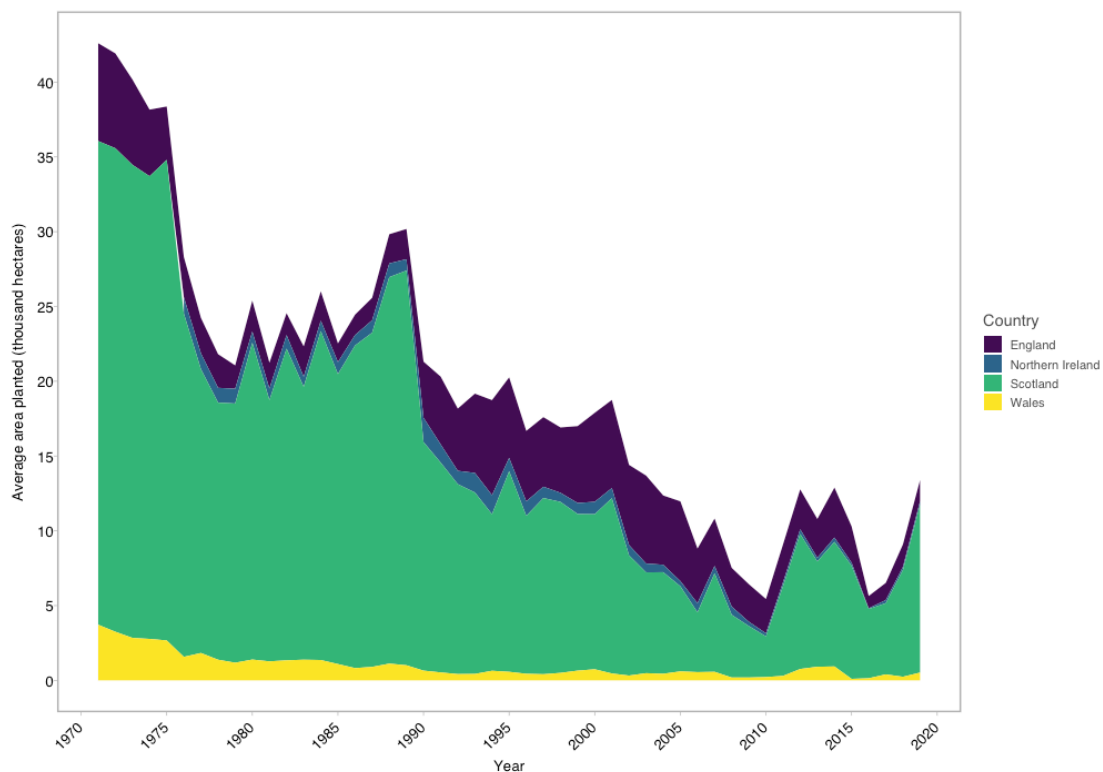


Figure 2.1: Average area of total woodland planted over time, per UK country. Source: Forest Research Statistics 2019

between policy aspirations and actual levels of woodland planting. Reports showed that woodland planting in 2016 was at its lowest level for more than five years (Priestley & Sutherland, 2016; Ward & Watson, 2018) - figure 2.1. This has since increased in Scotland (rising from 4.6 thousand ha planted in 2016 to 11.2 thousand ha planted in 2019) but stayed consistent or continued to decrease in Wales and England (Ward & Watson, 2018). The 2019 figure for Scotland has exceeded the annual target of 11,000 ha associated with the Climate Change Plan, but given years of previous decline and variability illustrated by figure 2.1, the key will be to maintain this rate sustainably. These persistent challenges are reflected in the identification of woodland expansion, in particular in relation to climate change mitigation, as a 'wicked problem' beset by conflicting

goals, values and perspectives (Duckett et al., 2016; Rittel & Webber, 1973; Shindler & Cramer, 1999). This is due to the difficulty of implementing woodland expansion in the face of conflicting food and climate change policy goals, low acceptability of woodland planting among farmers, volatile stakeholder perceptions, and, in Scotland, grazing pressure from high deer populations (Duckett et al., 2016; Environment Climate Change and Land Reform Committee, 2017).

A review of evidence in a Scottish context has suggested that we need a clearer articulation of woodland benefits, improved evaluation of woodland creation schemes, and improved understanding of trade-offs with other land uses (Thomas et al., 2015). Research has also shown that there is a lack of synergies between the many policies and plans promoting woodland networks and corridors (Muñoz-Rojas et al., 2015). More generally, further research is required to elucidate the relationships between different (forest and non-forest) land use ES provision levels, whether these be synergies, trade-offs, or groupings in multifunctional ‘bundles’ (Cord et al., 2017). Therefore, research needs to make clear the effect of woodland expansion in different contexts, in order to provide robust, context-specific evidence. This is especially pertinent given the urgency of initiatives concerned with carbon sequestration and biodiversity protection, and the risk of rapid, poorly-informed actions leading to suboptimal or counterproductive outcomes. Assessment of the extent of current knowledge about the effects of woodland expansion in the UK is therefore necessary not only for national-level policy making but also as a case study of internationally-relevant challenges in land system planning and management.

This chapter outlines a systematic review undertaken to assess the evidence base for the effects of woodland expansion on biodiversity and ES in the UK. The review had two main objectives: 1) To systematically collate and synthesise both academic and grey literature studying woodland expansion in a UK context; and 2) To characterise the evidence base on the effects of such woodland expansion on biodiversity and ES and highlight where further research might be required. To achieve these objectives, three research questions are addressed: 1) What knowledge do we currently have about the effects of woodland expansion on biodiversity and ES provision?; 2)

What are the main gaps in this knowledge?; and therefore 3) What does this mean for developing strategies for woodland expansion that maximise biodiversity and ES provision? The first two questions directly address results from the review, while the third forms the basis for the discussion in this chapter.

2.2 METHODS

A systematic review (SR) of both academic literature and unpublished ‘grey’ literature, was undertaken following established guidelines (Collaboration for Environmental Evidence, 2013). These guidelines adapt established guidance from the health services sector into a systematic review process suited to assessing environmental methodologies. The guidelines put forward a number of transparent and repeatable steps, each of which are outlined below.

2.2.1 DATA COLLECTION

Online searches were carried out on electronic databases, organisational websites and internet meta-search engines. Search terms were developed around the Population, Intervention, Comparator, Outcome (PICO) framework (Collaboration for Environmental Evidence, 2013). As ‘ecosystem services’ is a relatively new term, keywords that related to each ES category were included, to capture all relevant research prior to and since the emergence of ES research. A full list of search terms used for all databases and websites can be found in Appendix A. The academic electronic databases Web of Science and Scopus were searched, and the first 50 Microsoft Word document and PDF hits from Google Scholar and Google were examined for appropriate literature. Several organisational websites were also searched for relevant information. All literature returned by the searches underwent a three-stage filtering process, using pre-defined inclusion and exclusion criteria. All articles were initially filtered by title and then abstract. Following the abstract filter, full texts were assessed and either accepted or rejected from the final

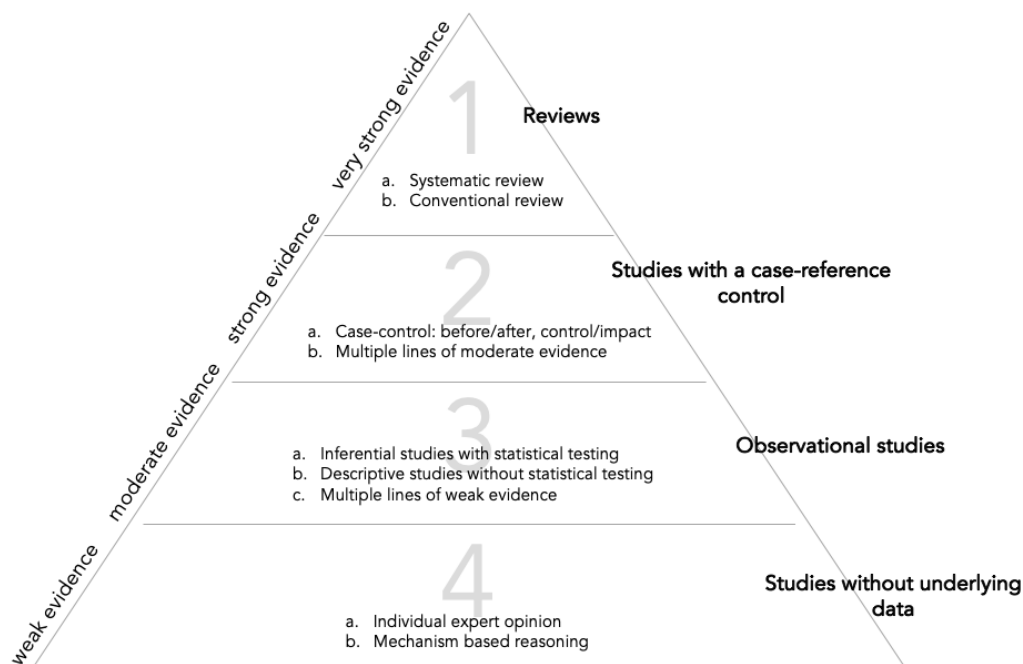


Figure 2.2: The Level of Evidence (LoE) hierarchy ranking reproduced after Mupepele et al. (2016)

review. The SR identified studies conducted in England, Scotland, Wales, Northern Ireland and Ireland, as well as the UK as a whole. Duplicates were removed. Some documents (26 in total) could not be accessed due to restrictions or were book chapters that could not be sourced online or in available libraries, and these were also excluded. The entire filtering process was carried out by the primary researcher. However, all progress and decisions made were discussed regularly with supervisors (co-authors on the resulting paper) in order to minimise reviewer bias and the inclusion/exclusion process was recorded for transparency (Appendix A).

2.2.2 DATA ANALYSIS

The final set of articles underwent an iterative process of characterisation, data extraction and critical appraisal in terms of study quality. Each study was categorised by a range of attributes including location, ES category, unit of study, woodland type, comparator/control habitat, and outcome measure. Papers were assigned to an ES category based on the Common International Classification of Ecosystem Services (CICES). Biodiversity was considered as a separate category. The quality of study design was further assessed using a tool developed to assess the strength of evidence of ES and conservation studies (Mupepele et al., 2016). This tool (Figure 2.2) uses a hierarchy of evidence to rank studies based on their experimental design, and thus lent itself well to assessing a wide range of studies with different units of study and types of data. The pyramid ranks study designs according to the strength of the evidence they produce. Within this hierarchy, systematic reviews (LoE1a) are regarded as providing the highest evidence level, with studies based on mechanistic reasoning providing the lowest. In this case, the ‘strong evidence’ level 2a included either studies that took measurements prior to afforestation as well as during or after, or studies which considered a different (usually open) habitat in comparison to an afforested or woodland habitat. Modelling studies require a slightly different interpretation in terms of their LoE. Models which represent theories, without underlying data, are given the lowest level (LoE4). If models have data input to determine their parameters, they achieve LoE3b, and if this data is tested and validated then this increases to LoE3a. To reach LoE2b or LoE2a, modelling studies must confirm their predictions on several unrelated datasets, or be built on data from controlled studies. The entire study database, with references, can be accessed in Appendix A. The scope of the review was intentionally broad throughout, in order to show the spread (and any bias) of evidence available. This resulted in a diverse set of studies with very different methodological designs and types of data. This precluded the use of formal quantitative techniques or meta-analysis, and therefore the analysis focuses on a narrative synthesis of the evidence.

Table 2.1: A summary of the number of papers returned from the initial searches, and at each subsequent filtering stage

Systematic Review Stage	No. of papers
Studies captured using search terms in electronic databases (including duplicates)	1,552
Studies captured using search terms in electronic databases (excluding duplicates)	1,347
Studies remaining after title and abstract filter	474
Studies remaining after full text filter	160

2.3 RESULTS

2.3.1 SUMMARISING THE EVIDENCE BASE

An initial search was carried out on the 2nd February 2016. The search was updated on the 7th April 2017 using the main databases (Web of Science and Scopus) from the first search. Table 2.1 shows the number of papers returned at each stage in the SR process.

Most evidence relates to the regulating and maintenance ES category (82 studies) and biodiversity (54 studies) (Figure 2.3). Within both categories, there is a bias towards studies of conifer plantations (74 studies). There is very little evidence relating solely to provisioning (1 study) and cultural categories (2 studies). However, it is important to note that some studies which consider multiple topics include aspects which fit in those categories (21 studies). Given the weighting of the evidence, this section focuses on summarising findings from papers within the biodiversity and regulating and maintenance categories, before going on to assess evidence for ecosystem disservices, and papers which consider multiple ES. The guidelines followed by the review emphasise that SR methodologies should collate and synthesise data without adding interpretation (Collaboration for Environmental Evidence, 2013).

2.3.2 BIODIVERSITY

Most studies of biodiversity focus on birds (22 studies), invertebrates (16 studies) and ground flora (5 studies), highlighting evidence gaps for the effects of new woodland on other taxa (e.g. mammals). For studies of conifer plantations (30/54 studies), several broad findings based on the evidence can be identified. In the early stages of Sitka spruce plantations studies have recorded a shift in ground vegetation from small stature herbs to more competitive grasses as plantations grow (Buscardo et al., 2008; Oxbrough et al., 2006). The shading effect of dense non-native coniferous plantations at later stages has been found to significantly reduce ground vegetation cover, but this is noted to reflect the density of the tree canopy more than the species planted (Wallace et al., 1992). A more diverse woodland flora has been found to develop in some conifer stands over time particularly where lower stocking densities allow a greater amount of light through to the forest floor (Essex & Williams, 1992; Wallace et al., 1992; Wallace & Good, 1995). A comparison of plantations with different species mixes and stand ages across Ireland illustrates differing effects on vegetation communities (French et al., 2008). In line with previously outlined findings, closed canopy sites dominated by Sitka spruce (*Picea sitchensis*) had very low numbers of ground flora and were found to be striking in their lack of diversity. By contrast, Japanese larch (*Larix kaempferi*) stands at all ages supported an abundant and species rich community of bryophytes, but these were mainly fast-colonising generalists, essentially meaning that the vegetation community beneath larch represented 'moorland-with-trees' (a function of the previous land use) as opposed to a true woodland flora. A mature Ash (*Fraxinus excelsior*) stand was found to support a vegetation community closest to native woodland, aided by a location on base rich free-draining soils and proximity to mature native woodland. This aligns with the assertion that it is likely that the biodiversity of newly established stands depends on the availability and colonisation ability of native woodland species (Thomas et al., 2015). There is widespread evidence for carabid species (Carabidae) turnover following the establishment of conifer plantations, with open ground species becoming less common,

Category	Metric/Service	Level of Evidence (LoE)				
		Very Strong	Strong	Moderate	Weak	
Biodiversity	Community structure					
	Connectivity/Species movement					
	Functional diversity					
	Species abundance					
	Species abundance and breeding success					
	Species abundance and diversity					
	Species density					
Regulating and Maintenance	Regulation of chemical composition of atmosphere and oceans					
	Regulation of temperature and humidity, incl. ventilation and transpiration					
	Control of erosion rates					
	Hydrological and water-flow regulation (including flood control and coastal protection)					
	Decomposition and fixing processes and their effect on soil quality					
	Weathering processes and their effect on soil quality					
	Regulation of the chemical condition of freshwaters by living processes					
	Bio-remediation by micro-organisms, algae, plants and animals					
Provisioning	Biomass					
Cultural	Characteristics of living systems that are resonant in terms of culture or heritage					
	Characteristics of living systems that enable aesthetic experiences					
Multiple						
Key	Conifer plantation		Native woodland		Agroforestry	
	Broadleaf plantation		Riparian		Multiple	

Figure 2.3: The biodiversity metrics and CICES ecosystem service categories considered by the 160 papers. Each paper is represented by a symbol relating to the type(s) of woodland it studies, and is assigned a Level of Evidence (LoE) based on its study design

and generalist and forest specialists becoming more so (Buse & Good, 1993; Day & Carthy, 1988; Karen et al., 2008; Lin et al., 2007). There are differing conclusions as to whether this turnover significantly changes overall carabid diversity compared to previous or comparative land uses. Day & Carthy (1988) found that although species richness and alpha diversity were lower in forested compared to moorland plots, this was not statistically significant. By contrast, Buse & Good (1993) found the greatest abundance, species richness and diversity occurred in non-afforested sites. Nonetheless, there is strong agreement between studies that fostering and maintaining diversity in forest structure and species is essential for maintaining overall carabid diversity, with rides, clear-fell areas and early successional habitats allowing open ground specialists to continue to thrive (Buse & Good, 1993; Karen et al., 2008; Lin et al., 2007; Spake et al., 2016). When taking into account all the stages of the forest cycle, as well as the effect of locality, it has been concluded that on the whole forests can be as species rich (in terms of carabids) as surrounding open habitats (Coll & Bolger, 2007). A recent study of carabid functional diversity finds that, as increasing canopy cover generally drives down functional diversity, management which emulates natural disturbance regimes through gap creation and close-to-nature forestry will be beneficial to carabids (Spake et al., 2016).

Spider and bird species also demonstrate turnover with woodland expansion. Pre-afforestation land use has an influence on both these communities, with evidence suggesting that improved grasslands are most likely to benefit from woodland expansion, showing increased species diversity and richness, whereas wet grasslands and peatlands are more sensitive due to their more distinct species assemblages (Oxbrough et al., 2006; Wilson et al., 2012). Peatlands, although low in overall bird diversity, are home to rarer habitat specialists, and are found to be most sensitive to afforestation (Wilson et al., 2012). There is strong evidence that edge effects generated by conifer plantations negatively affect a number of open ground bird specialists, particularly in upland contexts (Buchanan et al., 2003; Douglas et al., 2014; Graham et al., 2015; Lavers & Haines-young, 1997). However, similar to findings from studies of carabids, diversity in stand

age and forest structure can have positive effects, with most bird species abundances being positively related to the extent of shrub cover at the edge of plantations (Calladine et al., 2013), and black grouse (*Tetrao tetrix L.*) abundance being positively associated with younger pre-thicket forest (Pearce-Higgins et al., 2007). One long-term study carried out over a 12-year period of coniferous afforestation on an upland grassland showed significant turnover of both vegetation and bird species, with a significant increase in the overall number of breeding bird pairs (Sykes et al., 1989).

Several studies consider the effect of coniferous afforestation within the wider landscape, and once again, the effects differ depending on the context and species considered. In lowland farmland, no detectable differences in total farmland bird species richness or abundance were found between farmland sites with very little forest cover and those approximately one-third afforested (Pithon et al., 2005). By contrast, conifer plantations have been associated with declines in presence and breeding performance of both ravens (*Corvus corax*) (Marquiss et al., 1978) and golden eagles (*Aquila chrysaetos*) (Marquiss et al., 1985; Watson, 1992; Whitfield et al., 2001). Similar studies of red kites (*Milvus milvus*) in Wales found no firm evidence for an effect of woodland expansion on species occurrence (Newton et al., 1981). Still, it is important to note that many of these studies are based on the effect of plantations planted in the 1970s, which were often densely planted and heavily dominated by non-native conifers. Modern plantations are encouraged to have more sympathetic designs, such as areas of open ground, riparian buffers and areas of broadleaf woodland, and thus may not have the same effect.

The effect of growth stage has been found to have a more significant effect of bird assemblages than species mix, with species associated with younger woodland stages being typical of open, un-forested habitats, which were turn strongly influenced by the pre-afforestation habitat (Wilson et al., 2006). In older stages, assemblages were characterised by woodland generalist species such as the Chaffinch (*Fringilla coelebs*), Coal tit (*Parus ater*), Robin (*Erithacus rubecula*) and Wren (*Troglodytidae*). Other studies indicate that availability of young woodland is par-

ticularly important for several bird species. A national comparison of Tree pipit (*Anthus trivialis*) and Lesser redpoll (*Acanthis cabaret*) abundance with changing woodland cover over time shows that abundance declines with a decrease in the availability of young woodland (Burgess et al., 2015). Studies of Black grouse (*Tetrao tetrix*) also indicate distributional shifts in populations, with population declines where pre-thicket forest matures, and establishment of new populations near to new native pinewoods (White et al., 2013). Populations were found to be greatest where new native woodland comprised approximately 30% of the land area and averaged 5 years old (Scridel et al., 2017).

A greater number of studies have begun to consider biodiversity in relation to other types of woodland in recent years, but there is a lack of controlled, field-based evidence for the effect of native woodland expansion on biodiversity. Studies suggests that earthworm (*Lumbricus terrestris*) communities are larger under re-established native woodland than surrounding moorland (Butt & Lowe, 2004) whereas studies of moths in Woodland Grant Scheme sites found lower species abundance and richness compared to mature woodland (Fuentes-Montemayor et al., 2015). A collation of vegetation surveys from over 100 years of broadleaf woodland colonisation in two abandoned fields in lowland farmland also found substantial turnover of individual species, with total flora estimated to be richest just before canopy closure, but it is noted that the methodology is limited by a patchy record and different survey methods used throughout the study period (Harmer et al., 2001).

Most evidence for native woodland is derived from reviews, landscape scale GIS or modelling methodologies, primarily focusing on the potential for increasing woodland connectivity to enhance biodiversity at the landscape scale. Reviews state that regenerating native woodland allows natural colonisation by plants and fungi, with anecdotal evidence stating that regenerating woodland in a Scottish national nature reserve supports species such as blaeberry (*Vaccinium myrtillus* L.) and bog myrtle (*Myrica gale* L.) that replace dominant grassland species (Armstrong, 2015; Bunce et al., 2014). Earlier GIS-based work focused on functional connectivity

suggested that targeting new native woodland adjacent to ancient woodland patches increases core habitat area and functional network size, enabling faster colonisation of woodland species (Bailey et al., 2006; Hope et al., 2006; Quine & Watts, 2009). In terms of the effect of planted conifer woodlands in facilitating species movement, wood ant populations have been found to make use of newly formed non-native plantations to expand, showing that these plantations can provide a suitable habitat (Procter et al., 2015). More recent modelling approaches such as circuit theory and individual-based modelling suggest that using spatially targeted woodland creation to fill regional ‘bottlenecks’ has potential improve species expansion response to climate change (Hodgson et al., 2011), but that it is difficult to accommodate for multiple species when targeting woodland creation (Synes et al., 2015). Some strategies, such as creating small woodland patches next to larger patches of existing woodland, can provide benefit to the widest range of species (Synes et al., 2015).

2.3.3 REGULATING AND MAINTENANCE ECOSYSTEM SERVICES

Studies relating to the regulation of water are also dominated by research focusing on conifer plantations. Previous reviews have concluded that woodland expansion can alleviate flooding via three main mechanisms: 1) greater water use compared to other land uses; 2) greater hydraulic roughness compared to more open habitats, having a slowing effect on flood flows; and 3) a soil ‘sponge effect’, with more organic matter and tree roots, and less soil disturbance, allowing woodland soils to hold more water (Nisbet et al., 2011; Nisbet & Thomas, 2006). There is a collection of strong evidence to suggest that conifer plantations have higher water use when compared to a variety of other land uses, and that this is associated with reductions in peak flows and reduced ‘flashiness’ in forested catchments (Heal et al., 2004; Hornung & Newson, 1986; Johnson, 1998; Nisbet et al., 2011). A single study looking at naturally regenerated Scots pine woodland concludes that it is likely to have a similar magnitude of water use compared to non-native plantations (Haria & Price, 2000). Fewer studies explicitly consider the effect of broadleaf

plantations or naturally regenerating native broadleaf woodland on flood flows, but two reviews conclude that although these types are expected to have slightly lower water use than coniferous woodland, they can still have a dampening effect on flood flows when compared to other more open land uses (Roberts & Rosier, 2005; Thomas & Nisbet, 2007). Riparian and floodplain woodland is found to be particularly effective at reducing peak flood magnitude (Broadmeadow & Nisbet, 2004; Dixon et al., 2016).

Scale is a key issue when thinking about the effect of woodland on flood control (Nisbet et al., 2011; Nisbet & Thomas, 2006). Given current evidence, the smaller the area of woodland in a catchment, the less the effect on reducing flood peak, and there continues to be little support for a significant effect on extreme flood flows at a wider landscape level (Nisbet et al., 2011). Nevertheless, there is evidence for a forest impact on flood flows at a local level, and for smaller flood events (Nisbet & Thomas, 2006), as well as more recent studies suggesting that small areas of floodplain woodland in the upper and middle catchment can have a large effect on reducing peak flood magnitude (Dixon et al., 2016).

The largest number of studies of regulating and maintenance ES (29) relate to regulation of the chemical composition of the atmosphere through carbon sequestration and storage. Evidence for the effect of afforestation on soil organic carbon (SOC) is dominated by chronosequence studies of Sitka spruce (*Picea sitchensis*) plantations. A previous review of the effect on SOC of converting grassland to forestry found inconclusive evidence, citing inherent problems of soil heterogeneity and few relevant UK datasets as an issue (Reynolds, 2007). Overall, studies suggest an initial loss of SOC due to a combination of site-specific factors (e.g. site disturbance, drainage, higher root activity/respiration, thicker litter layer), followed by a recovery and/or increase in SOC with stand age, or by the second rotation (Black et al., 2009; Byrne & Farrell, 2005; Saiz et al., 2006; Zerva et al., 2005). A long-term study of naturally regenerating native woodland found a significant increase in SOC (Powelson et al., 1998), whereas an Ireland-wide study found no significant change in SOC between afforested (either coniferous, mixed, or broadleaf) and

non-forested (paired pre-afforestation habitat) sites (Wellock et al., 2011). Taking into account carbon stored in the forest floor has a positive effect, with conifer stands in particular having significantly larger carbon stores than broadleaf or mixed stands (Wellock et al., 2011).

Studies which also consider aboveground biomass in the growing trees (i.e. total ecosystem carbon) show significant increases in overall carbon, with woodlands becoming more significant overall sinks as stands age (Peichl et al., 2012; Wellock et al., 2011). Recent analysis of silvopastoral systems suggest that they may be able to achieve a higher level of overall carbon storage than equivalent areas of either woodland or pasture (Beckert et al., 2015; Upson et al., 2016). A small number of studies consider non-carbon GHG dynamics. The evidence is limited, site specific, and difficult to generalise. The initial disturbance caused by conversion of a grassland to broadleaf plantation was found to increase nitrous oxide emissions, but this effect decreased to approximately one third the previous grassland level of emission with increasing woodland age (Mishurov & Kiely, 2010). Elsewhere, conversion of grassland to Sitka spruce (*Picea sitchensis*) caused an increase in nitrous oxide emissions, but a decrease in methane emissions, whereas an Ash (*Fraxinus excelsior*) plantation had no clear effect on either GHG (Benanti et al., 2014). Another study considering three transitions (bog planted with pine (*Pinus*), grassland planted with pine, and birch (*Betula*) regenerating on moorland) found that afforestation resulted in a stable and consistent sink of methane in all cases (Nazaries et al., 2013).

In terms of modelling approaches, various national scale models predict that woodland expansion can sequester significant amounts of carbon, especially fast growing Sitka spruce (*Picea sitchensis*) (Nijnik et al., 2013), but also broadleaf or native woodland (Perks et al., 2010; Sozanska-Stanton et al., 2016). In a comparison of UK climate mitigation actions, afforestation of acid grasslands with broadleaf woodland is predicted to sequester carbon at the highest rate compared to a range of other options (Sozanska-Stanton et al., 2016). The economic value of sequestration potential depends on choice of discount rate, yield class, and social value of carbon (Bateman & Lovett, 2000; Brainard et al., 2009). Scenario analysis suggests that increasing plant-

ing on lowland agricultural land would be more beneficial than the current trend for planting on low quality upland land, but this assumes a loss of carbon from initial site preparation and drainage (Brown et al., 2014b).

2.3.4 CULTURAL AND PROVISIONING ECOSYSTEM SERVICES

The single paper focusing purely on a provisioning service uses a mathematical model to estimate the effect of an agroforestry system on sheep yields and timber production. Results suggest that such a system can be financially viable, but that it is very sensitive to discount rate and timber prices (Doyle et al., 1986). Only two papers consider purely cultural ES, considering the impact of woodland expansion in rural case studies in Ireland (Carroll et al., 2011; Dhubháin et al., 2009). Perceptions of forestry and afforestation differed significantly between regions, with one case study with a longer history of forest cover showing positive values for amenity and recreation, whereas another had negative perceptions linked to the dominance of Sitka spruce, which was considered to have negligible amenity value (Dhubháin et al., 2009). Another case study comparison showed similarly mixed reactions to afforestation, with large, dense blocks of coniferous plantations exacerbating feelings of social isolation in one region, while in the other contributing to greater landscape diversity and feelings of inspiration (Carroll et al., 2011). A more locally nuanced approach to forest planting is suggested to achieve greater social acceptance of future woodland expansion (Carroll et al., 2011).

2.3.5 ECOSYSTEM DISSERVICES

Some evidence points towards the potential negative effects of afforestation, in particular relating to the regulation of the chemical condition of freshwaters. There is strong evidence to suggest that coniferous woodlands are more effective at scavenging acid pollutants compared to other land uses, and thus that they can have an acidification effect on soils and freshwater (Allen &

Chapman, 2001; Jenkins et al., 1990; Rees et al., 1995; Waters & Jenkins, 1992). Whether broadleaf or native woodlands have the same effect is still the focus of investigation, with the only two field-based studies having contrasting, location specific results (Gagkas et al., 2011; Ryan et al., 2012). However, reduced atmospheric deposition, soil buffering capacity, and sustainable forest management initiatives such as the use of more diverse species mixes and riparian buffer strips are expected to reduce acidification (Curtis et al., 2014; Ferrier et al., 1993).

In addition, despite the potentially beneficial effect of flood attenuation, research has highlighted that there could also be a negative effect of afforestation on water yield during dry weather. There have been contrasting results relating to groundwater recharge but modelling of a range of potential afforestation scenarios (including both conifer and broadleaf woodland) has predicted a maximum decrease in groundwater levels of less than 0.3m, concluding that an increase in woodland cover may not exacerbate water stress (Zhang & Hiscock, 2010). Allen & Chapman (2001) reviewed the effect of forest cover on groundwater resources and concluded that generally woodland expansion (again considering multiple types of woodland) can reduce groundwater yield through interception and transpiration, with both potential positive and negative effects dependent on site specific factors, including land cover, rainfall, infiltration, evapotranspiration and spatial distribution of the water table.

2.3.6 RELATIONSHIPS BETWEEN ECOSYSTEM SERVICES

A small proportion of studies (21) consider more than one ES and could not be assigned to just one service or metric (Figure 2.3). Within these studies, there are varied combinations of topics considered, with study designs dominated by reviews, spatial analyses and mixed-method approaches. Overall, these findings highlight that there are a limited number of studies and no consistent method for assessing the effect of woodland expansion on more than one ES at a time. This is an important finding given the need to understand relationships between ES for effective policy making. Further developing this challenging topic is beyond the scope of this review and

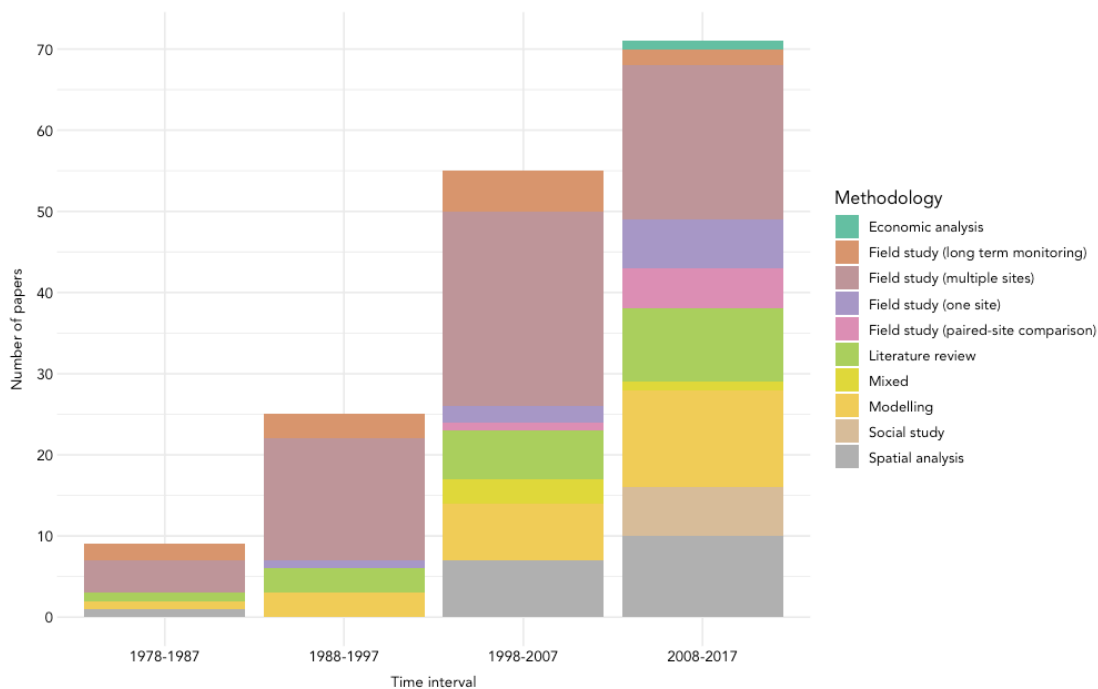


Figure 2.4: Changes in the methodologies used to study afforestation over time

is an important area for future research. This should build upon valuable work already carried out to assess relationships between ES (Lee & Lautenbach, 2016).

2.3.7 STUDY DESIGN

There has been an increase in the number of papers focusing on woodland expansion over time, with field-based methodologies dominating (86 studies), but there has been a diversification in the methodologies employed over time, with social studies in particular being a relatively recent occurrence (Figure 2.4). Table 2.2 summarises the methodologies employed and assesses their applicability to ES research. Given the long term nature of woodland development, and the likelihood that any resulting ES provision will vary over time, there is an obvious lack of long-term monitoring studies, with literature reviews, modelling, and chronosequence studies which

Table 2.2: The strengths and weaknesses of the methodologies employed by the 160 studies, in relation to the ES categories they consider

Study Methodology	Biodiversity	Regulating & Maintenance	Provisioning	Cultural	Multiple	TOTAL	Strengths & Weaknesses
Field study (one site)	2	7	NA	NA	NA	9	Site specific, difficult to generalise findings
Field study (multiple sites)	29	36	NA	NA	3	65	Consider effect across many sites with different settings e.g. pre-afforestation land use, soil type, tree species, stand age. Chronsequences attempt to tackle effects through time.
Field study (long term)	5	7	NA	NA	NA	12	The ideal type of study for long-term woodland development, but limited in number with very varied methodologies
Modelling	5	16	1	NA	1	23	Offer tools for exploring the effect of long-term land use changes and their effect. Address complex interactions. Ideally parameterised with data from field studies, but often lack testing/validation
Spatial analysis	13	3	NA	NA	2	18	Consider effect across landscapes. Attempt to consider synergies, bundles, trade-offs
Review	NA	12	NA	NA	7	19	Collation of wide range of evidence
Economic analysis	NA	1	NA	NA	NA	1	Place economic value on services. Useful for cost-benefit analysis
Social study	NA	NA	NA	2	4	6	Consider values and preferences associated with afforestation, often across ES categories
Mixed	NA	NA	NA	NA	4	4	Varied and inconsistent design. Some consider multifunctionality/multiple benefits

examine the effect of different stand ages on the species or ES in question, perhaps aiming to fill this gap.

2.4 DISCUSSION

Given the research questions outlined in the introduction, this section considers how the evidence base outlined in the results can be used and built upon to design strategies for afforestation which maximise biodiversity and ES provision. First, the evidence base outlined by the review is compared and contrasted to wider international findings, and evidence gaps are highlighted. Following this, considering the evidence base outlined by the review, this final section aims to reflect upon how this base might be used to develop effective strategies for woodland expansion in the UK.

2.4.1 STRONG EVIDENCE FOR PUBLIC GOODS

At a global scale, reforestation has been identified as the land-based strategy with the greatest potential for climate mitigation (Griscom et al., 2017), and the UK level evidence reported here supports this. Despite this, the assumption that faster growing tree species (such as Sitka spruce (*Picea sitchensis*) planted extensively in the UK) will be most beneficial to carbon sequestration has recently been challenged (Körner, 2017). These productive forests typically serve the timber industry, and thus any carbon sequestered has shorter residence times than slower growing species, with wood products only considerably contributing to carbon sequestration if their overall use rises (Körner, 2017). For the carbon pool to significantly change in the long term, the maintenance of slower growing old-growth stands, which also increase and protect soil organic carbon (SOC) stocks, is expected to be more beneficial (Körner, 2017; Schwartz et al., 2017). Although evidence for carbon sequestration in old-growth stands in the UK (as a function of woodland/land use history) is limited, international evidence clearly shows the importance of old-growth stands in this and other contexts (Körner, 2017; Luyssaert et al., 2008). However, in countries that are net importers of timber, such as the UK, it is important that strategies for climate mitigation consider the protection and maintenance of old-growth stands alongside efficient management of faster growing tree species to meet demands for wood products and prevent moving issues of carbon sequestration to other countries. Overall increases in the amount of carbon sequestered are likely to be as a function of expanding woodland cover, retaining old growth stands and greater use of timber products in buildings.

In terms of SOC, the results align well with other reviews. Both European (Bárcena et al., 2014) and global (Guo & Gifford, 2002; Laganière et al., 2010) meta-analyses found a strong influence of former land use, with afforestation having a more positive impact on SOC on cropland soils than pastures or natural grasslands. A more recent global meta-analysis taking into account sampling depth and carbon-nitrogen interactions found a significant increase in stocks on both cropland and pasture 30-50 years after afforestation, with stocks before this being either depleted or

unchanged (Li et al., 2012). Given these findings, together with established UK guidelines which prevent afforestation on deep peat soils (a peat layer greater than 50cm) (Forestry Commission, 1998), it seems likely that woodland expansion strategies can benefit soil carbon stocks.

The strong evidence found for woodland expansion's contribution to water flow regulation and flood control aligns with international reviews showing reduced water yield with afforestation (Dijk & Keenan, 2007; Farley et al., 2005). Woodland expansion is more likely to regulate local 'flash' floods than major events, and there are a wide variety of factors that are important to take into account when determining the overall impact on water resources, including tree species physiology, plantation design and management, the benchmark against which changes are assessed, and the water system (or catchment) configuration (scale of afforestation, timing of impacts, location in the catchment) (Dijk & Keenan, 2007). The knowledge gap for the effect of native woodland is found elsewhere, with a study of the key drivers (e.g. species composition, tree canopy status) of natural forest water use highlighting gaps in current functional knowledge regarding water use by many forest tree species (Aranda et al., 2012). In terms of the potential disservice of acidification of freshwaters, the evidence presented here suggests that this effect is location specific, depending on the soil buffering capacity, tree species, and level of atmospheric acid deposition. Thus, acidification is not an inevitable consequence of afforestation (Hong et al., 2018), especially when taking into account guidelines in the European Water Framework directive to reduce acid pollution, and national guidelines to avoid planting in acid-sensitive catchments (Forestry Commission, 2014b).

2.4.2 RETHINKING BIODIVERSITY METRICS

Forest biodiversity research presents particular challenges, given the long timescales and often large spatial scales over which it takes place, as well as huge variation in study design (Spake & Doncaster, 2017). The results presented here illustrate this, with a variety of methodologies used, and a lack of long-term monitoring of changes in biodiversity with woodland expansion. This

review highlights the patchiness of evidence available for the effect of woodland expansion on biodiversity, with evidence limited to a small number of bioindicators (e.g. carabids, birds) and biased towards dominant woodland types in particular areas of the UK (e.g. non-native conifer plantations in Scotland). New experimental designs are aiming to address these challenges. For instance, a large-scale UK-based natural experiment utilising historic woodland creation sites (Watts et al., 2016) has shown that bird species responses to woodland creation depend on local and landscape-scale factors that interact across time and space (Whytock et al., 2017).

There is an obvious bias towards studies of the effect of conifer plantations on an also limited set of indicator species, with this being attributed to the history of woodland expansion in the UK referred to in the introduction. Globally there has been much debate about the implications of plantation forests for biodiversity (Brockerhoff et al., 2008), and it has been suggested that much of the literature reporting lower biodiversity in plantation forests has been based on inappropriate comparisons such as with natural or native forest rather than alternative human land uses (Stephens & Wagner, 2007). This is not the case for the UK evidence, with most comparisons being made to previous or adjacent land use (e.g. either grassland or agriculture). The effect of plantations on biodiversity has been found to vary considerably depending on the original land cover, with positive effects most likely to occur when plantations are established on degraded or intensively used lands (Bremer & Farley, 2010). This agrees with the finding that afforestation on improved grasslands has a more positive effect on species diversity than afforestation on semi-natural grasslands. Generally, given the evidence presented here, fostering and maintaining diversity in new woodland species mix, structure, and stand age over time is expected to be beneficial to a range of taxa. The lack of strong evidence for the effect of naturally regenerating native woodland on biodiversity means that no firm conclusions can be made, and this is an important area for future research.

Given the likely species turnover from open-ground specialists to generalists and forest-specialists shown by this review, and evidence for the development of woodland flora over

long time-scales, any assessment of overall changes in biodiversity will inevitably involve a subjective choice between species assemblages. A shift in focus of the biodiversity metrics used could be more informative for land use change decisions. Most of the evidence here is based on plot-based samples for single taxa, defined as alpha diversity. It has been suggested that measures of beta (spatial) and gamma (total) diversity may be better suited to assessing land use change at the landscape level (Wehrden et al., 2014). Long-term studies could also help us to consider the time over which species groups/assemblages fluctuate after land use change, with slower response by specialist species compared to more generalist species. There is also increasing focus on metrics such as functional diversity, or the roles that groups of species play in an ecosystem (Aerts & Honnay, 2011). Only one paper found by this review uses functional diversity as a metric (Spake et al., 2016), and future research should focus more on metrics such as this. There are also increasing numbers of attempts to link biodiversity to ecosystem services, with the majority of relationships being found to be positive, although many are still poorly understood (Harrison et al., 2014). This is an important area for further research.

2.4.3 EVIDENCE GAPS

The significant lack of evidence for the effect of woodland expansion on provisioning and cultural ES is interesting given that the primary objective of many woodlands is for fibre (i.e. timber), and that they also play major cultural and recreational roles in the UK and beyond (Ward & Watson, 2018). It is proposed that biomass and timber are perhaps taken for granted in terms of ES provision, due to their very tangible outputs, and that yields are most commonly recorded in other forms (e.g. in national inventories rather than academic research papers). Recreation is a commonly used indicator for cultural ES from woodlands (Edwards et al., 2009; Moseley et al., 2017; Quine et al., 2011; Scarpa et al., 2000). It may not have been picked up by this review due to the focus of the search strategy on woodland creation, as it is easier to measure recreation use in established woodlands than to monitor its development over time. Methodologies to measure

other cultural ES (i.e. aesthetic, heritage, symbolic, existence values) have only begun to be significantly developed in recent years (Chan et al., 2016; Kenter, 2016), and the lack of evidence may be compounded by the fact that people may more easily recognise values for established woodlands, but less so for newly created ones. This knowledge gap is a common problem beyond the UK. The social aspects of ecological restoration, in particular negative ones such as farmers' worries about loss of land, have not been studied as frequently (Bullock et al., 2011), and cultural ES were not reported on in a global meta-analysis studying the effect of ecological restoration on biodiversity and ES, as cultural services were not measured explicitly by any of the restoration studies reviewed (Rey Benayas & Bullock, 2012).

2.4.4 WHAT DOES THIS MEAN FOR DEVELOPING STRATEGIES FOR WOODLAND EXPANSION THAT MAXIMISE BIODIVERSITY AND ES PROVISION?

Given the multiple objectives for woodland expansion in the UK and internationally, there is a need to develop strategies which promote synergies and minimise negative trade-offs between ES and with other land uses. Considering the evidence base outlined by this review, this final section aims to reflect upon how this base might be used to develop effective strategies for afforestation in the UK.

INCENTIVISE PUBLIC GOODS WITH STRONG EVIDENCE BEHIND THEM

The results of this review show that evidence for the effects of woodland expansion is mostly biophysical and can be classified as relating to 'public goods', in that it shows substantial but general and largely intangible benefits to society through climate mitigation and flood risk reduction. It has previously been recognised that the strong desire for change (e.g. policy aims for afforestation) is driven by public good values, and that the public good argument may simply not be effectively operationalised, with incentives such as subsidies and grants not being put be-

hind the evidence to encourage planting (Slee, 2006). To date, payments as part of the Common Agricultural Policy (CAP) have had a very strong influence on land use in the UK and Europe more widely, with agricultural production being prioritised and subsidised (Van Zanten et al., 2014).

Reform of agricultural/land use subsidies could create new financial incentives for woodland expansion, drawing on the evidence base for carbon sequestration and flood regulation benefits in particular. However, reform such as this has been noted to present a formidable challenge, with money for woodland benefits having to compete with other grant systems (Slee, 2007; Slee et al., 2014). Spatially explicit research on locating plantation forestry in New Zealand suggests that where net private benefits are negative, public support such as Payment for Ecosystem Services (PES) should be implemented (Barry et al., 2014). PES would differ from traditional woodland grant schemes by providing a more continuous stream of income for the ES provided. The recently published 25 Year Plan for the Environment emphasises that whatever may follow the CAP post-Brexit will be strongly focused on a natural capital approaches, with a new Environmental Land Management System which will pay farmers public money for public goods (HM Government, 2018). This shows that there is a significant opportunity for public funds to be put behind the evidence presented here for the benefits of woodland expansion.

FURTHER DEVELOP INTEGRATED MODELLING APPROACHES TO ASSESS LAND MULTI-FUNCTIONALITY

Policy objectives for woodland expansion in the UK aim for ‘multiple benefits’, but there is very limited spatially-explicit evidence for the effect of afforestation on more than one ES at a time. Given the increasing focus in ES research on developing integrated modelling approaches (Costanza et al., 2017) and assessing ES relationships (Cord et al., 2017), this is a clear area for further research. Within woodlands, the potential for multi-functionality is high. A European-wide study has shown that there is a high unrealised potential for multi-functionality in EU

forests, with this being dependent on management (Plas et al., 2017), while a UK review has shown that diverse management is beneficial to ES provision (Sing et al., 2017). Nonetheless, despite the high potential for multifunctional woodlands, at the landscape scale, the complexity of trying to achieve multi-functionality is huge. As a target, it is generally considered at the landscape scale, meaning that attempts to achieve multi-functionality must tackle complex interactions among multiple land covers, land uses and stakeholders (Mastrangelo et al., 2014). Amongst these stakeholders, there are a multitude of different values, and balancing the well-being of diverse stakeholders often involves different types of trade-offs, some of which may be ‘taboo trade-offs’ between morally incommensurable values (Daw et al., 2015).

Further complexities relate to methodological shortcomings. Landscape assessments are usually based on the transference of ES values obtained at ecosystem level (Mastrangelo et al., 2014). This issue is reflected by the results of this review, with most evidence being collected at the site scale, despite ES assessments requiring information relevant or applicable to larger scales. The choice of ES assessed is also often dependent on the availability of data and models, and assessments rarely incorporate stakeholders visions and preferences meaningfully (Mastrangelo et al., 2014), meaning that the ES that really matter to local people are not always evaluated. There is also much debate relating to alternative strategies of land sharing (making farmland more friendly for biodiversity) and land sparing (making more space for un-farmed habitat). Discussion in this debate has become polarised based on misinterpretation of the many definitions and related concepts, and it is argued that insights from use of the model should be integrated with social and political knowledge, while recognising that choices made relating to land use change will always be underpinned by ethics (Phalan, 2018). Cord et al. (2017) highlight the potential for scenario approaches to further explore the biophysical constraints of landscapes and potential limitations for multi-functionality, but also acknowledge that significant challenges remain in terms of integrating the biophysical focus of many studies with stakeholder preferences. Given the lack of research on stakeholder preferences illustrated by this review, the next section con-

siders why this may be the case, and how further research might tackle this.

SOCIAL BARRIERS

As previously noted, woodland expansion, in particular in relation to its potential role in climate change mitigation, has been described as a ‘wicked problem’ (Duckett et al., 2016). Stakeholders have different perspectives and goals, both in relation to the successful implementation of woodland planting, and to climate change in general (Duckett et al., 2016). Despite significant evidence for public goods arising from woodland expansion, barriers to woodland creation have been shown to be mostly social. Studies have shown that landowners may be reluctant to plant trees for many reasons. Despite decades of Forestry Commission grants for new woodland and attempts to create voluntary carbon markets for woodland (Forestry Commission, 2014a), the desired levels of planting have not been achieved (Thomas et al., 2015). There is a wide cultural gap between forestry and farming in the UK (Duesberg et al., 2013; Scambler, 1989; Slee et al., 2014; Wynne-Jones, 2013) and a bureaucratic application process, as well as a lack of information and advice, have been further cited as discouraging factors (Lawrence & Dandy, 2013; Lawrence & Edwards, 2013; Moseley et al., 2014). The forest ownership structure has had a major role in this divide, with rights to trees on tenanted land often vested in the landlord, resulting in alienation of tenants from the farm woodland on their land (Wong et al., 2015). As a large majority of land and forests in the UK and Ireland are owned privately, woodland expansion requires the involvement of private landowners, a large number of whom have been found to have generally negative attitudes to woodland creation (Lawrence & Dandy, 2013). The public good argument can also not be assumed to be inherently effective in generating action. The focus on woodland for carbon sequestration in Wales has been characterised as a distraction from the development of better governance strategies that learn from literature on farmer behaviour and uptake of previous environmental schemes (Wynne-Jones, 2013). Real or perceived trade-offs of new woodland with the ES or profitability of other land uses may have a role in holding wood-

land expansion back, and disagreements are often rooted in the core values and behaviours of land managers (Slee et al., 2014). Research shows that ‘nudge’ type approaches, along with deliberation with stakeholders, may help to overcome misconceptions (Moseley et al., 2014). These can include providing defaults and prompted choices e.g. adding woodland creation (with an emphasis on climate change mitigation) to application forms for grants for land management (Moseley et al., 2014).

TRADE-OFFS AND SYNERGIES

Taking into account these barriers, elsewhere it has been argued that the focus of previous research on biophysical potential for multi-functionality has obscured the importance of social factors, such as taboo trade-offs, or incommensurable values (Cord et al., 2017; Daw et al., 2015). In Scotland in particular, embedded traditions and personal views and passions need to be balanced with aspirations for diversification, resilience, and ecosystem approaches (Bowditch et al., 2019). The emerging Forest and Landscape Restoration (FLR) agenda argues that we lack the knowledge needed to operationalise and implement restoration successfully at different scales whilst also addressing the needs and aspirations of landholders, and that however much evidence supports the potential value of woodland expansion, social acceptability often lags behind (Chazdon et al., 2017; Ghazoul & Chazdon, 2017). With very few studies relating to public or land holder preferences for afforestation and land use change, this review confirms this knowledge gap. However, the limited number of findings do suggest that a more locally focused approach to woodland expansion may help to ensure that strategies take account of public preferences.

Any type of land use change is expected to generate winners and losers, with conflicts based on stakeholder values, and it is argued that there is increasing need for deliberative and participatory research methods to understand these conflicts (Martinez-Harms et al., 2015; Valluri-Nitsch et al., 2018). Significant challenges remain in terms of choosing standard values for decision making around ES (Cord et al., 2017), and attempts to develop these at the national scale have

been criticised, due to the difficulties in reaching consensus developing appropriate indicators for particular settings (Slee, 2007). Trade-offs and synergies with other land uses, and between ES, are going to be context specific (Chazdon et al., 2017) and therefore local assessments which involve active participation of land managers are argued to be necessary to make discussions and decisions around socio-cultural effects of woodland expansion clearer (Slee et al., 2014). Recent work advocating the use of relational and shared values between stakeholders will be particularly beneficial (Chan et al., 2016; Kenter, 2016), as may working with visions, or ‘positive scenarios of ideal futures’, which can help to highlight areas of common ground and initiative discussion and collaboration between stakeholders.

2.4.5 IMPLICATIONS

Overall, given the strong evidence for public benefits from woodland expansion, together with social barriers and a lack of evidence for socio-cultural effects, there is a need for more context specific, participatory research with multiple stakeholders to better assess trade-offs and synergies generated by afforestation in different contexts. Although not a novel idea, an increasing number of different areas of research, as well as practical landscape scale initiatives, have emerged in recent years which can guide further research or actions in this area. In a Scottish context, it has been argued that locally focused action research and collaborative learning will help to better understand and resolve conflicts (Slee et al., 2014), and the Regional Land Use Partnerships piloted as part of the Scottish Land Use Strategy have been an attempt to put this into action (Scottish Government, 2016). Lessons from these may be applicable to the UK as a whole and more widely. Many other landscape scale initiatives internationally are piloting similar ideas, increasingly focused on involving local stakeholders in dialogue and decision making for sustainable development, for example Model Forests (Bonnell et al., 2012) and UNESCO Biosphere Reserves (Ishwaran et al., 2008). Globally, the FLR agenda proposes a framework for integrating agricultural and restoration/environmental policies, conceding that there will be a mixture

of ‘muddling through’ with the best available evidence (Sayer et al., 2008) whilst also developing cross-level environmental governance (Brondizio et al., 2009; Chazdon et al., 2017). Overall significant challenges remain in terms of improving understanding and coordination at local levels, while also coordinating actions at a national level to ensure that policy goals for woodland expansion are met.

2.5 CONCLUSIONS

This review has characterised the evidence base for the effect of woodland expansion, encompassing afforestation, reforestation, woodland creation, and forest landscape restoration, on ecosystem services in the UK. Currently, the largest body of evidence exists for the effects of conifer plantations and public benefits such as carbon sequestration and water regulation. Research should aim to tackle evidence gaps relating to a broader consideration of other taxa and metrics for biodiversity; natural regeneration; native woodland; farm woodlands; cultural and provisioning ES; and particularly multiple ES. It is recommended that site specific and, if possible, long-term research should be carried out on naturally regenerating and new farm and community woodlands in particular. The public good argument needs to be more effectively operationalised in order to meet planting targets, perhaps through new forms of incentives relating to Natural Capital or Payment for Ecosystem Services (PES) schemes. In addition to this, it is argued that context specific, participatory research and implementation may be the best way forward in terms of assessing the effect of woodland expansion, and in making the best decisions for land-use in the future.

3

Green Gold to Wild Woodlands; understanding stakeholder visions for woodland expansion in Scotland

The following chapter is largely based on a published paper (Burton et al., 2018a). VB carried out the research and wrote the manuscript, with comments and guidance from supervisors (co-authors), and is grateful for comments from two anonymous reviewers. Thanks are extended to everyone who assisted with the running of the workshop in March 2017. Facilitation was carried

out by Osbert Lancaster, Marc Metzger, Darren Moseley, David Edwards, and Michael Dunn. Notetakers were Aster de vries Lentsch, Jacob Ainscough, Anja Liski, and Jonathan Morley.

3.1 INTRODUCTION

What does society want from its relationship with the land in the 21st century? With a ‘perfect storm’ of ecological and social challenges converging (Beddington, 2009) and the recognition that we are exceeding planetary boundaries (Rockström et al., 2009), there is a strong argument to be made for transformative changes in the ways that we coexist with the natural world. However, sustainability remains a contested concept, with a wide range of possible interpretations of the term grounded in different world-views (Beder, 2006; Giddings et al., 2002). We are now in an age of post-normal science, characterised by uncertainty and plural values (Funtowicz & Ravetz, 1993; Ravetz, 2004) This is especially obvious in the case of debates surrounding sustainable land use and land use change.

Scotland has an ambitious national Land Use Strategy, which builds on wider shifts from sectoral to multifunctional land use (Glass et al., 2013; Stockdale & Barker, 2009; Warren, 2002) to define overarching principles for sustainable land use (Scottish Government, 2011, 2016). However, there remain contested views about land use among many different stakeholders, as well as inequalities in terms of property rights and resources between those stakeholders (Bonn et al., 2009; Glass et al., 2013; Valluri-Nitsch et al., 2018). The agenda for woodland expansion, in the form of a government aspiration to increase woodland cover to 21% by 2032 (Forestry Commission, 2009; Scottish Government, 2018) provides an interesting lens for this contention. Indeed, achieving woodland expansion goals in Scotland has been classified as a ‘wicked problem’ (Duckett et al., 2016; Rittel & Webber, 1973). This is due to the difficulty of implementation in the face of conflicting food and climate change policy goals, low acceptability of woodland planting among Scottish farmers, volatile stakeholder perceptions, and grazing pressure from high deer populations (Duckett et al., 2016; Environment Climate Change and Land Reform Committee,

2017).

Woodland cover in Scotland is low both historically and in comparison with other countries in Europe (Thomas et al., 2015). It also has one of the most concentrated patterns of land ownership in the world, a legacy of feudal tenure (McMorran, 2016), as well as the largest average forest holding size in Europe, dominated by large estates and absentee investors (Forest Policy Group, 2011). A recent comparison of ownership structures across Europe shows that they are rarely formed or influenced by policy, but Scotland is an exception to the rule in this regard, with the 2003 Land Reform (Scotland) Act introducing the Community Right to Buy (Weiss et al., 2018). With this, the Scottish Government aims to diversify the concentrated pattern of land ownership. Furthermore, the Community Empowerment (Scotland) Act 2015 provides a framework for empowering community bodies through the ownership of land and buildings and strengthening their voices in decision making (Skerratt et al., 2016).

Since the end of WWI, woodland cover has increased from 5% to 19% via the expansion of the public Forestry Commission estate, and a succession of grant schemes and tax incentives supporting private woodland planting. This increase was characterised by an initial dominance of conifer investment forestry, shifting towards increasing emphasis on broadleaved woodlands for multiple, predominantly environmental, purposes (Wong et al., 2015). In recent years, annual woodland creation targets have consistently been missed, and the overall increase in woodland cover has stalled (Forestry Commission, 2017). Many valuable ecosystem services (ES) are provided by woodlands in the UK (Quine et al., 2011; Sing et al., 2017; UK National Ecosystem Assessment, 2011), and globally forest restoration is accepted as a strategy to tackle climate change, biodiversity loss, and increased flood risk (Bullock et al., 2011; Rey Benayas & Bullock, 2012). Recommendations from an independent review improved a woodland planting grant application process previously criticised as being overly bureaucratic (Mackinnon, 2016) and there is broad cross-party support in Scotland for increasing woodland cover. However, several barriers to further woodland creation remain, including a continuing farming-forestry divide and con-

cerns around real or perceived conflicts with other land uses (Lawrence & Dandy, 2013; Lawrence & Edwards, 2013; Moseley et al., 2014). The forest ownership structure has had a major role in this divide, with rights to trees on tenanted land in Scotland vested in the landlord, resulting in alienation of tenants from the farm woodland on their land (Wong et al., 2015).

Futures-thinking, encompassing a wide range of scenario approaches, aims to address psychological and other barriers to thinking openly and creatively about future possibilities and their implications for planning (Cork, 2016). Scenario planning offers a framework for developing more resilient policies when faced with uncontrollable, irreducible uncertainty (Metzger et al., 2018; Peterson et al., 2003). In particular, ‘visions’, or normative scenarios which revolve around positive descriptions of desired futures (Rounsevell & Metzger, 2010), are seen as a way to pose challenges, stimulate dialogue between stakeholders, and build consensus on shared priorities (Pérez-Soba et al., 2018). In order to effectively mobilise science for sustainability, we must manage the boundaries between knowledge and action in ways which balance salience (relevance to decision makers), credibility (scientific quality), and legitimacy (respecting diverse values and beliefs) (Cash & Clark, 2003). As such, it is argued that stakeholder engagement, and participatory methods with high saliency and legitimacy, should be used to better define normative visions of future worlds (Rounsevell & Metzger, 2010). Furthermore, understanding and acknowledging different visions is an important step towards collaboration between stakeholders (Valluri-Nitsch et al., 2018). Previous research has shown that participatory scenario development can help people learn about the issues being addressed and how they can work together to deal with them, building adaptive capacity among stakeholders to implement change (Reed et al., 2013). It is also increasingly argued that better narratives or ‘story-telling’ are required to translate science through to evidence-based policy (Davidson, 2017), and visions could have an important role to play in this regard. Spelling out the how’s of achieving a vision is expected to be particularly beneficial (Metzger et al., 2018; Shipley & Michela, 2006). The topic of woodland expansion is particularly suited to scenario research given its long-term nature, the many

uncertainties that need to be taken account of, as well as the need to understand the trade-offs which will inevitably need to be made when planning land use decisions.

This paper presents a novel mixed-methodology used to elicit five distinct visions for how woodland expansion might ideally unfold in Scotland over the 21st century. The objectives were:

- 1) To use existing published sources and stakeholder input to determine the values that different Scottish stakeholders have for woodland expansion, and to translate these into alternative storylines, or visions.
- 2) To identify areas of common ground and divergence between the visions.

3.2 METHODS

Stakeholders were identified across particular sectors, ensuring that representatives were included from each main group: the public sector, private sector, charitable sector, and community groups (Colvin et al., 2016; Durham et al., 2014). This identification was carried out by the principal researcher, and in consultation with co-authors, using an interest/influence matrix, where stakeholders are placed on a matrix according to their relative interest and influence (Durham et al., 2014; Reed et al., 2009c). Selection maintained an organisational, Scottish focus, aiming to identify all stakeholders with a strong interest in, or influence on, forestry and woodland expansion in Scotland.

3.2.1 CONTENT ANALYSIS TO UNDERSTAND VIEWS ON WOODLAND EXPANSION

For each stakeholder, a search was carried out on their website to find material relating to the stakeholder organisation's aims or vision for woodlands and forestry in Scotland. These materials, including a range of published documents and webpages, underwent an iterative process of

inductive coding (Bryman & Burgess, 1994) using NVivo software. Themes relating to how each organisation viewed woodlands and their future development were extracted, and structured within broader Society, Technology, Environment, Economy, Policy and Governance (STEEP) categories (Rounsevell & Metzger, 2010). STEEP analysis is commonly used in long-range business or environmental planning, and encourages clustering of important drivers and themes relating to a particular topic within each category (Bradfield et al., 2005). The main coded themes within each STEEP category are shown in Appendix B.

3.2.2 DEVELOPING DRAFT WOODLAND EXPANSION VISIONS

The themes from the content analysis were used to develop draft visions. Scenarios, including visions, can be developed in a number of different ways, but a common approach is to split identified themes using a two-by-two matrix based on four ‘critical elements’ (Cork, 2016). The critical elements were chosen based on consistently recurring key themes identified by the content analysis. The coded themes within each STEEP category were then positioned on the matrix (Appendix B), resulting in five clusters, which were developed further to produce five visions for woodland expansion. Although there was some overlap, and a gradient of themes between clusters, outlying themes were used to justify distinct clusters. Using the information coded from the documents, each clustered draft vision was named, described, and a narrative further developed in terms of what that vision meant for the desired woodland types, locations, resulting ecosystem services and governance structures. This involved a certain amount of interpretation, but this was a key reason for asking for direct stakeholder input and feedback, to check whether the clustering carried out was appropriate.



Figure 3.1: The workshop hosted 18 participants from a range of organisations and sectors. The pictures show the break-out tables used to host vision-specific discussions, the stylised landscapes and tiles used to support discussions, and a ranking exercise used to assess participant's views on the likelihood of reaching a common vision for woodland expansion.

3.2.3 STAKEHOLDER FEEDBACK TO FINALISE THE VISIONS

A full-day workshop was organised to receive feedback and input into how the draft visions were created and presented (Figure 3.1). The workshop aimed to develop further understanding about which ecosystem services landscapes would ideally provide under each vision and which woodland types would contribute to providing these. Participants were also asked which actors and governance mechanisms could assist in achieving each vision. Invitations to attend a workshop were sent out to 71 organisations. 29 people agreed to attend the workshop, with 18 of these able to make it on the day. During workshop planning, participants were assigned to groups with the vision that best aligned with their interests. The reduced numbers on the day meant that planned groups had to be rearranged and one group dropped. As there was minimal representation for the *Wild Woodlands* vision, this group was dropped from the workshop. In order to receive input on this vision, four additional stakeholders whose organisational views aligned with *Wild Woodlands* were interviewed separately. The interviews were designed using the same materials and questions as used in the workshop.

The list of organisations represented by both the workshop and interviews is given in Table 3.1. Representation of stakeholders across sectors was dominated by NGOs (9) and was fairly even between public and private (5 and 4 respectively). Although invited, no one from the community sector was able to attend. However, the NGO Reforesting Scotland, who were in attendance, have a strong remit to encourage local communities to manage their woodlands. Following suggestions from these stakeholders, seven new documents were also coded and were included in the final analysis (Appendix B). Stakeholders were assigned to the draft vision that best aligned with their expertise and published objectives, and formed break out groups for vision-specific discussions. Others have concluded that future scenario research needs to make more effective use of visualisation techniques (Reed et al., 2009c). Both the workshop and interviews used stylised graphical materials to provide prompts for landscapes, woodland types, ecosystem services and actors/stakeholders (Metzger et al., 2018). A number of materials were used

Table 3.1: A summary of the organisations involved in the workshop and semi-structured interviews, by sector

Sector	Organisations
Public sector	Forestry Commission Scotland, Forest Enterprise Scotland, Scottish Government (Land and Biodiversity Team), Scotland's Futures Forum, Cairngorms National Park Authority
Private sector	National Farmers Union, Tilhill Forestry, Scottish Land and Estates, Wild Media
Non-Governmental Organisation (NGO)	Confederation of Forest Industries (Confor), Royal Society for the Protection of Birds (RSPB), National Trust for Scotland, Reforesting Scotland, Woodland Trust, Soil Association, Association of Scottish Hardwood Sawmillers, Trees for Life, John Muir Trust
Research	James Hutton Institute, Kings College London
Community sector	No attendees

for both workshop and interviews. Large stylised landscapes representing lowland and upland environments were adapted from existing materials developed by Adaptation Scotland. In addition, a graphic design company was used to produce illustrations of different woodland types, ecosystem services, and potential actors expected to influence land use and woodland expansion (e.g. government agency, private landowner). Prior to the workshop and interviews, woodland type categories were chosen using guidance from the National Forest Inventory, Forestry Commission guidance on native woodland, as well as WEAG recommendations (Woodland Expansion Advisory Group, 2012). A wide range of woodland types were included as prompts to provide sufficient detail and options for different combinations or priorities. During analysis these were grouped into categories for simplification/visualisation purposes (Table 3.2). Vision specific discussions were split into three sessions. The first involved discussing the draft vision as it had been described from the content analysis, and suggesting changes. The second used the stylised landscapes. The smaller tiles representing woodland types were placed on the landscapes by participants, to represent the types of woodland they wanted in the vision, and where they ideally saw new woodlands being located. Following this, participants were asked to choose five

Table 3.2: A description of all the woodland types included within each wider woodland category

Woodland category	Woodland types
Native	Upland birchwood; upland mixed ashwood; native pinewood; native scrub; upland oakwood; wet woodland; lowland mixed deciduous
Plantation	Conifer; short rotation coppice; short rotation forestry
Mixed	Deciduous and coniferous
Farm	Small farm woodlands, productive farm woodlands, farm-forestry small holdings/crofts; agroforestry
Linear	Riparian woodlands; shelterbelts; hedgerows with trees

ranked tiles representing different ES next to each landscape, to represent the priority ES that the vision would provide. The final discussion considered how the vision might be achieved. Participants were asked to choose the five most important elements of the vision, identify important actors who would play valuable roles in making the vision happen, and then discuss and record the ideas they had for the important elements of the vision being achieved. All materials used for these discussions are in Appendix B. Plenary sessions were used for discussions about broad land use implications and the relationships between the visions.

All discussions were recorded and transcribed. The transcriptions were coded, using the same process as applied to the original documents. Small additions and clarifications were made to the draft visions using these data, to produce the final visions. After the workshop, the visions were illustrated to facilitate communication (Figure 3.2). All visions illustrations are included in Appendix B.

3.3 RESULTS

The online search resulted in a total of 53 published sources (30 documents, 7 policies, 5 consultation responses, 11 webpages). A full list of all the materials can be found in Appendix B. A post-workshop survey with a 68% response rate indicated that the majority (11/12) of respondents

rated the discussions as either relevant or very relevant to their everyday work, and all respondents (12/12) viewed the expected outputs from the workshop as being of use to themselves or their organisation.

3.3.1 FIVE ALTERNATIVE WOODLAND VISIONS

The content analysis identified four critical elements on gradients from utility to conservation and land sharing to land sparing (Figure 3.2). These choices were based on recurring themes identified from the coding process, with there being a clear gradient between future woodlands being desired mainly for productive use and those desired mainly for biodiversity and conservation. Land sharing (integrating conservation and production on the same land) and land sparing (separating conservation and production) have been identified as important concepts in the debate around optimising future land use (Paul & Knoke, 2015; Phalan et al., 2011), and using these as the second axis enabled consideration of the relationship between new woodlands and other habitats and land uses. Five distinct clusters were identified (Figure 3.2), and each vision is described below. The weight of vision creation lay with the content analysis, with the stakeholder workshop and interviews suggesting only minor tweaks to wording. Figure 3.3 provides illustrations for two visions. All vision illustrations can be viewed in Appendix B and are available as public dataset under a Creative Commons 4.0 licence (Burton & Metzger, 2018).

GREEN GOLD

Woodland expansion largely comprises large scale, productive, sustainable plantations, which adhere to high environmental standards, and are an integral part of Scottish land use and the national economy. There is a focus on productive species which provide high value timber (e.g. non-native conifers), but plantations are designed with some areas of native species, riparian buffers and open spaces. The carbon stored in forests and forest products are highly valued.

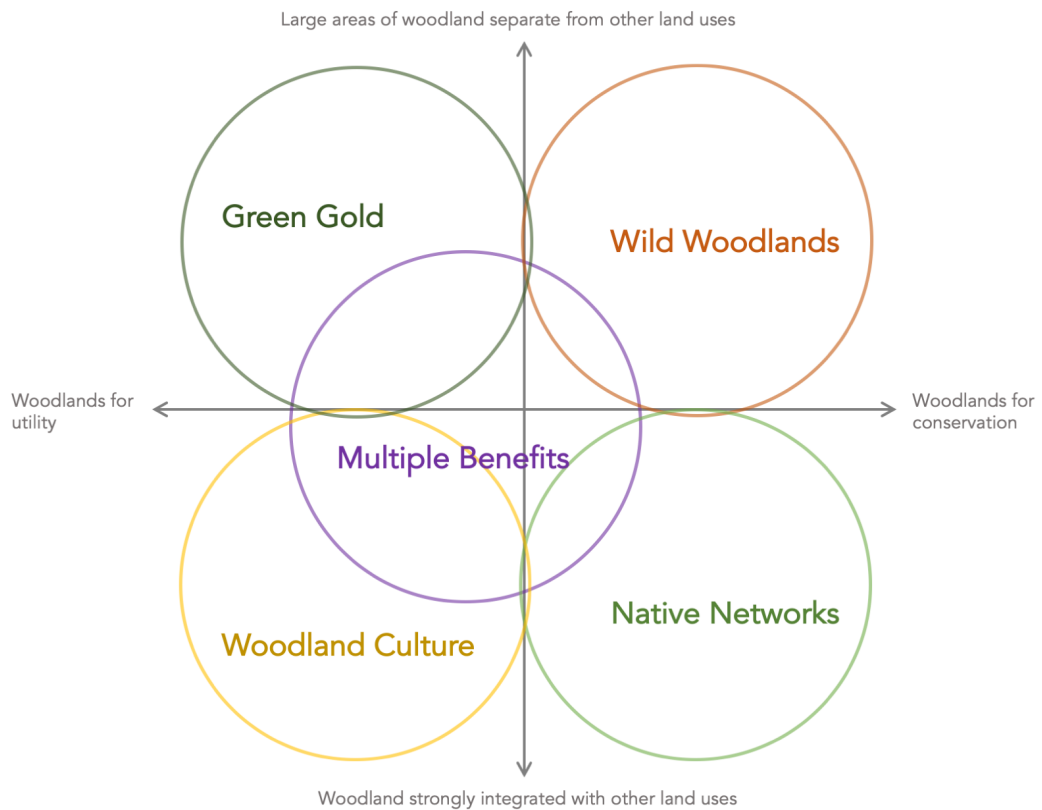


Figure 3.2: The two by two matrix used to elicit the visions. The critical elements of utility to conservation and land sharing to land sparing provide the axes. Coded themes were located on the matrix based on how they related to these elements. Each set of clustered themes is represented by a circle. This figure received positive feedback from both the workshop and interviews, with participants feeling that it effectively mapped out the current views held on how woodland expansion might proceed in Scotland.

MULTIPLE BENEFITS

Sustainably managed trees and woodlands ‘stitch-in’ and complement a diverse mix of land uses at the landscape scale. Emphasis is on ‘the right tree in the right place’, whether this be a conifer plantation for timber production, riparian woodland for water regulation or a native woodland prioritising biodiversity conservation. Agricultural land is a key asset to be protected, but forestry is seen by farmers and land owners as a potentially integral part of their portfolio.

NATIVE NETWORKS

Native and semi-natural woodlands are protected, restored and reconnected at all scales, enabling integration with other land uses, and avoiding fragmentation of important open ground habitats. Natural regeneration and transition zones are encouraged between land uses. Woodland networks play a valuable role in developing climate change resilience and providing greenways (sustainable green travel routes) for recreation.

WOODLAND CULTURE

A well-forested and productive landscape encompasses small-scale diversity of tree species, woodland type and tenure. Communities are empowered and many manage local woodlands, with local people make their living from woodlands in a wide variety of ways, and hutting (Hunt, 2016), where people own small woodland huts for recreational use and reconnecting to the land, is commonplace. All woodland types are potentially productive, and small-scale processing technology is widely accessible, supporting local timber, wood-fuel and non-timber forest product markets.

WILD WOODLANDS

Larger areas of land are given over to natural processes, with widespread naturally regenerating native woodland being a key indicator of dynamic, biodiversity rich wild land. Wild land is incompatible with most modern farming, but silvopastoral and transhumance systems thrive on the edges of wild areas. Productive forestry comprises native species e.g. Scots pine (*Pinus sylvestris*), and is managed under continuous cover approaches. Natural transitions between land uses are encouraged and biodiversity is restored, including native species reintroductions.

3.3.2 COMPARING THE VISIONS BY THEME

Here each vision is compared according to several key themes which arose as important topics in the content analysis, and were subsequently principal questions in the workshop and interviews.

WOODLAND TYPES

An indication of the preferred woodland categories for each vision is shown in Figure 3.4. The simplification of woodland type preferences into ranked categories masks some distinctions. *Green Gold* incorporates a strong preference for plantation forests, with preference within this for non-native conifers providing high value timber. However, emphasis is also placed on developing diverse plantations that have a large proportion of native broadleaves, producing some hardwood timber, and riparian buffers which protect water courses. In *Wild Woodlands*, any upland plantations are synonymous with native pinewoods, managed under a continuous cover, low-impact silvicultural approach. In the lowlands, areas of short rotation coppice and forestry are envisaged, being easier to access for product extraction and closer to areas of population than upland woodlands. A desire for greater integration of woodlands and forestry with agriculture and farming is observed across the visions. The extent of this varies from *Green Gold*, which sees

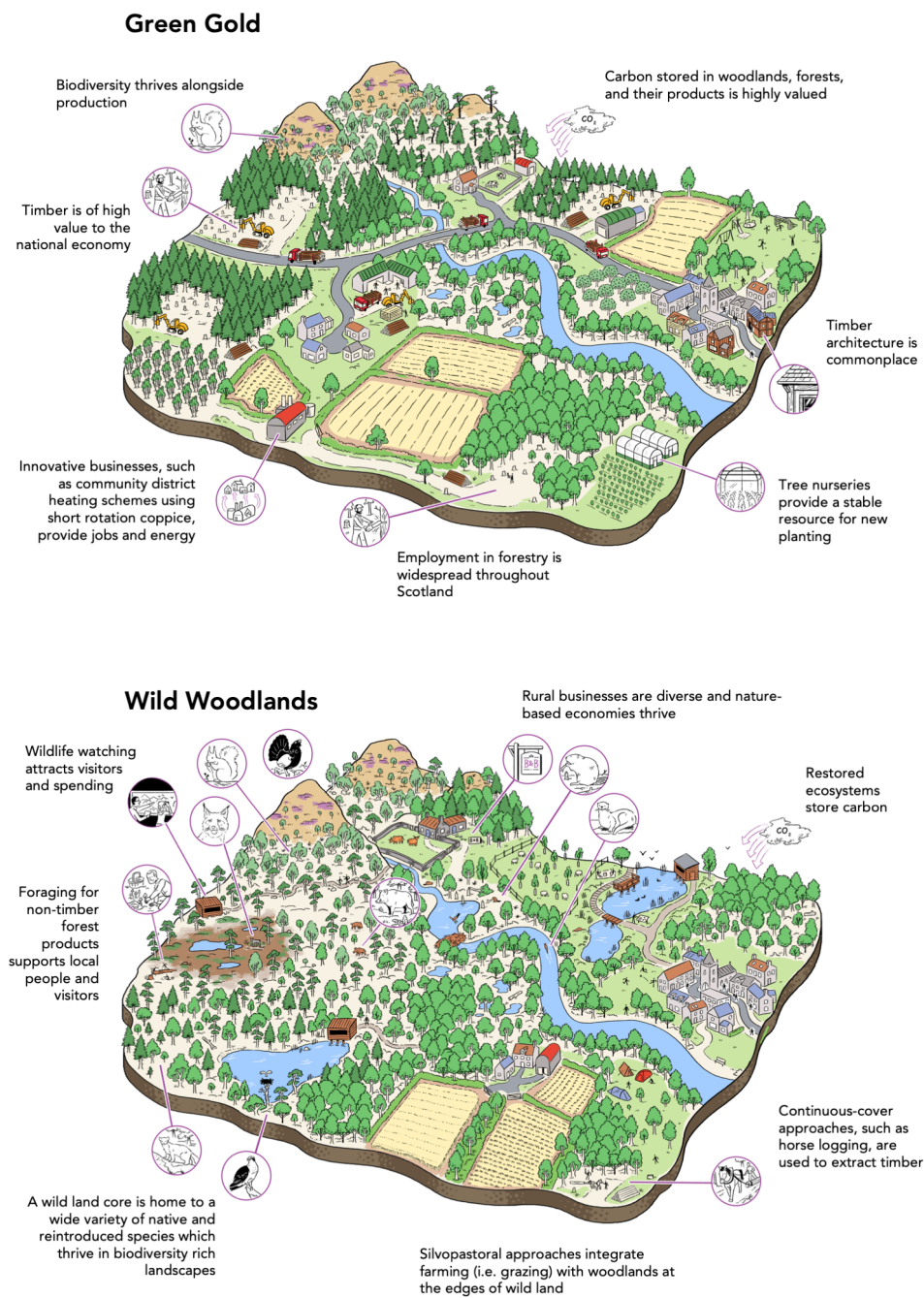


Figure 3.3: Illustrations of a catchment under the Green Gold and Wild Woodlands visions respectively. All visions have been illustrated (Appendix B) and are available as public dataset under a Creative Commons 4.0 licence (Burton and Metzger 2018)

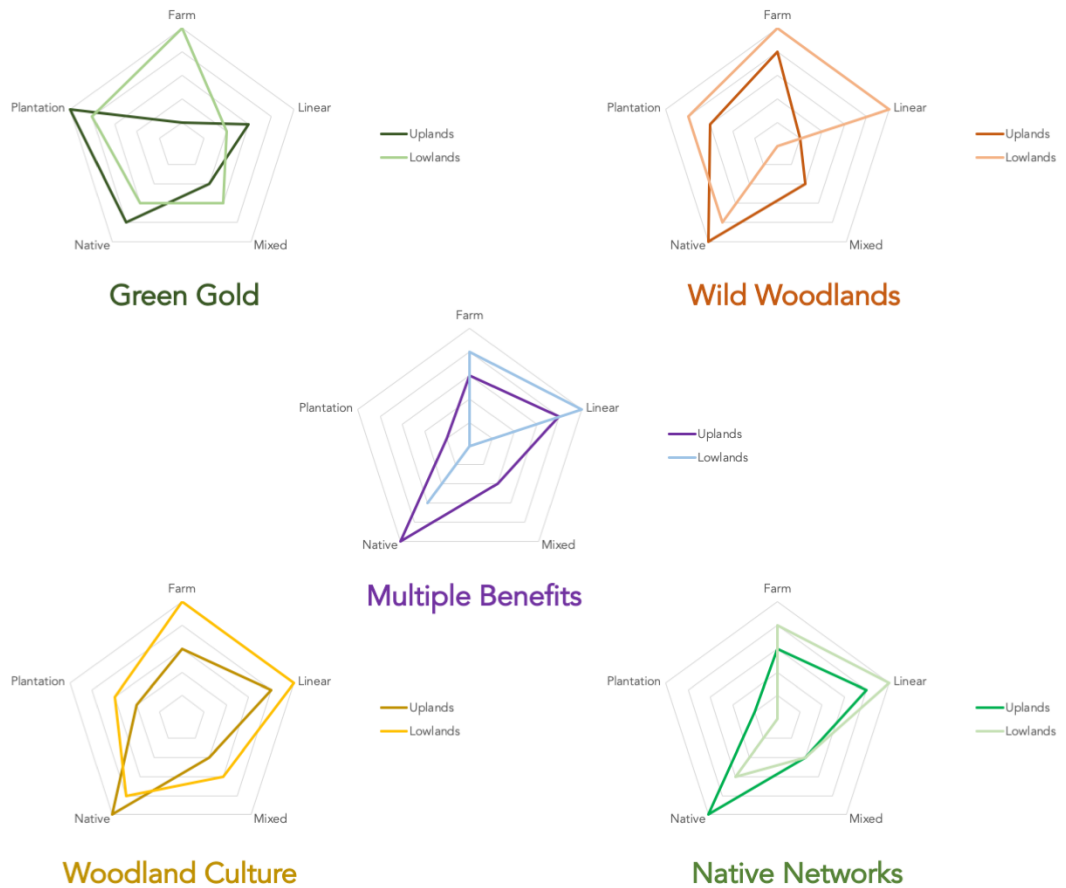


Figure 3.4: The woodland preferences for each vision elicited from stakeholders. The woodland type categories are described further in Table 3.2. Workshop groups and interviewees were asked to place desired woodland type tiles on stylised upland and lowland landscapes. These tiles were then counted and sorted into categories.

farmers being more willing to allocate areas of their farm to productive woodland, and *Multiple Benefits*, which sees small farm woodlands and silvopastoral agroforestry as becoming more commonplace, to *Native Networks* and *Wild Woodlands*, which envisage more integrated, small-scale, lighter use of native woodlands by farmers, landowners or crofters. *Woodland Culture* envisions the strongest integration, with woodlands being incorporated into productive farming businesses in a variety of ways. Linear woodlands (mostly riparian buffers, but also shelterbelts and hedgerows with trees) are important components of woodland expansion across visions, particularly in the lowlands. *Woodland Culture* appears to be the most ‘rounded’, or diverse vision, with the most evenly spread woodland preferences across categories, although there is still a preference for native woodlands in the uplands. There is strong preference for native woodland across visions, although the details of this vary. *Green Gold* emphasises the value of native woodland as an important component of plantations whereas both *Native Networks* and *Wild Woodlands* include more widespread natural regeneration of native woodland. *Woodland Culture*, *Native Networks* and *Wild Woodlands* all envisage more widespread natural transitions in the uplands, with hillsides forming gradients of native scrub, birchwoods and Caledonian pinewood.

LOCATION AND SETTING

Both *Green Gold* and *Wild Woodlands* emphasise large areas being given over to woodland, on land which may currently be economically fragile and which can therefore be expected to be given over to other uses in the future. In particular, *Wild Woodlands* envisions whole catchments being given over to natural processes, and it emphasises the value of this approach for creating space for biodiversity to adapt and fluctuate. By contrast, both *Multiple Benefits* and *Native Networks* see woodland expansion complementing, or “stitching-in” amongst other land uses. *Native Networks* is slightly more dynamic, emphasising the encouragement of natural ‘transition zones’ of natural regeneration and other natural processes between land uses. Of all the

visions, *Woodland Culture* sees woodlands as being the most widespread, making up “the defining landscape structure” (participant quote), particularly in the uplands, and integrating with other land uses and practices wherever possible. *Wild Woodlands* takes a similar position, with it being argued that “it’s hard to see where more trees won’t be beneficial” (participant quote). As a result, these visions would advocate woodland cover expanding far more than the current aspiration of a 3% increase.

PEOPLE, INTERESTS AND MOTIVATIONS

A gradient of participation, or involvement of people, can be observed between the visions. *Woodland Culture* and *Wild Woodlands* strongly emphasise Community Empowerment, Land Reform, and developing a “groundswell of public support” for each vision. *Native Networks* also envisages “connecting people and nature”, in particular through encouraging recreation and travel through greenways provided by woodland networks. In comparison, *Multiple Benefits* and *Green Gold* emphasise “appropriate engagement”, with a focus on informing and consulting as opposed to true involvement or collaboration (Durham et al., 2014). For *Green Gold*, plantations are designed with benefits to local communities in mind, and there are new innovative collaborations between investors and local communities in the form of initiatives such as community district-heating schemes. In *Multiple Benefits*, tailored advice and facilitation gives land owners and managers the freedom and flexibility to make the best choices for their land.

ECONOMY

Linking new woodlands into the economy came through strongly in several visions. In particular, *Green Gold* and *Woodland Culture* emphasise the employment value of new woodlands, as does *Multiple Benefits* in upland landscapes. For *Green Gold*, this is weighted towards the production of high value timber and biomass that have importance to the national economy, while

Woodland Culture envisages a well-forested landscape supporting decentralised local economies with a wide variety of timber, non-timber forest products (NTFPs) and other forest related businesses. The ability of local people to make a living from local woodlands was strongly emphasised in *Woodland Culture*. *Multiple Benefits* also describes a diverse and productive forestry sector, with a variety of activities ranging from timber production to recreation benefiting from new woodlands. Both *Native Networks* and *Wild Woodlands* envisage some small-scale, lighter use of woodlands through low-impact silvicultural systems, and both place more emphasis on the recreation and tourism value of new woodland, as well as arguing for some form of investment or payment for the public benefits (such as carbon sequestration and flood control) provided by new native woodlands.

GOVERNANCE

Green Gold envisages a free market within regulations, with high value timber and innovative funding sources, such as connecting new developments to woodland creation, supporting a diverse and strong forestry sector. Regulations, and incentives such as subsidies, create a “level playing field” between forestry and other land uses. There is a general willingness and enthusiasm for investing in forestry. Both *Multiple Benefits* and *Native Networks* see improved tailored public funding for new woodlands combined with innovative funding in the form of Payment for Ecosystem Services (PES). *Native Networks* sees this going slightly further, with long-term funding for woodland secured, and tailored public funding giving greater support to new woodlands that increase connectivity or allow natural transition zones to develop.

Both *Woodland Culture* and *Wild Woodlands* are more transformative in terms of governance, arguing for a rethink of current habitat and species designations, thus allowing woodland to be planted, or to regenerate, on land that is currently protected. *Woodland Culture*, *Wild Woodlands*, and *Native Networks* all argue for either a complete ban on sporting practices such as deer stalking and driven grouse shooting in the way they are currently carried out (i.e. muirburn

practices maintaining heathland for grouse, very high deer numbers resulting in high grazing pressure), or for new regulations or incentives to encourage better practices. *Wild Woodlands* argues that both hunting for deer and grouse shooting could be carried out on a smaller scale amongst new woodlands, as is the case in much of Scandinavia. Decision making is most decentralised in *Woodland Culture*, with democratic forest governance being in the hands of local people and communities. Community Empowerment and Land Reform are seen as integral first steps towards achieving this.

All visions view education as being hugely important, with it being less sectoral, with woodlands and forestry being integrated into curriculums in a variety of ways. *Woodland Culture*, *Native Networks* and *Wild Woodlands* emphasise the growth of ‘forest schools’, and outdoor education. The media’s influence in communicating and encouraging support for each vision to the public was also recognised across the board.

WHICH ECOSYSTEM SERVICES ARE ENVISAGED FROM FUTURE LANDSCAPES?

The workshop participants and interviewees were asked to rank the priority ecosystem services that they envisaged upland and lowland landscapes providing in their vision (Figure 3.5). Biodiversity is seen as the top benefit resulting from *Native Networks* and *Wild Woodlands* across landscapes. It also features in the priority benefits in all other visions, with the exception of *Green Gold* in the lowlands. Timber is the top benefit envisaged for *Green Gold* across both landscapes, but it does not feature in the priorities of *Multiple Benefits*, *Native Networks*, or *Wild Woodlands*. The workshop group responsible for *Woodland Culture* chose not to select a smaller number of ES at all, instead focusing on the diversity of the vision and the wide range of potential ES being provided across landscapes. Employment is valued highly in the uplands by several visions (*Multiple Benefits*, *Green Gold*, *Woodland Culture*), and continues to feature in the lowlands for *Woodland Culture* and *Green Gold*. *Multiple Benefits* sees soil stability or quality as an underpinning service, and so ranks this as a highly important benefit resulting from

realising the vision in both upland and lowland landscapes. Unlike all other visions, aesthetics came through strongly as a benefit from both landscapes for *Wild Woodlands*.

In the lowlands, food is seen as a priority benefit for both *Multiple Benefits* and *Native Networks*, in the sense that woodland expansion should not compromise prime agricultural land. Water quality is also a greater consideration in the lowlands, compared to the uplands, with *Woodland Culture*, *Green Gold*, *Wild Woodlands*, and *Native Networks* all rating this highly. There is a spike towards health and wellbeing in the lowlands under several visions (*Wild Woodlands*, *Woodland Culture*, *Multiple Benefits*, *Native Networks*). As a workshop group, *Native Networks* included an additional ES (climate change resilience) for both landscapes.

3.4 DISCUSSION

3.4.1 MOBILISING SCIENCE FOR SUSTAINABILITY

This chapter has presented a mixed-method approach which combined document analysis and inductive coding together with a participatory workshop and semi-structured interviews. This approach was taken in order to ensure the credibility, saliency and legitimacy of the research through participatory processes that prioritise the needs and diverse values of decision-makers, while reducing the resource intensity normally associated with vision elicitation (Cash & Clark, 2003; Pérez-Soba et al., 2018; Rounsevell & Metzger, 2010). The post-workshop survey indicated that a high level of saliency had been achieved, while legitimacy was ensured through the wide range of stakeholders involved (71 invitees to the workshop, with 18 attending and four more interviewed across several interest groups (Table 3.1).

Nevertheless, the process adopted here had some limitations. It is difficult to predict who will be able to attend stakeholder events, however carefully invitations are balanced (Reed et al., 2013), and although over 70 organisations were invited across groups, the final attendance was slightly skewed towards the NGO sector. Even allowing for imbalances in the representation

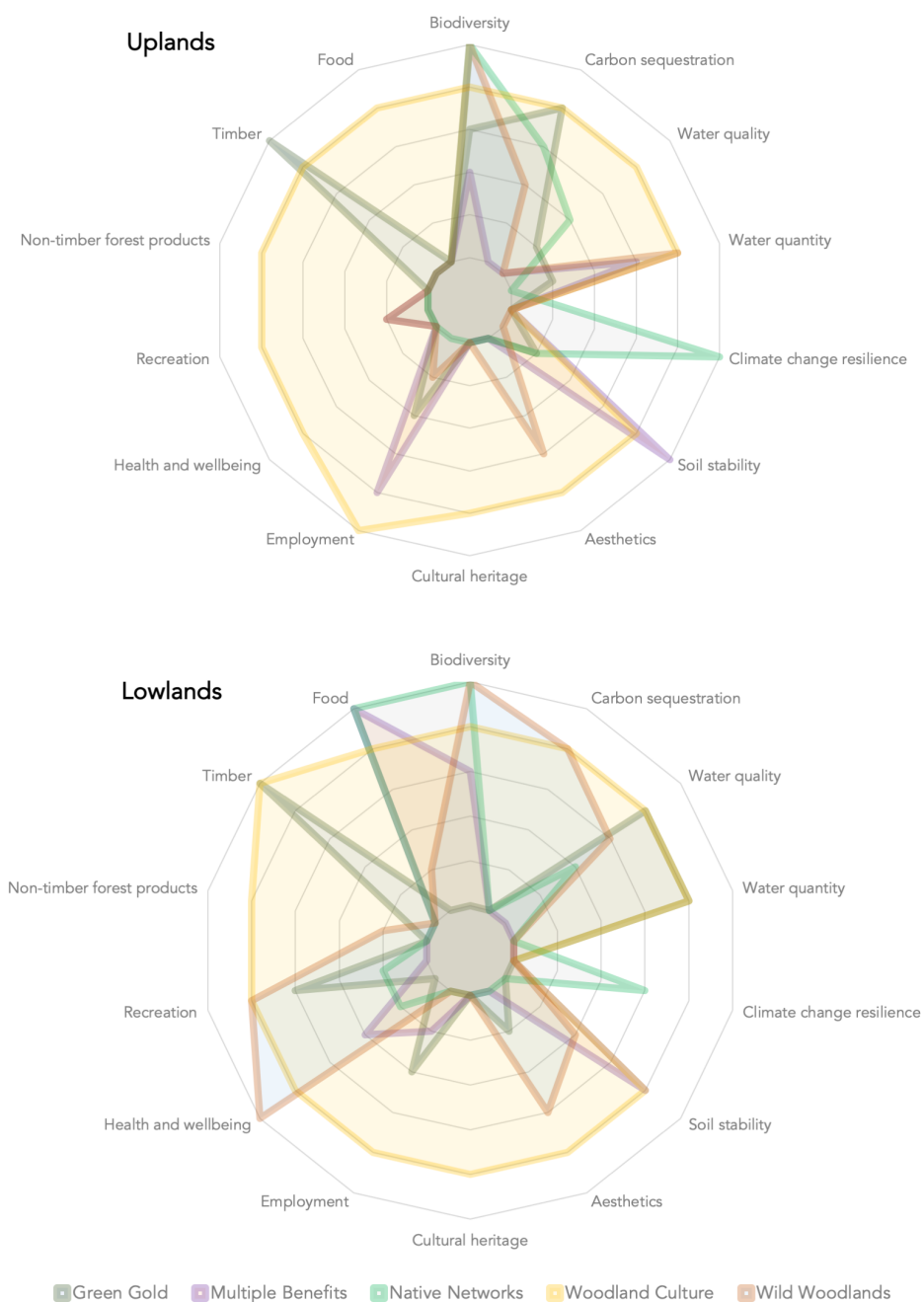


Figure 3.5: A comparison of the priority ecosystem services desired by stakeholders from upland and lowland landscapes under each vision. The task was to choose the top 5 ES desired from each landscape, but in some cases workshop groups kept more than 5 (i.e. Woodland Culture), or added a new ES not included as a prompt (e.g. climate change resilience).

of particular interest groups, the 22 participating stakeholders might be viewed as ‘the usual suspects’ (Colvin et al., 2016; Reed et al., 2009a), with expertise and values based on top-down, national-level perspectives. The approach can therefore be defined as a ‘neoliberal-rational’ form of stakeholder engagement, with the objective being to involve stakeholders to efficiently obtain knowledge and data rather than to enable the participation of people ‘on the ground’ who may be unable to make their voices heard through established channels (Mielke et al., 2016). Interesting further avenues of research could include more ‘democratic’ forms of stakeholder engagement (Mielke et al., 2016) to integrate the expertise and values of local people and land owners/managers in order to translate how visions might work in specific local contexts. However, there are acknowledged to be problems with this approach, for example; a lack of sufficient knowledge, or preference for the status quo over change (Reed et al., 2009c). In addition, some participants with a strongly sectoral focus criticised the positive, idealistic nature of the visioning process, and its potential for obscuring trade-offs between woodland and other land uses. However, this positive approach is intrinsic to the nature of visions and their value as potential solutions to environmental problems, because it elicits forward-thinking storylines that can move beyond current constraints and identify transformational solutions to achieve desired futures (Gebhard et al., 2015; Jensen, 2002).

The process of eliciting visions has been found to ‘initiate communicative arenas in heterogeneous groups of stakeholders’ (Gebhard et al., 2015), and in doing so, help to articulate different values. The workshop stimulated a great deal of dialogue between stakeholders, particularly in the plenary sessions, where facilitation focused on comparing and contrasting ideas from each vision. Follow-up telephone interviews with some participants found that the workshop process was positively received, with it giving people the opportunity for people to engage with other sectors, share views in a balanced way, and learn something new (Hall et al., 2018). The use of novel visualisation techniques, in the form of stylised landscapes, and tiles representing different woodland types and actors, was also praised for stimulating discussion and ideas. Overall, the

document analysis, initial presentation of the visions to the stakeholders, and discussions held around the visions, helped to identify common ground between aims for woodland expansion.

3.4.2 COMMON GROUND AND DIVERGENT AIMS

Common ground is most obvious around the expected carbon, water and biodiversity benefits of new woodlands. This aligns with the findings of a UK policy review that identified the most frequently cited ES provided by forests and woodlands as climate change mitigation, biodiversity, water quality and flood protection (Sing et al., 2017). Research has shown that woodland creation can be a cost-effective method of climate change mitigation and flood prevention (Jacob et al., 2014; Nisbet et al., 2011; Thomas & Nisbet, 2007; Valatin & Price, 2014), and afforestation is an important component of the UK's strategy to meet the terms of the Paris Agreement (Bell et al., 2016). *Native Networks* was the only vision to explicitly link these two benefits together in the concept of 'climate change resilience'; an emerging policy focus that is clearly prioritised by stakeholders even in the absence of well-developed strategies for its realisation.

Biodiversity is also valued in all visions, but there is a gradient in how it is perceived. In most visions (*Green Gold*, *Multiple Benefits*, *Woodland Culture* and *Native Networks*), woodlands are seen as being important for biodiversity, and in turn biodiversity is seen to underpin many other valuable benefits provided by woodlands. However, in these four visions the focus is on historical continuity of species and valuable habitats. *Wild Woodlands*, in contrast, represents a more transformative, dynamic view of biodiversity, with the aim of giving over larger areas of land to restoration and natural regeneration, allowing for fluctuations in the identity and extent of species and habitats (nevertheless with woodland being a key indicator of restoration). As such, *Wild Woodlands* positions itself within the new paradigm of accepting future novelty in the composition, functions and structure of woodlands and abandoning attempts to return to historical reference states (Ghazoul & Chazdon, 2017).

Timber and employment were valued most highly by *Green Gold* and *Woodland Culture*, which

were positioned towards high utility on the visions matrix, as well as *Multiple Benefits* in the uplands. These visions also rated biodiversity highly, illustrating an assumption that sustainable management can deliver all of these benefits. A review of the effect of management intensity on ES from forests suggests that high intensity management can have negative effects on biodiversity, although non-native plantation forests can also deliver biodiversity benefits by enhancing landscape connectivity for woodland species (Sing et al., 2017). Less intensive management, conversely, which allows for diverse species and age structures alongside (mimicked) natural disturbances, can be expected to be most beneficial across a range of species but at the cost of reduced timber yields (Sing et al., 2017). This highlights an inconsistency between what is wanted from future forests and what may actually be achievable, and suggests that either biodiversity or timber production may have to be prioritised. Conversely, it may be that more (i.e. more woodland than stated in the aspiration), diverse woodlands managed in a low impact way, could meet demand for timber over larger areas.

Both *Multiple Benefits* and *Native Networks* rate food as the top benefit in the lowlands, acknowledging the importance of agricultural land uses in lowland areas where soil quality supports them. Food was not chosen by any vision as a top benefit in the uplands, reflecting the low productivity and marginal nature of Scottish upland farming, particularly given potential loss of subsidy post-Brexit (Skerratt et al., 2016). In *Woodland Culture*, a full diversity of potential ES were maintained as the group emphasised that decisions on prioritising benefits would vary by context, based on decisions made by local people.

3.4.3 GOVERNANCE MECHANISMS

The most notable differences between wider Scottish land use visions have been shown to exist in terms of land governance (Valluri-Nitsch et al., 2018). While this is also the case for these woodland-specific visions, large areas of common ground are also evident, particularly in the selection of some form of landscape scale or regional collaboration and decision making by all

workshop groups and interviewees. This aligns with the Regional Land Use Partnerships that were piloted through both iterations of the Land Use Strategy (Scottish Government, 2011, 2016) and aimed to implement an Ecosystem Approach involving a wide range of stakeholders and giving local people a much stronger influence over land use in their area. This links to the growing global agenda for Forest and Landscape Restoration (FLR), which, in contrast to site-scale restoration, is increasingly advocated on the basis that it allows development not only of the large scale ecological processes needed to generate ES, but also agricultural and environmental policies that support people's livelihoods (Chazdon et al., 2017; Dudley et al., 2005). Participants viewed partnerships such as these as particularly valuable for their ability to bring together a wide range of stakeholders and to facilitate debate about land use trade-offs and synergies, though felt that some form of facilitation or professional mediation may be necessary given the polarised views and potential conflicts about land use change. Nevertheless, it has been acknowledged that no one spatial or temporal level is appropriate for governing ecosystems, and that multi-level governance and new institutions working across levels are required (Brondizio et al., 2009). In addition, there is a fundamental tension between empowering local people and assuming they will want large-scale woodland expansion or landscape restoration. There is therefore a balance to be struck in terms of new governance giving decision making power to local people, yet also communicating the potential benefits of restoration.

In addition to regional collaboration, all workshop groups and interviewees saw a role for some new form of investment to provide income for landowners and managers for the ES or Natural Capital that new woodlands provide. This type of funding was envisaged for woodland types which were unlikely to provide income in other ways (e.g. timber) but that provide wider, long-term public benefits, such as biodiversity conservation or water regulation. Although the term was rarely specifically mentioned, this links to the concept of Payment for Ecosystem Services (PES). Spatially explicit economic modelling in New Zealand has illustrated that where the net private benefit of afforestation is negative, policy mechanisms such as PES can be used ef-

fectively to encourage woodland creation (Barry et al., 2014). Using public money to support desirable land uses is not new, with subsidies having supported the farming sector for decades, and grant schemes providing money to cover woodland planting costs. The explicit linking of public money to ES is currently missing, however. As a mechanism for nature conservation, PES have been the subject of both scepticism (McCauley, 2006; Redford & Adams, 2009) and support (Schröter et al., 2014). In the case of encouraging land use changes such as woodland creation, which are long-term and have little to no immediate benefit, they have the potential to play a powerful role. They would differ from traditional woodland grant schemes by providing a more continuous stream of income in return for the ES provided. Participants suggested that the necessary finance could come from corporate social responsibility (CSR) schemes, large utility companies, or from a dramatic subsidy reallocation post-Brexit.

The most notable area where the visions diverged in terms of governance concerned the extent of Land Reform and Community Empowerment. Both these agendas aim to improve governance of the possession and use of land to facilitate an economically successful, socially just and environmentally sustainable Scotland (Land Reform Review Group, 2014). The Land Reform (Scotland) Act (Scottish Parliament, 2003, 2016) established the Scottish Land Commission, and among other things gave communities the right to buy land, and the power to buy land in order to further sustainable development. The Community Empowerment Act (Scottish Parliament, 2015b) further enables the purchase of abandoned, neglected or detrimental land (defined as harming, directly or indirectly, the environmental wellbeing of a community), and community participation in decision making. The National Forest Land Scheme was another important mechanism for facilitating community ownership (or lease and management) of land by communities and NGOs and allowed community acquisition of Forestry Estate Scotland land (Wong et al., 2015). This has since been replaced by the Community Asset Transfer Scheme (CATS).

In both *Woodland Culture* and *Wild Woodlands*, it was argued that both these agendas would

need to be further developed, being prerequisites to many of the changes desired in each vision. For *Woodland Culture*, Community Empowerment and a significant increase in community capacity (e.g. developing local skills and resources) was envisaged before the central aspects of the vision (e.g. strong local control and engagement in woodlands and a variety of woodland businesses) could be achieved. In line with this, *Woodland Culture* also envisaged an increase in the availability of funding for smaller ventures, for example the planting of small woodlands or supporting related businesses, such as small-scale wood processing.

For *Wild Woodlands*, Land Reform was the more immediate concern, with the current concentrated pattern of land ownership (Wightman, 1999) being a key factor, particularly under the current culture in which many large estates essentially hold land in ecological stasis through high grazing pressure and muirburn for grouse (Armstrong et al., 2014; Halley, 2017). Indeed, grazing pressure was acknowledged to be a severely limiting factor in terms of natural regeneration of woodland, and *Wild Woodlands* included very strong landscape scale deer management (with population reduction preferred over fencing). Recent reports on deer management has concluded that deer are a major factor in limiting the recovery of woodland condition, and that the present reliance on fencing comes at a cost to the public purse, with wider implications for biodiversity and deer welfare (Environment Climate Change and Land Reform Committee, 2017; Pepper et al., 2019; Scottish Natural Heritage, 2016). It was acknowledged that a change of ownership would not necessarily mean a change of management, and that single private owners ('*Green Lairds*') with large land holdings and resources could aid achievement of the visions if their interests were aligned (as e.g. with new ownership at Glenfeshie Estate in the Cairngorms National Park resulting in large-scale woodland regeneration). Nevertheless, stakeholders involved in *Wild Woodlands* wanted transformational change in land ownership, while enhancing democratic processes, even if this was not in itself conducive to achievement of the envisioned woodland expansion. Thus, they stressed the importance of encouraging wider cultural shifts and the role of education, media and science communication in ensuring such expansion oc-

curred. The shift towards more participatory and interactive modes of policy making, favouring negotiation and trade-offs between different interest groups, has previously been identified as a barrier to rewilding (Belt, 2004). As a result, it is argued that in order to gain wider traction, such ideas will require strategic high-level action (Jepson, 2016). This highlights a fundamental tension between stakeholder proponents of Wild Woodlands wanting to maintain participatory democratic processes, and the likelihood of success likely depending on high-level, top-down strategy. A key consideration here may be the differing timelines over which stakeholders were considering changes. If rapid changes are wanted, then a national strategy may be more likely to succeed. However, the stakeholders interviewed for Wild Woodlands often talked on very long timescales, proposing that changes to education and effective science communication would slowly engender societal changes which would in turn lead to democratic support for a national strategy for wilder land use and restoration of nature.

Overall, it can be argued that *Multiple Benefits*, *Green Gold*, and *Native Networks* represent more ‘status quo’ visions, mostly involving tweaking of current systems of incentives and regulations. By contrast, *Woodland Culture* and *Wild Woodlands* are more transformative, involving more dramatic changes in terms of Land Reform, Community Empowerment, and challenging current land use practices. Although these visions came under some criticism from some participants for being less realistic, or likely to happen, work in rural Estonia has found that the use of more ‘surprising’ or ambitious visions can be popular, and boost motivation in terms of long term planning (Palang et al., 2000). There are also calls for transformational change in land use in response to climate change (Kates et al., 2012), with reforestation highlighted as offering a particularly important pathway towards climate change mitigation (Griscom et al., 2017). They can also be linked to theory around the ‘radical rural’, defined as emerging transformational and utopian ‘future ruralities’ which are appearing in response to the search for sustainability and low-impact development (Halfacree, 2007). The more transformational visions also link with wider Scottish (Valluri-Nitsch et al., 2018) and European Union (Pérez-Soba et al., 2018) visions

(particularly amongst young people) for multifunctional landscapes, radical shifts to bottom-up governance, self-sufficiency and larger individual behavioural changes in terms of diet and travel (Metzger et al., 2018). In any case, all interests are inherently valid and necessary to account for.

3.4.4 HOW TO MOVE TOWARDS A COMMON VISION?

Previous research has indicated that there is a lack of synergy between policies advocating woodland multi-functionality and connectivity (Muñoz-Rojas et al., 2015), and improved coordination among actors and across scales may be necessary to achieve such synergy. Visions have a role to play in this because they stimulate dialogue and help to build consensus on shared priorities. However, the extent to which differences between visions can be resolved remains an open question. There was much discussion at the workshop about the extent to which the visions could be merged, or whether woodland planning could be weighted towards certain visions in appropriate areas. Many argued that Scotland's Land Use Strategy already formed a common vision. The third Principle for Sustainable Land Use in the Land Use Strategy states that: "Where land is highly suitable for a primary use (for example food production, flood management, water catchment management and carbon storage) this value should be recognised in decision-making" (Scottish Government, 2016). This can be interpreted to mean that all visions could be implemented where the land most suits the objectives of that vision. This also links to the second recommendation of Muñoz-Rojas et al. (2015), who argue that spatially explicit planning instruments are required to increase synergies in planning for woodland expansion. There could be an opportunity to move away from considering the visions axes as opposing sectors, and instead using them as different options for guiding landscape scale planning within specific regions or landscapes in Scotland, depending on the objectives of the stakeholders in that vicinity.

3.4.5 CHALLENGES AND OPPORTUNITIES

These results present both challenges and opportunities. Firstly, to what extent is a spatial strategy that incorporates all visions possible? To date, spatially explicit research has included an analysis of suitability for woodland expansion at the national level (Sing et al., 2013), and nested modelling of responses to climate change at the regional and national levels (Brown et al., 2014b), but neither of these take into account governance or land owner decision making. The Land Use Strategy and Land Reform and Community Empowerment agendas suggest that decisions should be made, or at least strongly informed, by local stakeholders. However, as highlighted previously, this may be to the detriment of the necessary national-level planning as well as constraining the areas in which particular changes may be possible. This is particularly true given engrained cultural divides between, on the one hand, farming and sporting interests and, on the other hand, the generally more forestry and conservation-oriented interests represented by these visions. Novel approaches such as those developed by Bowditch et al. (2019) could provide mixed-method platforms for tackling this complex challenge. They found that an approach combining walking interviews with landmanagers, collaborative action discussions, and detailed resilience mapping of estates (highlighting areas which could transform, adapt, stay the same, or offer opportunities for collaboration) can help to generate discussions and align policy aspirations with the objectives of land managers.

Another limiting factor was identified as the 3% increase in woodland cover stipulated by the current Government aspiration, which represents a miniscule amount of change when spread over the whole of Scotland. Some stakeholders and visions (in particular *Woodland Culture* and *Wild Woodlands*) argued for larger increases in woodland cover. Finally, many of the changes envisaged, particularly in the more transformative visions, are intrinsically linked to wider, longer-term societal shifts that are very difficult to achieve. Together, these issues clearly constrain the extent to which all of the objectives articulated by these visions can be achieved.

In terms of opportunities, there is increasing discussion around the concept of rewilding in Scotland (Brown et al., 2011). Rewilding, with a focus on restoring natural processes and ecological dynamics, falls within the framework of restoration ecology, and is promoted as an ambitious alternative to current approaches to nature conservation (Jepson, 2016; Lorimer et al., 2015). The concept generates significant debate given its range of possible definitions, and concerns that it may affect local livelihoods. Previous research has shown that rewilding was the least popular scenario amongst stakeholders in an analysis of predominantly English and Welsh upland scenarios (Reed et al., 2009a). However, it has recently been argued that rewilding and ‘re-peopling’ are not exclusive to one another (Hunter, 2017). This presents an interesting avenue in terms of linking the *Wild Woodlands* and *Woodland Culture* visions. South-west Norway is also increasingly argued to be an ideal comparison to, or exemplar for, the Scottish Highlands, both ecologically and in terms of integrating increased woodland cover with other land use practices (Halley, 2017). The combination of these two more transformative visions, with emphasis on giving back space to nature and power to local people, fits within the emerging Forest Landscape Restoration (FLR) agenda (Chazdon et al., 2017; Ghazoul & Chazdon, 2017).

The number of initiatives advocating working at a landscape scale is increasing globally (e.g. Model Forests, Biosphere Reserves) and in the UK (e.g. Futurescapes, Living Landscapes), improving understanding of how to develop sustainable socio-ecological systems in different regions (Angelstam et al., 2013). This suggests an opportunity to move beyond the ‘usual suspects’ in land use policy and to work with visions at a landscape scale, with input from local stakeholders. Participatory, values-based research would also help to address the potential inconsistency in giving decision-making power to local people who may not share the same visions for woodland expansion or landscape restoration. The policy reforms required by Brexit provide an opportunity and a need for such research, to ensure that new policies reflect people’s visions, knowledge and values.

3.4.6 FUTURE RESEARCH

Interesting avenues for further research can be identified around linking qualitative storylines (i.e. the visions) with quantitative models (e.g. of climate and socio-economic change) to assess whether or not realistic scenarios of land use change match up with what is desired by society (Kok et al., 2014; Verkerk et al., 2016). Whether the visions can be achieved will also be dependent upon individual landowner behaviour (Brown et al., 2018). Thus, agent based modelling is a promising future avenue of research, as it can be used for scenario analysis whilst also representing heterogeneous land ownership and behaviour across landscapes. Furthermore, the effects of key pressures and risks on land use planning are still insufficiently considered (Muñoz-Rojas et al., 2015), and thus there is an opportunity for scenarios research to explore these further. To date, there has been little to no evaluation of visioning processes to assess whether or not they assist with long term planning (Shiple & Michela, 2006). Future research should undertake an evaluation exercise of studies where visions have been developed, to assess their effectiveness.

3.5 CONCLUSIONS

This chapter has presented a mixed-method approach for eliciting visions for woodland expansion in Scotland. The streamlined approach is argued to be salient and legitimate at a national level. The visions articulate the wide variety of objectives and values associated with woodland expansion in Scotland. At a national level, there is a great deal of consensus between stakeholders that woodland expansion can offer valuable public benefits in terms of carbon sequestration, water and flood regulation, and biodiversity conservation. Some stakeholders envisage more dramatic changes, e.g. giving over larger areas of land to natural processes and natural regeneration by dramatically improving deer management and changing sporting practices, or fostering smaller scale local control of land and woodland expansion. Landscape scale collaboration and decision making, as advocated and tested through the Land Use Strategy, is widely perceived

across visions to be the way forward in terms of governing decisions for woodland expansion and other land use changes. New incentives, perhaps some form of Payment for Ecosystem Services, were viewed within all visions as a potential mechanism for encouraging more woodland creation, particularly for woodland types which are less likely to provide income in other ways in the long term e.g. for native woodlands providing biodiversity and water regulation benefits. Discussions highlighted that Brexit provides a window of opportunity in the next couple of years to change incentives and regulations relating to woodland, and other land uses, which have previously been strongly determined by the Common Agricultural Policy. Finally, the local context was acknowledged to be hugely important by more than one vision. It was recognised that some quarters might find the level of consensus for more woodland in the visions threatening, and that decisions for land use change would be best made by local people. Overall, the visions engaged and stimulated dialogue between stakeholders, and can support more joined up and effective approaches to land use planning.

4

Establishing CRAFTY-Scotland: an agent-based model of future land use dynamics

Section 1.2.3 in Chapter 1 outlined developments in land use change modelling, and how agent-based modelling (ABM) in particular has emerged as a promising technique with which to explore future scenarios of environmental and socio-economic change. Chapters 2 and 3 have tackled the first two research questions of this thesis; outlining what we currently know regarding

the effects of woodland expansion on biodiversity and ecosystem services, and what ‘visions’ (or ‘positive descriptions of ideal futures’) national level stakeholders have for woodland expansion in Scotland. This chapter will describe the method developed to establish an ABM of land use change for Scotland, with a particular focus on woodland expansion. The main objective is to develop a model that takes into account biophysical suitability for woodland, land manager values and behaviour, as well as providing a means to simulate the previously developed stakeholder visions and associated societal demand. The final research chapter will apply the model in order to address the final research questions.

4.1 INTRODUCTION

Linking qualitative visions of the future with quantitative models of biophysical and socio-economic change has been highlighted as an exciting and essential avenue for landscape ecology research, providing the opportunity to assess whether or not realistic scenarios of land use change match up with what is desired by society (Brown et al., 2018; Kok et al., 2014; Verkerk et al., 2016).

In this case, the agents in question represent the different types of land managers operating in Scotland. Thus, it is important to first give a fuller picture of the main forms of land management found in Scotland and the motivations behind them. Scotland is home to a distinct pattern of land use and associated forms of land management. A large part of the land is classified as upland in character, most of which is also designated as ‘Less Favoured Area’ (LFA), where land productivity is limited by physical factors including harsh climate, short growing seasons, poor soil fertility, steep slopes, and high altitudes (Glass et al., 2013). Throughout the UK, upland areas have been influenced and shaped by a range of factors through time, including extensive forest clearance, use for grazing by domestic livestock, land improvement for agriculture and hunting/field sports, persecution of wildlife (in particular predators and animals viewed as ‘vermin’), industrial acidification, and extensive conifer afforestation (Glass et al., 2013; Ratcliffe

& Thompson, 1988). In recent years, tourism, recreation, and renewable energy developments have emerged as additional drivers of change. These trends have been particularly obvious in Scotland, with a strong sectoral focus in rural land use policy throughout the late 1900s meaning that agriculture and forestry dominated, limiting the delivery of wider rural objectives (Valluri-Nitsch et al., 2018).

Valluri-Nitsch et al. (2018) summarised the current situation for various land use sectors in Scotland. Key sectors include: forestry, agriculture, crofting, recreation and tourism, renewables, sporting, and biodiversity and conservation. In terms of area, agriculture and sporting sectors dominate, with 80% of the total land area in Scotland comprising of rough grazing, and large estates (average size 5000-8000 ha) managing for sporting land uses (predominantly focused on grouse and deer) (Valluri-Nitsch et al., 2018). Much of the LFA in Scotland is also associated with High Nature Value (HNV) farming systems, which recognise that low intensity (often livestock) farming systems are associated with European habitats and landscapes considered to be of high native conservation value (Morgan-Davies et al., 2017). The most productive farming areas for crops (around 9% of land) and mixed cropping and grazing are located on the east coast of Scotland, where lower altitudes and a comparatively drier/warmer climate allow.

High deer numbers associated with the large areas of land managed for field sports have a strong influence on land use. Although acknowledged to provide a number of socio-economic benefits including supporting employment, rural tourism and sale of venison, densities have increased by approximately 60% since the 1960s, and grazing by deer and other herbivores is a major cause of unfavourable condition of natural features in protected areas, with a third of all native woodlands in unsatisfactory condition due to herbivore impacts (Scottish Natural Heritage, 2016). As previously outlined in Chapter 1, woodlands and forestry make up a much smaller proportion of land use, with 19% woodland cover of which the majority (79%) is coniferous, a legacy of historical conifer planting post-WWI. Scotland's native forests are highly fragmented and cover only 4% of land, with long term monitoring indicating that there have been significant climate,

pollution and grazing impacts through time, contributing to a possible extinction debt (Hester et al., 2019).

As outlined previously, the pattern of land ownership in Scotland is unique, and a key factor in determining land use patterns (Chapter 1). Land use and land management decisions in Scotland are made within the context of this distinct pattern of land ownership that has evolved over many centuries (Glass et al., 2013). Private landownership dominates (some 83% of land in total) (Skerratt et al., 2016), with estates being defined as 'continuous and discrete areas of land held by one owner, whether the owner be an individual, a company, a trust or an institution (Armstrong & Mather, 1983). Just over 400 private landowners are expected to own 50% of land (Glass et al., 2019) and estate size has been estimated to be "large" (10,000 ha - 20,000 ha) or "very large" (20,000 ha +) for 14% of estates, with this small percentage covering 63% of total land area in Scotland (Skerratt et al., 2016). This feature, a legacy of feudal tenure, is one of the most concentrated patterns of private landownership in the world and a contentious and politicised topic (McMorran, 2016). Field sports remain a common motivation for estate ownership and management, and less diversified sporting focused estates are often somewhat insulated from market pressures by private off-estate income (Skerratt et al., 2016). Estate ownership also exhibits a high degree of continuity, on average remaining in the same ownership for 122 years, with 5% of estates exceeding 500 years under the same ownership (Skerratt et al., 2016). In addition to this dominant form of private ownership, around twelve percent of Scotland is owned by public bodies such as Forestry Commission Scotland (now Scottish Forestry), local authorities, Scottish Natural Heritage, The Crown Estate, and the Ministry of Defence (Glass et al., 2013). Increasingly, and especially since the first Land Reform legislation in 2003, land is also owned by communities and non-governmental organisations (NGOs).

Most of the advantages associated with this current pattern of landownership are related to the economies of scale generated by large land holdings (Glass et al., 2013). In some parts of Scotland, disadvantages are associated with highly concentrated land ownership, which can be an

impediment to economic development if communities are excluded from the decision making process or investment activities are imposed upon them, thus causing significant and long-term harm to the communities affected (Glass et al., 2013, 2019). The disadvantages associated with concentration are not purely associated with private landownership, and smaller scale private ownership could be a valuable new mechanism for providing new sources of capital for rural development (Glass et al., 2013). Private estates can provide many benefits where community involvement is done well, with job creation, direct spend in the local economy and indirect economic impacts (Hindle et al., 2014). They can also provide social benefits in the form of housing, public access and interpretation, and community facilities. The recent diversification in terms of increasing public, NGO, and community land ownership has produced a number of social, economic and environmental benefits including changing emphasis in deer management, new opportunities for crofters, and development of strategic partnerships to deliver landscape scale approaches (McMorran, 2016). As a result, continued increasing diversity and reduced concentration of ownership is expected to increase rural resilience in the future (Glass et al., 2019).

Given the range of land uses and land managers, the pattern of land ownership and the need to take into account multiple ecosystem services, a flexible and adaptable modelling approach was required. ABM presented itself as being much more suited to the Scottish setting than a focused economic or optimisation model approach, which would not have been able to take account of wider intrinsic values of land managers as well as many other aspects of the visions. An approach needed to be developed which could: represent the main land use types, provide small scale detail whilst also accounting for a large scale landownership pattern, account for trade-offs between multiple ecosystem services produced by different land managers, and also take account of important influencing factors such as deer density. The Competition for Resources between Agent Functional Types (CRAFTY) modelling framework provided an ideal basis for this approach thanks to its design criteria (Murray-Rust et al., 2014). The CRAFTY framework:

- Runs at large scales, but also at fine resolution (i.e. it could be run for the whole of Scot-

land)

- Represents potential productivity of the land for a range of land management styles (e.g. woodland suitability, agricultural productivity)
- Represents diverse human behaviour and land management
- Takes account of societal demands (for services), and the competitiveness of land managers depends on this
- Represents multifunctional land use and is responsive to trade-offs
- Takes account of the values of different land managers
- Deals with long-term allocation of forest types

This chapter describes how the CRAFTY modelling framework was implemented for a Scottish context, and critically discusses the extent to which the objectives outlined below could be met based on data availability and model limitations.

4.1.1 MODEL OBJECTIVES

The ‘Competition for Resources between Agent Functional Types in Scotland’ (CRAFTY-Scotland) model is designed to model land use change in Scotland, with a particular focus on woodlands.

The CRAFTY modelling framework was developed by Murray-Rust et al. (2014) with the aim of combining the strengths of both bottom-up and top-down modelling approaches, allowing scenarios of land use change to be explored over large spatial scales, whilst also taking account of heterogeneous human behaviour at finer scales. The model framework is designed to be flexible,

adaptable, and applicable to both theoretical and real-world situations. The framework has previously been applied to examine the effect of broad forms of behavioural variation in theoretical and European contexts (Arneth et al., 2014; Brown et al., 2014a, 2018, 2019b), and to explore the effects of forest owner decision making and climate change in Sweden (Blanco et al., 2017b, 2017a). This is the first time CRAFTY has been specifically adapted for a real-world Scottish context.

CRAFTY-Scotland aims to explore the effect of:

- Land manager behaviour e.g. management objectives and intrinsic values
- Changes in governance based on stakeholder developed visions for woodland expansion
- Interactions between these elements

On:

- Ecosystem service delivery
- Likelihood of achieving national targets and stakeholder defined visions for woodland expansion

The following sections describe the aspects of the model, its central assumptions, and input data used for parameterisation.

4.2 MODEL BASICS: ENTITIES, VARIABLES, AND SCALES

CRAFTY-Scotland is represented by a grid of cells. Each cell has defined levels of a range of ‘capitals’, which describe the availability or productivity of a variety of environmental, social or economic resources. Capitals are:

- Potential productivity for several tree species (productivity is inherently related to suitability and thus also indicates where is appropriate for different types of woodlands to establish and grow)
- Crop productive potential
- Grassland productive potential
- Water runoff (this gives an indication of where a flood regulation service would be most required i.e. in areas of high runoff)
- Human capital - individuals knowledge, skills, and motivations
- Social capital - structures, institutions, and social networks
- Manufactured capital - infrastructure e.g. roads
- Financial capital - productive power
- Land owner attitudes to woodland, forestry and nature conservation

Further details for each capital are given in Table 4.3. The ‘agents’ within the model represent land managers operating in Scotland. Agents are not intended to represent specific individuals or land-owners, but instead are made up of a functional role which characterises their objectives and function within the land use system, as well as a behavioural component. The assumption behind this functional role is that land managers can be grouped into functional types that capture key land use and behavioural differences, whilst aggregating out less informative individual differences (Arneth et al., 2014; Rounsevell et al., 2012a). An agent is able to leverage the capitals available in a cell (representing a land use parcel) to produce a range of services. A ‘production

function' is assigned to each agent, which determines the amount of each service it can produce based on how sensitive it is to the capitals it 'owns'. For example, a forester agent focusing primarily on timber production would produce an amount of softwood timber that depends primarily on the level of non-native conifer capital in its cell, but also capitals which represent labour (human capital) and ability to extract the timber (manufactured capital). By contrast, even if there is a high level of crop capital available in that same cell, the forester agent has no production capacity for crops, and thus would not produce a crop service.

The functional roles that are assigned to each agent summarise a typology that defines the general characteristics of land management in Scotland. Individual agents within a type do not have to be identical, as all agent characteristics can be taken from a distribution to provide within-type variance/heterogeneity. The effect of this within-type variance has been explored in a number of previous uncertainty and sensitivity analyses (Brown et al., 2014a, 2018, 2019b), and so CRAFTY-Scotland prioritises exploring variance in other model aspects, for example novel ways to incorporate governance and represent the effect of different governance mechanisms on agent decisions. The typology of woodland, agricultural, and estate owner agents was developed based on a combination of previously developed typologies (e.g. CRAFTY-Europe, CRAFTY-Sweden), knowledge of different land-based sectors in Scotland, and discussions around the stakeholder-defined visions and what kinds of land managers would be required to meet the key aspects of each one (Table 4.1). The production files which describe each agent's capital sensitivities and service productivities are located in Appendix C. The Scottish landscape is represented in CRAFTY-Scotland by a grid of cells with a spatial resolution of 1km². Each cell represents a single land use parcel and can be owned by a single agent. It is acknowledged that management decisions can happen on a smaller scale than this, however this resolution was chosen based on previous applications of the CRAFTY framework, and tests which explored the run-time implications of cell size. In addition, 1km² is smaller scale than the average land holding in Scotland, with the average being around 1.3km² (Department for Environment

Food and Rural Affairs, 2018). As a result, it provided a reasonable compromise resolution at which to represent decision making, and also provided the ability to ‘fragment’ ownership in very concentrated areas (e.g. large estates). Further detail on this process is given in Chapter 5. Heterogeneity across space is represented by the relative amounts of the different capitals in each cell. For example, a cell in a native woodland region will have a much higher native broadleaf capital than grassland capital (Figure 4.2). A time-step within CRAFTY-Scotland is a single year, as this is generally the time span over which land managers make decisions.

The behaviour of land managers is represented primarily through ‘giving-up’ and ‘giving-in’ thresholds. These thresholds define the competitiveness levels at which land managers will either ‘give-up’ if they are no longer producing enough services to stay afloat and meet societal demand, or ‘give-in’ to other land managers who have a higher competitiveness. The thresholds provide an opportunity to represent the intrinsic values of land managers. As outlined in Section 4.1, estates often operate outside of market pressures, thus continuing to manage land for specific services (e.g. field sports) regardless of land productive potential and societal demand for those services. They also provide a simple way to represent long-term land use changes such as a conversion to woodland i.e. it is expected that once a cell has been converted to woodland, it will continue to be managed for woodland throughout the model run as the woodland grows and matures. As a result, high giving-in thresholds as assigned with CRAFTY-Scotland to all woodland managers and estate owners.

There are three possible mechanisms for land use change defined within an allocation model:

- 1) An agent may abandon land if their competitiveness score falls below their defined giving-up threshold
- 2) Unmanaged land can be taken over by a newly created agent
- 3) Direct competition between agents – an agent may take over if its competitiveness is

greater than or equal to the existing agent's competitiveness plus its giving-in threshold.

4.3 INPUT DATA

The following sections provide details on the data used to define agents, capitals and services, all pre-processing steps taken, and key assumptions made. Data processing was carried out in RStudio (R version 3.6.0) and ArcGIS Desktop (version 10.6.1).

4.3.1 LAND USE AND LAND MANAGER DISTRIBUTION

A digital baseline land cover map was created by combining the Land Cover Map (2015) (LCM), National Forest Inventory (2015) (NFI) and Native Woodland Survey Scotland (2014) (NWSS) data (Table 4.2). These datasets were reclassified with the aim of capturing the main current and expected forms of land management, with a focus on forestry, but also competing land uses (Appendix C). The reclassified datasets were converted into 25x25 metre rasters. These rasters were then aggregated to a 1km² resolution, using defined thresholds of habitat types within each cell to define the dominant land cover for that cell (see below). These thresholds were chosen to capture the dominant land use or cover in each cell, with the remaining proportion of other uses at a level representable by variable agent production functions. In some cases, landownership and designation data were used to refine the locations for specified land manager types. Locations were assigned using the following rules:

- Urban areas/waterbodies: artificial areas or water bodies >70%
- Woodland: LCM broadleaf and conifer >= 60%
 - Mixed: combinations of species categories

- Productive conifer: LCM conifer, NFI conifer, NWSS non-native and NWSS native pine $\geq 70\%$
 - Productive broadleaf: NFI broadleaf or NFI coppice $\geq 70\%$ and NWSS native broadleaf species $\geq 70\%$
 - Conservationist native: conservation designation present, native woodland category $\geq 70\%$
- Arable
 - Intensive: LCM arable $\geq 70\%$, IAP agricultural intensity $> 50\%$
 - Extensive: LCM arable $\geq 70\%$, low agricultural intensity. Either extensive across the whole cell, or intensive management over only a fraction of the cell
- Pastoral
 - Intensive: LCM intensive grassland $\geq 70\%$
 - Extensive: LCM extensive grassland $\geq 60\%$ (either extensive across the whole cell, or intensive management over only a fraction of the cell)
- Estate
 - Traditional multifunctional: private Deer Management Unit (DMU) present, woodland cover window based on SRUC surveys, arable, grassland and heather window (coverage more than 1% but less than 50%)
 - Sporting: private DMU present, heather coverage $\geq 80\%$, deer density $\geq 40\%$
 - Conservation: private DMU present, conservation designation on more than 50% of the land

- Agroforestry: narrow windows (between 45 and 55%) for combinations of mixed woodland and arable or pastoral land
- Marginal: any remaining land not already defined by previous rules

4.3.2 REGIONS

Scotland is comprised of a number of administrative regions, most recently defined by Forest and Land Scotland (FLS) as five distinct areas (Figure 4.1). These include: Highlands (North), Perth & Argyll (West), Grampian (East), Central Scotland (Central), and Southern Scotland (South). To prevent the Islands (usually included as part of the Highlands), which have very distinct land use compared to many other parts of Scotland from distorting the results, they were defined as a sixth separate region. In order to explore how the model works at regional scales which have different characteristics, proportions of landcover, and thus different levels of resources, results are mostly considered at regional level, using the FLS regions.

4.3.3 CAPITAL PRODUCTIVITY

As shown in Table 4.3, the data for each of the capitals used to define land productivity within the model was derived from a variety of sources. This section describes each dataset and any pre-processing undertaken to prepare the data for use within CRAFTY-Scotland.

TREE SPECIES PRODUCTIVITY

Spatial datasets of the potential yield class output from different tree species were produced using the Ecological Site Classification (ESC) model developed by Forest Research (Pyatt et al., 2001). This uses a combination of data on accumulated temperature, continentality, wind risk, moisture deficit, soil moisture regime, and soil nutrient regime to predict biophysical suitability

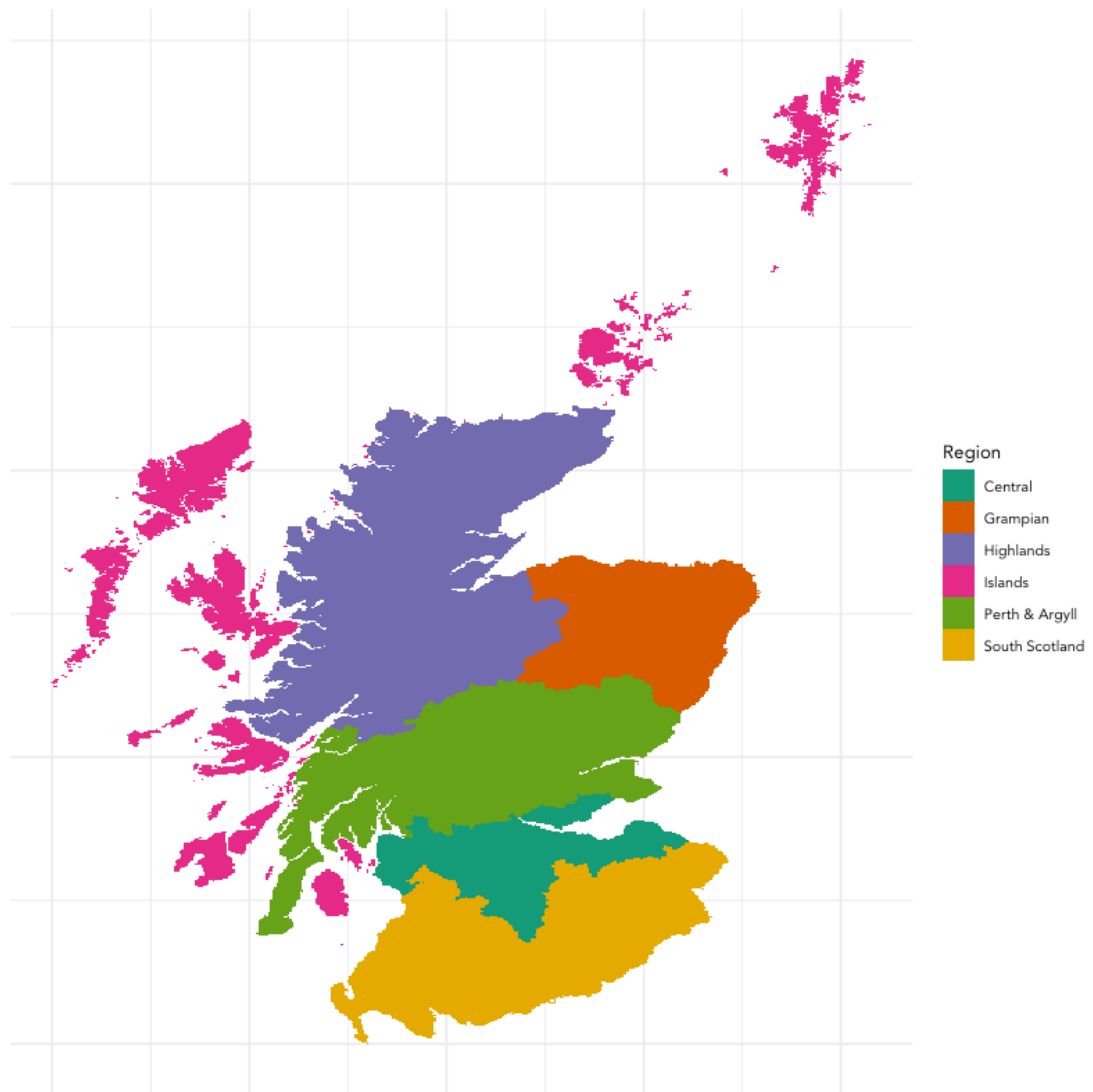


Figure 4.1: Each of the 6 administrative regions used for analysis within CRAFTY-Scotland. These are predominantly based on the FLS regions, with the exception of separating the Islands from the Highland region.

and associated potential yield class (timber growth) for a range of tree species. ESC was run using climate data for the current period for all available tree species. The yield class output was taken as an indicator of potential productivity. A single species was chosen to be an indicator species for each main woodland type capital. For example, potential Sitka spruce (*Picea Sitchensis*) yield was assigned as the capital for non-native conifer woodland, whereas silver birch (*Betula pendula*) was chosen as the capital for native woodland. Choices were made in consultation with experts and ESC users at Forest Research.

POTENTIAL AGRICULTURAL PRODUCTIVITY

The Land Capability for Agriculture (LCA) dataset (Bibby et al., 1982) was used as the capital for agriculture. This classification uses the physical characteristics of the land (soil, climate, and topography) to rank land across Scotland on the basis of its potential productivity and cropping flexibility. The ranked data lent itself well to being applied within CRAFTY. The ranks were normalised to provide an indication of low to high potential productivity [0,1]. The crop capital utilised LCA classes 1, 2, 3.1, 3.2, 4.1, and 4.2 as these classes support crop species. The rest of the classes were used as capitals for grasslands/livestock.

HUMAN, SOCIAL, FINANCIAL AND MANUFACTURED CAPITAL

IMPRESSIONS was a European project aiming to explore the effects of high-end climate change and help decision-makers to take action on integrated adaptation and mitigation strategies. The IMPRESSIONS Integrated Assessment Platform (IAP) is a freely available web-based platform hosting a cross-sectoral, multi-model tool for simulating European land system change (Harrison et al., 2015, 2019; Holman et al., 2017). The platform provides comprehensive data at the European scale that has been extensively evaluated, validated, and utilised (Brown et al., 2014a; Harrison et al., 2013, 2015, 2019; Kebede et al., 2015; Pedde et al., 2019), so it is a well-established

basis for these capitals. A Scottish case-study of the project has provided a specifically adapted version of the IAP, which provides datasets on multiple relevant services. Among these are Human, Social, Financial and Manufactured capitals, the details of which are given in Table 4.3. These data did not require additional processing and were simply sampled to the 1km² resolution of CRAFTY-Scotland.

LAND OWNER ATTITUDES

A key aspect of CRAFTY-Scotland is its ability to take account of societal attitudes or values. A challenge during model development was to work out how to represent land owner attitudes, which can have an influence over large areas of land in Scotland due to current ownership patterns. As outlined, comprehensive data on landownership in Scotland is lacking, so data from several different sources were collated to provide an indicative dataset and spatial indicator of private landowner and farmer attitudes towards woodland, forestry, and habitat creation. The datasets included:

- A proxy for spatial locations and size of private land holdings
- Results from surveys of estate owners relating to their attitudes and future management objectives (Hindle et al., 2014)
- Results from surveys of farmers relating to their attitudes towards woodland expansion (Hopkins et al., 2017)

As a proxy for private estate land ownership, Deer Management Unit (DMU) boundaries (Scottish Natural Heritage, n.d.) were filtered to include private land only. In many cases, DMUs are created based on property boundaries, but they also sometimes rely on the extent of areas used as beats for stalking, so they can't provide a completely accurate picture of estate ownership.

However, they do provide the best freely available indication of current land holding size and locations.

Two large studies have been conducted on estate owners (Hindle et al., 2014) and farmers (Hopkins et al., 2017) in Scotland. Together, these datasets provided an indication of the proportions of estate owners and farmers with specific attitudes towards woodland and aspirations for future land management. To create spatial indicators of attitudes, proportional results from each of these surveys were randomly allocated to either: a) whole private landholdings, or b) 1km² assigned as agricultural agents. The randomisation ensured that survey results remained anonymous. For now, attitudes are only assigned to private land and farming land. The indicator could be improved by including attitudes assigned to public, NGO, and community land.

DEER DENSITY

High deer density is an important factor in preventing natural regeneration of woodland in Scotland (Scottish Natural Heritage, 2016). Data on red deer density was downloaded from SNH Natural Spaces (Scottish Natural Heritage, n.d.). This was then processed to provide an indicative dataset of low to high deer density [0,1], with this forming a barrier to woodland agents where deer density is high.

BARRIERS TO WOODLAND

A number of capitals were incorporated to form barriers to woodland expansion. These included:

- Negative attitudes towards forestry, native woodland and habitat creation - these occur across a proportion of land holdings found by the SRUC surveys and Hopkins et al. (2017) to have no future objectives to afforest or create other habitats for conservation

- Deep peat - this occurs where peat is more than 0.5 metres in depth. These areas are policy protected from afforestation
- Deer density - high deer density is known to be a limiting factor to woodland establishment and growth (Scottish Natural Heritage, 2016)

These datasets were inverted so that they were scaled from $[1,0]$ with 1 being low and 0 being high. This can be seen in Figure 4.2 where most capitals increase from blue through green to yellow where they are more productive. For the barriers, the opposite occurs. Forest and woodland agents were assigned a high sensitivity to these barriers, and thus cannot establish or produce services in places where they occur.

4.3.4 INITIAL CAPITAL PRODUCTIVITY

Figure 4.2 illustrates the distribution and productivity for the capitals used within CRAFTY-Scotland for six regions. Figure 4.3 shows the total productivity of each capital within each region, illustrating the suitability of each region for each one.

4.3.5 LAND MANAGER SERVICE PRODUCTION

As illustrated in Table 4.4, the data used to parameterise service production values was compiled from a number of sources. Several datasets were used as they were provided, with no additional processing beyond normalising and extracting the data to the 1km^2 resolution. These are outlined below:

- Biodiversity: this was derived from an indicator of plant species richness produced by the James Hutton Institute (JHI). The dataset was obtained by downscaling the distribution



Figure 4.2: Spatial distribution of each capital across Scotland. Each capital is scaled from 0-1 [low-high]. Yellow indicates higher productivity, except in the case of 'barrier' capitals, where the values are inverted



Figure 4.3: Total productivity of each capital per region

of all native flowering species (from the Atlas of British and Irish Flora) to a 1km² resolution. For each 1km square, the values were rescaled between 1 (highest richness) and 0 (lowest richness).

- Recreation: Photo-sharing services provide geo-referenced crowd-sourced photographs which can provide valuable information on tourist hotspots and travel routes. Data for an indication of recreation value across Scotland came from a dataset produced from Panoramio photo density by JHI. This was produced by mapping the number of unique submitters to Panoramio in each 1km square as a (partial) indicator of the recreation service.
- Livestock: JHI have produced datasets of cattle and sheep density from Agricultural Census Data provided by the Edinburgh University Data Library (EDINA). Values of cattle (ranging from 0-4 per ha) and sheep (ranging from 0-220 per km²) were rescaled from 0 (low density) to 1 (high density). These two datasets were summed and rescaled again (from 0-1) to provide an overall indicator of livestock density.
- Crop production: the IMPRESSIONS IAP has generated productivity data for a range of crops. For CRAFTY-Scotland, an average productivity (tonnes per ha) of all relevant crops was taken as an overall indicator of crop production across Scotland.

Some datasets required additional pre-processing in order to provide suitable indicators for the model. The following sections describe these steps.

SOFTWOOD AND HARDWOOD TIMBER PROVISION

An indicator for softwood and hardwood timber production for each timber producing agent type was calculated based on a Growth Model previously developed at Forest Research (Mathews et al., 2016; McKay et al., 2003). This model calculates the potential biomass produced based

on the species, rotation length and spacing. It then uses a threshold diameter class to specify the number of logs expected to exceed a given diameter. The model, previously written in Python, was re-written in R. This generated a look-up table (Appendix C), which assigned a timber production value to each timber producing land manager type based on their specified indicator species yield class, rotation length and spacing.

CARBON STORAGE

An overall indicator for carbon sequestration was developed based on a combination of a soil carbon dataset produced by JHI and carbon values estimated for the National Forest Estate (NFE) produced by Forest Research. The soil carbon map, at 1km resolution, was produced based on estimates of soil organic carbon stocks (tonnes carbon) up to 1 metre depth. These estimates were obtained by relating field data contained in the National Soil Inventory of Scotland (NSIS) database, to a range of environmental variables using Digital Soil Mapping methods (Poggio & Gimona, 2014). The values, ranging between 60 and 1500 tons per ha, were rescaled between 1 (highest) and 0 (lowest). In order to also account for aboveground carbon stocks (tonnes carbon) held in woodland, estimates for carbon stored in NFE categories were associated with each woodland agent. A raster of the estimated total woodland carbon across Scotland was sampled to the 1km² model resolution, and average values per woodland agent were extracted. The two datasets were then added together and normalised to provide an indicator of total below and aboveground carbon.

FLOOD REGULATION

A simple indicator for the capability of different agents to provide a flood regulation service was assigned based on previously developed 'crop factors'. These were based on Sturck et al. (2014), who analysed flood regulation services at a European scale. They worked from previ-

ous literature to develop associations between CORINNE land cover classes and ‘crop factors’ which are hydrological modelling parameters designed to represent actual evapotranspiration from specific land uses and management characteristics. These crop factors were matched to the CRAFTY-Scotland land manager types (Appendix C). This service was assigned a high sensitivity to the water runoff capital for all agents. Thus, where run-off is higher, the potential for a flood regulation service to be provided by land managers in that region is also higher.

POTENTIAL LAND-BASED EMPLOYMENT

An indicator for employment was developed based on employment statistics provided for different land-based sectors in Scotland. Full-time equivalent (FTE) figures were researched for each land manager type (Appendix C). These figures were adjusted by the total numbers of each land manager/agent type in the model, to give an employment indicator per agent, per 1km².

BASELINE PRODUCTIVITIES

The amount of each service that each agent can produce was calculated based on the initial agent locations and the average amount of each service produced by the top 50 highest producing agents. In order to prevent different dataset units from dominating agent relationships and productivity, all capital and services were normalised to values between 0 (low) and 1 (high). All agent productivities (of different services) and sensitivities (to different capitals) are based on modelled data to make the parameterisation as robust as possible. Table 4.5 shows the baseline productivities for each agent. All agent files, illustrating the sensitivities of agent service production to all capitals, can be found in Appendix C.

DEMAND FOR SERVICES

Demand levels for ecosystem services are external to the model and defined prior to initialisation. Baseline demand was calculated by running the model for one time-step based on the current land use and capital/service distribution. The service supply values were taken from the console and used as the input values for initial demand. Future demand was based on interpretations of how future demand will change based on the priorities within each vision. Chapter 5 gives more detail on how these demand changes were implemented per vision.

4.4 BASELINE RESULTS

RUN TIME AND OUTPUTS

CRAFTY-Scotland takes approximately 40 minutes to run for the 80 year time period from 2020 - 2100, with a single time step taking around 30 seconds to process. The model outputs a csv file for each time step, with values per each 1km square for every capital, service, and agent. Stationarity was achieved with the initial model set-up, with the reference run showing that agent counts stay level throughout the time period if no demand or capital changes are made (Figure 4.4).

AGENT/LAND MANAGER LOCATIONS

The rules defined in Section 4.3.1 resulted in a reference map of land manager locations (Figure 4.5). The resulting woodland cover estimated within CRAFTY-Scotland derived from the combination of data covered 17.81% of Scotland, compared to 19% based on the latest forestry statistics (Forest Research, 2019). The underestimation is likely due to the use of the available slightly older datasets, which give a record of woodland cover in 2014-2015. The Forestry Statistics in 2016 estimated woodland cover at 18% (Forest Research, 2016), suggesting that the model

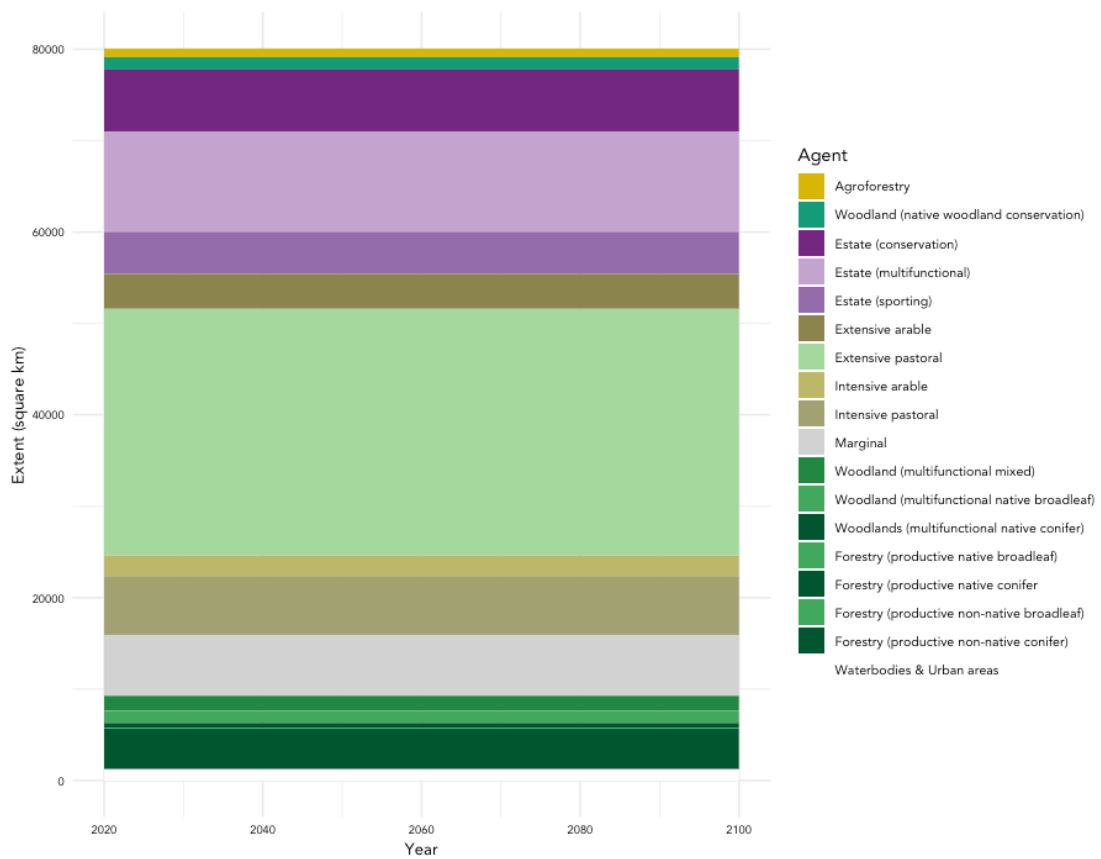


Figure 4.4: Agent stationarity through time under a reference model run

provides an accurate estimation of woodland cover based on the available data. It did not make sense to run the visions from a past time period (i.e. 2015), as they are explorative future scenarios and cannot be expected to accurately reproduce land use change over the past few years. In order to account for the underestimation, 1.19% was added to all woodland cover estimates from the model, to represent starting from 19% cover in 2020.

BASELINE SERVICE PROVISION

Initial service production was calculated after a single time step. Figure 4.6 shows the average service provision for each agent, per region.

AVAILABILITY

All code used to parameterise CRAFTY-Scotland is openly available at the following GitHub repository: <https://github.com/VeeBurton/GitCRAFTYr>. The model will be stored in the existing CRAFTY repository, and the results will be made available to explore via an existing web interface <https://crafty.shinyapps.io/CRAFTY-EU/>.

4.5 DISCUSSION

This chapter has described how the CRAFTY modelling framework was implemented for a Scottish context, and critically discusses the extent to which the objectives outlined below could be met based on data availability and model limitations. Integrated models which seek to understand the interactions between human decision making, our environment and ecological processes are of increasing importance (Synes et al., 2016). In establishing CRAFTY-Scotland, this chapter set out to develop an approach which could: represent the main land use types in Scotland, provide small scale detail whilst also accounting for a large scale landownership pattern,

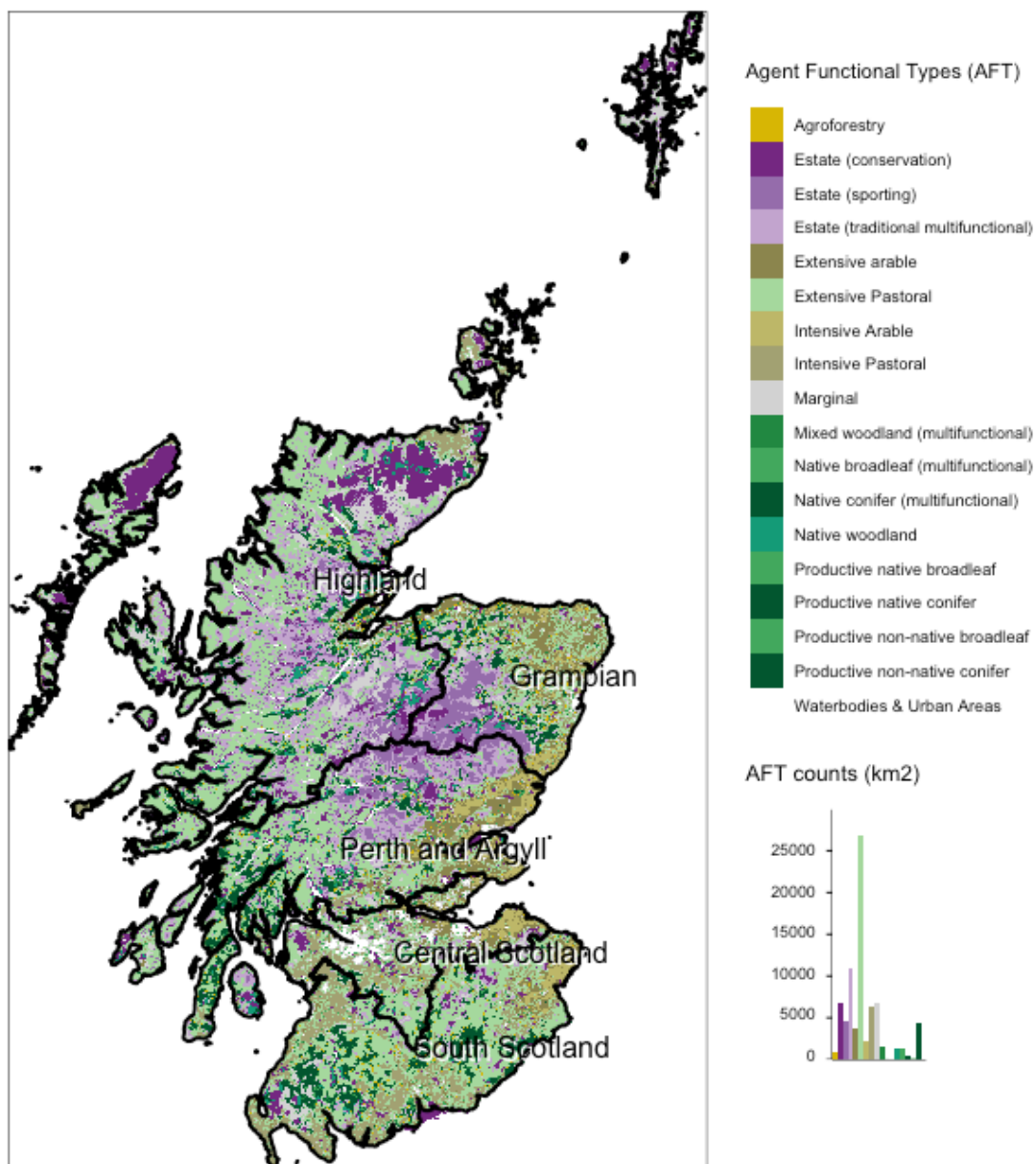


Figure 4.5: The initial locations of all agent types, based on land use, land ownership and designations

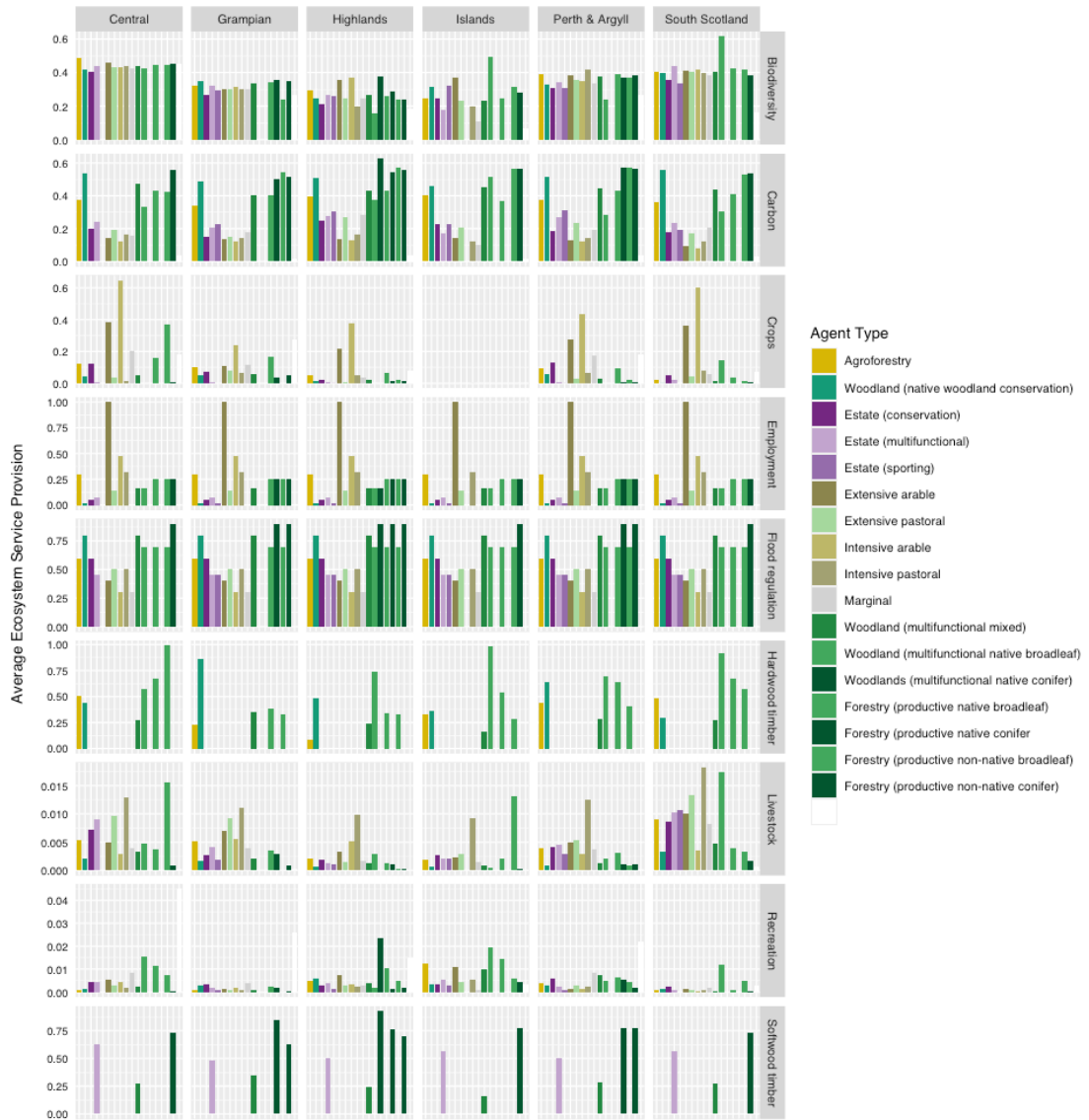


Figure 4.6: Baseline service provision, per region and agent type. Values have been normalised per service

examine trade-offs between ES produced by different land managers, and also take account of important influencing factors such as deer density. The approach also needed to be able to represent changes in governance envisaged by stakeholder developed visions for woodland expansion, as well as interactions between these changes and the aspects of the model mentioned above. Taking into account the initial aims, this section considers the data and modelling barriers, strengths, limitations and potential future applications of such a modelling approach.

4.5.1 STRENGTHS

INCLUDING DIVERSE, NON-ECONOMIC VALUES IN A MODELLING FRAMEWORK

A key assumption of many previous scenario approaches is that land managers display homogeneous and economically rational behaviour across space, time, and scenarios, but this can limit the understanding of the feasibility of scenario-based pathways towards societal visions for the future (Brown et al., 2018). By developing a typology of Scottish land managers, CRAFTY-Scotland is able to simulate heterogeneous behaviour across space e.g. land managers with different objectives and attitudes, and thus allow a more realistic assessment of the likelihood of ‘achieving’ different visions. In addition, integrating stakeholder values with the biophysical focus of scenario approaches which explore opportunities for multi-functionality has been highlighted as a key challenge for ES research (Cord et al., 2017). This model has made steps towards integrating non-economic, ‘intrinsic’ values. The CRAFTY framework is intended to allow various behaviours and attitudes to be represented in a few key parameters, which makes it very flexible. The novel inclusion of attitudes applied spatially, especially to represent influence across large areas, allowed initial exploration for how land ownership patterns might affect uptake of new land based policies, and this could be built upon in future research.

NOVEL APPLICATION FOR EMERGENT LAND USE CHANGE

All models involve assumptions and approximations, but where possible CRAFTY-Scotland used robust assumptions made based on the best-available data. By modelling relationships between the available data, clear assumptions could be made on how ES indicators may change in the future. The model includes a range of ES, and agents (land managers) with variable behaviours aren't forced to optimise or be economically 'rational'. In general, the model doesn't optimise land use, but allows it to emerge from drivers and agent responses - just as in the real world. Doing this at a national scale is novel.

INCORPORATING GOVERNANCE MECHANISMS

Advances in modelling may enable us to anticipate how different policy options are likely to affect the decision making processes of land managers, for example by coupling ABMs to biophysical models (Reed et al., 2009b). The use of land use ABMs to simulate representations of political decision making can contribute by generating empirically based projections that inform policy development, replacing misleading assumptions (Brown et al., 2019a). Governance mechanisms simulated within CRAFTY-Scotland don't have to directly cause or prevent change, or use economic levers, but can be directed at different ES, use different capitals, and interact with agent-decision making in a way that is not generally possible in simpler models.

4.5.2 LIMITATIONS

The limitations to CRAFTY-Scotland in its current form are mainly associated with data availability and the extent to which the indicators used can provide robust evidence for decision making.

REPRESENTING BIODIVERSITY

Biodiversity is an umbrella term for a complex collection of aspects, and the use of different indicators is not well defined, and varies significantly between country and discipline (Duelli & Obrist, 2003). Chapter 2 highlighted significant evidence gaps in data relating to a wider range of taxa and metrics to represent biodiversity in a UK context. These gaps are found worldwide and across disciplines, with substantial gaps in data and observations due to the accessibility, popularity, measurability, and even fundamental knowledge of different components of biodiversity (Hill et al., 2016). The choice of metric is important and affects the understanding of policy makers and the general public (Hill et al., 2016). Data availability and the indicator chosen are expected to be a limiting factor in results relating to change in biodiversity within CRAFTY-Scotland. The floral plant species richness indicator used is not necessarily correlated with the richness of other taxa. Other models have shown that, for example, species richness can remain stable in a given landscape, whereas other measures (e.g. compositional similarity) can be in sharp decline. This highlights a dichotomy between “species richness” and “conservation value” (Duelli & Obrist, 2003). Therefore further work is needed to produce an indicator of overall species richness.

Woodland biodiversity in particular is not well represented. This is a drawback given the focus, but it is also useful to consider the expected trade-offs that woodland expansion may cause different assemblages (i.e. floral species suited to open habitats). This is a common problem, with there being a lack of woodland biodiversity indicators applicable across Europe. Gao et al. (2015) reviewed the strength of evidence for biodiversity indicators in forest ecosystems in Europe, finding that many indicators on which forest monitoring and conservation planning are based are only weakly scientifically supported. The most promising indicator relationships based on statistical analysis were positive correlations found between deadwood volume and wood-living fungal species richness and the age of canopy trees and epiphytic lichen species richness (Gao et al., 2015). Looking at multiple biodiversity metrics in tandem within models will

support more robust indicator development, enable stronger predictions of biodiversity change, and provide policy relevant advice (Hill et al., 2016). Multiple indicators need to be applied if a wider spectrum of biodiversity is to be described (Gao et al., 2015). Instead of replacing the indicator for floral plant species richness, future applications of CRAFTY-Scotland could integrate additional indicators, particularly for woodland biodiversity, to gain a fuller picture of the expected effects.

CARBON DYNAMICS

The indicator developed provides a simple estimation of the total carbon stock under and including mature woodland. The soil carbon data was modelled based on regression analysis of soil properties and their relationships to a number of variables across Scotland, and was shown to be similar to previous estimates whilst including estimates of uncertainty (Poggio & Gimona, 2014). It can be used as input into simulation models to model the changes of carbon stocks with land use and climate changes, but it is acknowledged that it is a challenge to do this dynamically or mechanistically (Poggio & Gimona, 2014). The woodland carbon estimates are based on averages for woodland types found in the National Forest Estate. The findings from Chapter 2 suggest that an initial loss in carbon with woodland establishment is generally followed by an increase to a greater total carbon stock over time. Future approaches to improve the indicator should account for the carbon dynamics which may occur during woodland establishment and growth.

FLOOD REGULATION

The indicator for flood regulation could be improved by pre-processing through a hydrological model that takes into account soil and topography. Many environmental factors contribute to the role that land use has in either alleviating or worsening flooding. As outlined in Chapter 2,

these include water use by vegetation, water holding capacity, hydraulic roughness of the surface, topography, soil type and structure, and of course the characteristics (duration, intensity) of the precipitation event. The crop factor applied to each agent in CRAFTY-Scotland is just one aspect of hydrological modelling usually used to explore the effect of land use on flood flows. GIS-based runoff models can be used to more accurately predict water balance based on the crop factor, rainfall, runoff and other climate variables (e.g. evapotranspiration), and topography (e.g. Nisbet & Thomas (2006), Sturck et al. (2014), Buendia et al. (2016)). These models could either be loosely or dynamically coupled with CRAFTY to provide a more accurate indicator of flood regulation.

DEER

High wild deer density is a significant factor which limits natural regeneration of woodlands in Scotland (Environment Climate Change and Land Reform Committee, 2017; Pepper et al., 2019; Putman, 2012). The deer density data used as a barrier capital in CRAFTY-Scotland is based on red deer counts. Counts are generally undertaken either on foot (ground counts), by helicopter, or at night time using thermal imaging cameras, and are not always an accurate reflection of actual numbers. Improving deer count techniques is a research priority (Holland et al., 2017). In the lowlands and urban/peri-urban areas populations of roe deer have substantially increased, and counts are much harder to carry out in these areas due to the fragmented habitats and logistics associated with collaboration (Holland et al., 2017), and so data for deer populations in these areas is limited. More extensive use of thermal imaging could improve accuracy of population estimates (Holland et al., 2017), and incorporating more accurate data into CRAFTY-Scotland would improve estimation of the effect of deer densities.

4.5.3 IMPLICATIONS FOR RESEARCH

ABMs are ideally suited to participatory usage (Étienne, 2011; Matthews et al., 2007; Voinov et al., 2016). Adding a participatory element to CRAFTY-Scotland was beyond the scope of this thesis, but it is an obvious next step for future research. Participation could take a number of forms, from presenting of the results to the stakeholders involved in the visions workshop and interviews, to developing further applications which include stakeholders in the modelling process from the beginning and throughout. This would allow the opportunity for mechanisms and behaviours within the model to be formed and tweaked based on deliberation.

Although it can be effectively used, the use of secondary data in ES models should be done with caution, as it can lead to generalisation errors (Aitkenhead et al., 2015). Greater use of primary data has been advised (Aitkenhead et al., 2015), and additional or improved indicators could easily be incorporated into CRAFTY-Scotland due to the flexible and adaptable framework.

Although novel, the incorporation of spatially explicit attitudes across land holdings within CRAFTY-Scotland is currently quite abstract. The randomisation which had to be applied for data protection may limit the insights available from the model explorations. Perhaps a more powerful potential application could arise at regional or sub-regional scales, for example in landscape scale partnerships where land ownership, management and objectives are transparent and negotiable.

Finally, dynamic coupling of land use ABMs with Individual Based Models (IBMs) of ecological systems have particular promise, with applications expected to uncover non-linear dynamics, feedback mechanisms, time lags and surprising behaviours (Synes et al., 2016). CRAFTY has already been coupled with an IBM of pollinator demography and dispersal, showing that important system dynamics may be missed by uncoupled modelling approaches (Synes et al., 2018). In particular, given the limitations acknowledged with regards to how deer populations have been included within CRAFTY-Scotland, there is great potential for coupling an ABM of land

use change with an IBM of deer populations. Further development of such coupling will improve fundamental understanding of socio-ecological dynamics and thus improve management of land use systems.

4.5.4 CONCLUSIONS

The objectives for the establishment of CRAFTY-Scotland were to explore the effect of land manager behaviour and changes in governance on ES delivery and land use change. The model is intended to be exploratory only, to consider different trajectories and sensitivities, not to predict change. This chapter has explained the process of collating and processing data by which to do this. Model results are always conditional on the set up, and this chapter has aimed to explain how CRAFTY-Scotland is set up and to highlight the likely effects of that as far as possible. The process benefitted from the excellent existing data available on land use, existing ES models, and ES model results, and the CRAFTY framework offered an opportunity to combine many different types of data. ABM is particularly suited to the Scottish context because so much of Scottish land use, as well as the visions defined in Chapter 3, are determined by individual motivations instead of the economically optimal production system of the kind usually simulated by land use models. CRAFTY-Scotland is an experimental and novel approach, with it currently being more appropriate to discuss what goes into the model and how this is expected to affect the outputs. It is unwise to draw strong conclusions for decision making, but applying the model and discussing the results in a real-world context will highlight the most important issues to focus on for future research.

Table 4.1: The agent typology for CRAFTY-Scotland

Agent	Description
Productive non-native conifer	Production focused forest managers with non-native conifer plantations. Primary objective is softwood timber production. Very reliant on non-native conifer yield class capital.
Productive non-native broadleaf	Production focused forest managers with non-native broadleaf plantations. Although not currently common, this agent was viewed to be an important future manager under projected climate change and demand for non-native broadleaves, in particular sycamore. Primary objective is hardwood timber production. Very reliant on non-native broadleaf yield class capital.
Productive native conifer	Production focused forest managers with native broadleaf plantations. Primary objective is hardwood timber production. Very reliant on native broadleaf yield class capital.
Productive native broadleaf	Production focused forest managers with native conifer plantations. Primary objective is softwood timber production. Very reliant on native conifer yield class capital.
Native woodland (conservation)	Conservation focused forest managers. Primary objective is to conserve biodiversity. Very reliant on native broadleaf (for conservation) yield class capital.
Multifunctional mixed woodland	Forest managers with mixed woodlands and multiple objectives e.g. some timber, some conservation, some recreation etc. Less intense use.
Multifunctional non-native conifer	Forest managers with non-native conifer plantations for multiple objectives
Multifunctional native conifer	Forest managers with native conifer plantations for multiple objectives
Multifunctional non-native broadleaf	Forest managers with non-native broadleaf plantations for multiple objectives
Multifunctional native broadleaf	Forest managers with native broadleaf plantations for multiple objectives
Agroforestry	Farmers practicing silvo-pastoral or silvo-arable forms of agroforestry, combining trees with either grazing or crops, for timber, crop and livestock production.
Intensive arable	Farmers managing intensively for crop production.
Extensive arable	Farmers managing for crop production, less intensively either due to lower land productivity or other objectives.
Intensive pastoral	Farmers managing intensively for livestock.
Extensive pastoral	Farmers managing for livestock, less intensively either due to lower land productivity or other objectives.
Sporting estate	Estate owners whose primary objective is to provide deer stalking or grouse shooting.
Traditional multifunctional estate	Estate owners with a wide portfolio of activities, combining deer stalking and grouse shooting with farming, forestry, or recreation provision (e.g. holiday homes)
Conservation estate	Estate owners managing purely for conservation objectives
Marginal	Represents areas with minimal management, often where biophysical conditions preclude significant productivity i.e. high montane areas, deep peat areas

Table 4.2: Datasets used to define land manager distribution

Dataset	Acronym	Date	Source
Land Cover Map	LCM	2015	Environmental Information Data Centre - https://data.gov.uk/
National Forest Inventory	NFI	2015	Forestry Commission - https://data.gov.uk/
Native Woodland Survey Scotland	NWSS	2014	Scottish Government Spatial Data - https://data.gov.uk/
Deer Management Units	DMU	2016	Natural Spaces Gateway - https://gateway.snh.gov.uk/natural-spaces/

Table 4.3: Capitals that agents can utilise for service production

Capital	Definition	Input data [units; resolution]	Ecosystem Services (ES)	Data source
Tree species potential productivity	Baseline productive potential for tree species indicative of each forest agent	Yield class for each species (normalised to [0,1]) per ikm^2	Hardwood and softwood timber; carbon, biodiversity	Ecological Site Classification (ESC) – Forest Research (FR)
Crop productive potential	Potential crop production	LCA class (normalised to [0,1]) per ikm^2	Crop production	Land Capability for Agriculture (LCA) – James Hutton Institute (JHI)
Grassland productive potential	Sum of potential grassland productivity	Yield in (metric), (normalised to [0,1]), per ikm^2	Livestock	Impressions 'Integrated Assessment Platform' (IAP)
Water runoff	The amount of water supply (runoff) produced, ranked by Scottish sub-catchment	Amount of runoff produced [0,1] per ikm^2	Flood regulation	INVEST 'water yield' model – JHI
Human	Includes health, knowledge, skills and motivation of individuals. Broadly covers areas of education, job experience, skills and health.	Low to high [0,1] per ikm^2	All services	Impressions IAP
Social	Structures, institutions, networks and relationships that enable individuals to maintain and develop their human capital in partnership with others e.g. families, communities, businesses, trade unions, voluntary organisations, legal/political systems and educational and health institutions	Low to high [0,1] per ikm^2	All services	Impressions IAP
Manufactured	Material goods, tools, machines, buildings and other forms of infrastructure that contribute to the production process e.g. roads, dams, water pipelines	Low to high [0,1] per ikm^2	All services	Impressions IAP
Financial	The productive power of other forms of capital, allowing them to be owned and traded. Reflects the ability of a nation to claim resources from overseas	Low to high [0,1] per ikm^2	All services	Impressions IAP
Attitudes	Attitude to native woodland, Attitude to productive forestry, Attitude to nature (habitat creation)	[0,1], ikm^2	All services	Scotland's Rural College (SRUC) estate survey data and data from Hopkins et al. (2017)

Note:

IAP datasets can be viewed and downloaded here: http://www.impressions-project.eu/show/IAP2_14855

Table 4.4: Input data and sources for ecosystem service indicators used in CRAFTY-Scotland

Ecosystem Service (ES)	Input data [units; resolution]	Data source
Timber (softwood/hardwood)	Number of logs above a specified diameter class (for quality purposes), per species, summed to simplified softwood and hardwood. Per 1km ² , normalised [0,1]	Growth Model developed by Forest Research (McKay et al. 2003, Mathews et al. 2016)
Biodiversity	Plant species richness – distribution of all native flowering species, low to high [0,1], 1km ²	James Hutton Institute
Carbon storage	Soil organic carbon stocks at 1km ² + total woodland carbon (normalised to [0,1])	James Hutton Institute and Forest Research
Flood regulation	Low to high water retention [0,1] per agent/1km ²	Indicator developed based on crop factors for CORINE land use classes (Sturck et al. 2014)
Recreation	Low to high [0,1] density of submissions on an online photo-sharing service (Panoramio) per 1km ²	James Hutton Institute
Livestock	Sum of cattle and sheep density per 1km ² (normalised to [0,1])	James Hutton Institute
Crop production	Sum of various crop yields per 1km ² (normalised to [0,1])	Impressions IAP
Employment	Number of Full Time Equivalent (FTE) jobs provided per sector, related to agent type	Indicator developed based on employment statistics for different land-based sectors in Scotland

Ecosystem service implications of pathways to stakeholder visions for woodland expansion

The previous chapter described a method developed to establish an agent-based model of land use change for Scotland. By incorporating data on land productivity and representing diverse land management, the model is set up to explore whether or not realistic possibilities for land use change can match up with the visions for woodland expansion established with stakeholder input in Chapter 3. Key features of the CRAFTY modelling framework described are its ability to represent multiple ES, multifunctional land uses, and respond to trade-offs.

5.1 INTRODUCTION

The ES concept has gained increasing importance in environmental research, policy and practice since its emergence, predominantly as a way for decision makers to clarify how nature can support human well-being (Rieb et al., 2017), and the concept has been strongly integrated into UK forestry policy and decision making (Raum, 2018; Sing et al., 2017). In Scotland, forestry policy and planning since devolution has been strongly influenced by aims for both woodland expansion and multi-functionality (Muñoz-Rojas et al., 2015). However, there are conflicting objectives between stakeholders from multiple sectors and a lack of understanding of how exactly to achieve this multi-functionality (Muñoz-Rojas et al., 2015), which indicates that there are challenges in achieving synergy between policies, and consequently in achieving aspirations for more woodland cover. In a review of ES mapping in Scotland, limited work was found relating to trade-offs and synergies between services, or between policy areas (Aitkenhead et al., 2015), and in the case of woodland expansion it is acknowledged that more needs to be done to recognise trade-offs with other land uses (Thomas et al., 2015). More broadly, decision support tools for ES have been challenging to develop, as few are able to account well for a range of ES, or stakeholder perspectives on those ES (Rieb et al., 2017). Therefore, the CRAFTY frameworks ability to account for multiple ES as well as land manager preferences provides an opportunity to address these challenges.

To date, ES related research on woodlands in Scotland has largely focused on provision from established woodlands (Thomas et al., 2015). This was confirmed by the findings of Chapter 2, with a large part of the evidence for the effects of woodland expansion on ES being biased towards established coniferous plantations, largely on regulating ES. In terms of woodland expansion, spatial research has largely focused on suitability, opportunities and constraints for woodland expansion (Sing et al., 2013) and methods for increasing functional connectivity of woodlands (Moseley et al., 2008). There have also been valuable explorations of ‘hotspots’ for

woodland creation based on potential biodiversity, visual and recreation benefits (Gimona & Van Der Horst, 2007; Van Der Horst & Gimona, 2005). The Scottish Government Land Use Strategy (Scottish Government, 2011) included two regional pilot projects which aimed to encourage integrated thinking, provide methods for optimising land use, and resolve conflicts relating to future land use change. The results of these projects fed into the revised strategy (Scottish Government, 2016), yet both faced difficulties in effectively integrating an ecosystem approach (Claret et al., 2018), and the stakeholders consulted in Chapter 3 expressed a desire for similar approaches to be developed or learned from in the future. The most recent Scottish Forestry Strategy (Scottish Government, 2019) refers to Natural Capital (NC) in part and more broadly uses the term ‘benefits’ rather than ES, but this is more about communicating to wider audiences rather than shying away from the ES concept. Therefore, there remains a need to quantify these benefits and develop methods which may help to manage the synergies and trade-offs between them.

Policies and funding mechanisms have a strong influence on Scottish land use, in particular agriculture and forestry. Common Agricultural Policy (CAP) support plays a very important role in ensuring that Scottish farms are profitable. Originally put in place so that farmers were guaranteed a fair living, subsidies were given per animal in the 1980s, changing to payments per hectare of cropping land or number of livestock produced in the 1990s (Skerratt et al., 2016). Forestry policy has also traditionally been top-down and driven by national strategic objectives (Slee, 2007), with past funding for woodland expansion coming from the Scottish Rural Development Programme (SRDP) (Thomas et al., 2015). Policies have evolved from these more sectoral approaches to support multi-purpose environmental management providing multiple benefits to people and the environment (Warren, 2002). Within the CAP, this has been represented by the move to a ‘two-pillar’ approach, where Pillar 1 covers price and income support, and Pillar 2 covers wider rural development, agri-environmental measures, and support for Less Favoured Areas (LFAs). LFA support is now a separate scheme and is a key area of uncertainty

in terms of future support post-Brexit (Skerratt et al., 2016). The concepts of ES and NC have been strongly integrated at a conceptual level into Scottish policies, with further work required to develop proactive policy intervention and concrete measures (Claret et al., 2018). Declining subsidies for agriculture (Reed et al., 2009a) and the withdrawal of the UK from the EU have increased the uncertainty around funding for land management long term, and the development of new markets for desired ES is recognised to be of key importance going forwards (Skerratt et al., 2016). The lack of concrete measures implemented to support ES and NC concepts highlighted by (Claret et al., 2018) points towards a need to explore ways in which this can be improved. A key output from the visions development in Chapter 3, was to record possible new policies and governance mechanisms which could help to promote management and land use changes which would promote movement towards visions. Thus, there is an opportunity to model the effect of these potential new sources of funding and other governance mechanisms on land use change and resulting ecosystem services.

This chapter describes the process developed to simulate the different visions developed in Chapter 3 within the CRAFTY-Scotland model established in Chapter 4. It explores the results in order to address the final research question of the thesis; how these visions for woodland expansion might affect future ES provision. In particular, it will explore whether the visions seem feasible given land use and land manager attitude constraints, how ES relationships (synergies, trade-offs) are affected, and whether simulated governance mechanisms can influence land manager behaviour to promote pathways to visions.

5.2 METHOD

The modelling framework and set-up of CRAFTY-Scotland has been described in detail in Chapter 4. All model components for CRAFTY-Scotland are illustrated in Figure 5.1. This section describes how each vision was enacted within the model, and the metrics chosen to compare results between visions. For each vision, the model was run for a period of 80 years, from 2020

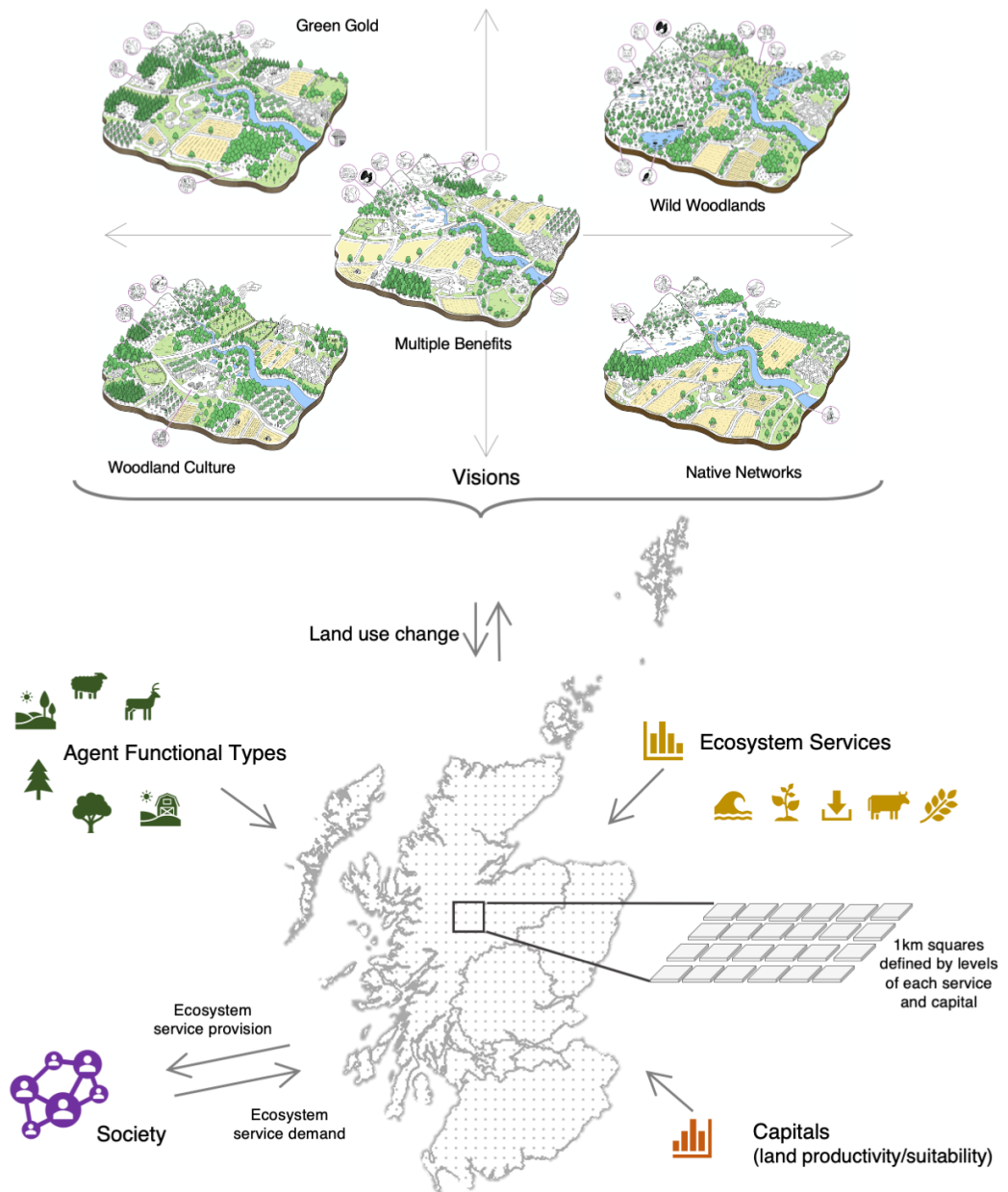


Figure 5.1: Model components of CRAFTY-Scotland

Table 5.1: Demand changes per vision

Service	Initial	Green Gold		Multiple Benefits		Native Networks		Woodland Culture		Wild Woodlands	
	2020	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Softwood timber	3495	10048.125	20970.0	3495.00	3495	3495.000	3495	10048.125	20970	3495.000	3495.0
Hardwood timber	73	182.500	365.0	73.00	73	73.000	73	209.875	438	73.000	73.0
Biodiversity	40925	71618.750	122775.0	86965.62	163700	117659.375	245550	102312.500	204625	117659.375	245550.0
Carbon	23061	49004.625	92244.0	23061.00	23061	57652.500	115305	57652.500	115305	49004.625	92244.0
Flood regulation	6904	9493.000	13808.0	17260.00	34520	17260.000	34520	17260.000	34520	17260.000	34520.0
Recreation	10980	10980.000	10980.0	15097.50	21960	19215.000	32940	27450.000	54900	19215.000	32940.0
Crops	1585	1287.812	792.5	2773.75	4755	3368.125	6340	3962.500	7925	1287.812	792.5
Livestock	2421	2421.000	2421.0	4236.75	7263	5144.625	9684	6052.500	12105	2421.000	2421.0
Employment	7513	10330.375	15026.0	21599.88	45078	7513.000	7513	21599.875	45078	10330.375	15026.0

to 2100, and the results (outputted as a csv file per year) were processed and analysed in RStudio software (R version 3.6.0). In order to explore distinctions in the results, they are presented by region (regions were outlined in Section 4.3.2).

5.2.1 ENACTING THE VISIONS WITHIN CRAFTY-SCOTLAND

In order to simulate each vision within CRAFTY-Scotland, changes were made predominantly in two areas of the model. First, capitals could be edited per vision, to reflect possible future governance changes such as a loss of subsidised support for marginal (extensive pastoral) agriculture (e.g. by reducing grassland capital productivity), or new financial incentives for woodland connectivity (e.g. by increasing native woodland capital productivity where previous models have shown that there is capability for improving functional connectivity). Second, external societal demand for ecosystem services could be varied based on the vision priorities. Table 5.1 illustrates the effect of manipulating the demand figures from the reference demand each year, reported at 2050 and 2100. Changes to demand were made gradually every year. The descriptions and justifications for how each vision storyline was enacted within the model are detailed below.

GREEN GOLD

This vision saw woodland expansion being comprised primarily by large scale, productive, sustainable plantations. High value timber was primarily expected to be provided by non-native conifer plantations. To achieve this, stakeholders suggested innovative funding mechanisms to incentivise planting (e.g. through connecting new developments to woodland creation). In order to represent such funding mechanisms, the non-native conifer and non-native broadleaf capitals were increased so that productive woodland agents would stand a greater chance of out-competing other agents where the (incentivised) capital allowed. The capital was increased only in areas identified by the Woodland Expansion Advisory Group (WEAG) as being ‘Phase 3’ land (Sing et al., 2013). These are areas with the most potential for woodland expansion (i.e. biophysically suitable and without any designations which would preclude land use change). In particular, Phase 3 areas exclude areas of prime agricultural land, and areas of deep peat. In addition, the vision saw a reduction in support (i.e. subsidies) for marginal agriculture. To represent this, the grassland capital within ‘Disadvantaged’ and ‘Severely Disadvantaged’ LFA areas was reduced by half, so that agricultural land managers relying heavily on that capital would do less well. To represent the societal demand envisaged by *Green Gold*, demand for priority services was increased in the following order: 1) Softwood timber (500% increase by 2100), 2) Hardwood timber (400% increase by 2100), 3) Carbon storage (300% increase by 2100), 4) Biodiversity (200% increase by 2100), 5) Employment & Flood regulation (both increase 100% by 2100).

MULTIPLE BENEFITS

This vision emphasised that new trees and woodlands should ‘stitch-in’ amongst existing important land uses, with agricultural land being a key asset, and a wide variety of woodland types being valued. In order to represent an incentive for multifunctional mixed woodlands, the mixed woodland capital was increased by 50%. In addition, forms of agroforestry were viewed as a

potential way to integrate woodland expansion and agriculture, and so the agroforestry capital (made up of a combination of predicted productivity for tree species suitable for various forms of agroforestry and crop/grazing productivity) was also increased by 50% to represent a financial incentive. To represent changing demand, priority services were increased in the following order: 1) Employment (500% increase by 2100), 2) Flood regulation (400% increase by 2100), 3) Biodiversity (300% increase by 2100), 4) Crops and Livestock (both increase 200% by 2100), 5) Recreation (100% increase by 2100).

NATIVE NETWORKS

The central aspect of this vision is increased connectivity of native and semi-natural woodlands, with this being funded through some form of Payment for Ecosystem Services (PES) which would encourage land managers to plant in areas that would contribute to connectivity. In order to represent this, data representing a national 'Forest Habitat Network' (FHN) was used. The Scottish Forestry Strategy outlined a major aspiration to develop FHNs through the restoration and improvement of existing woodland and the incorporation of targeted new planting. A Habitat Network Tool from 'BEETLE' (Biological and Environmental Evaluation Tools for Landscape Ecology) uses a focal species approach to assess the functional connectivity of habitat for specific and generic focal species. This was used in the Scotland FHN project to produce a spatial dataset which indicates the presence and spatial extent of FHNs at the national and regional scale (Moseley et al., 2008). The national FHN dataset was added to all native woodland capitals, to represent an incentive for connectivity where planting will contribute to developing the national FHN. To represent changing demand, priority services were increased in the following order: 1) Biodiversity (500% increase by 2100), 2) Carbon storage and Flood Regulation (400% increase by 2100), 3) Livestock and Crops (300% increase by 2100), 4) Recreation (100% increase by 2100).

WOODLAND CULTURE

Woodland Culture envisaged a well-forested and productive landscape encompassing small-scale diversity of tree species, woodland type and tenure. Land Reform, where diversity of land ownership is increased and communities are given greater power to manage land, was seen as a key mechanism by which this may be achieved. Representing this within CRAFTY-Scotland was a key challenge. As previously outlined in Section 4.3.3, several datasets were combined to provide a proxy for land ownership. Diversification of the scale of landownership has been defined as fragmenting large land holdings into smaller parcels (Skerratt et al., 2016). As a simple experiment to represent Land Reform, attitude capitals were broken up into smaller spatial extents, and re-randomised i.e. re-allocated across space. This meant that both positive and negative (barrier) attitudes to woodland expansion are gradually given influence over smaller and smaller areas of land (representing reduced land holding size and increased diversity). The re-randomisation ensures that there is a change in attitudes at various locations, representing changes in land ownership. This process of Land Reform is implemented in the vision starting from 2030, to represent the time taken for recent legislation to gain momentum in practice. As in *Green Gold*, it was expected that subsidies for marginal agriculture would decrease, so the grassland capital with 'Disadvantaged' and 'Severely Disadvantaged' LFA areas was decreased to represent a loss of subsidy. Community empowerment was another process seen as central to achieving this vision. To represent this, both human and social capital were increased by 10% to represent an increase in community knowledge and motivation, and new community networks and relationships respectively. Financial capital was also evened out across regions - with a 10% increase applied to regions with financial capital below 50% - in order to increase the productive power of land managers across Scotland, including those in rural regions. In terms of demand, unlike all other visions where priority ES were ranked from 1-5, the stakeholders involved in discussing *Woodland Culture* chose to prioritise all ES, representing the true diversity of the vision. As a result, demand for all ES were increased four-fold, with a five-fold increase for both timber services

and employment, to represent slightly higher prioritisation for those services.

WILD WOODLANDS

Incentivising larger scale regeneration of native woodland was a key element of this vision. As in *Green Gold*, WEAG Phase 3 areas were added to the model to represent an incentive for targeted woodland creation, but in this case they were added to native woodland and mixed woodland capitals instead of productive woodland capitals. To represent a loss of support for marginal agriculture, the grassland capital was reduced gradually in LFA areas in a similar way to the above visions. As in *Woodland Culture*, Land Reform was viewed as a key process by which attitudes might change in order to facilitate this large-scale change. The same process of breaking up and redistributing attitude capitals to represent Land Reform as in *Woodland Culture* was followed. In addition, the deer density barrier capital was reduced in strength through time, to represent the expected effect of an increase in regulation and landscape-scale coordination of deer management envisaged by stakeholders. To represent changing demand, priority services were increased in the following order: 1) Biodiversity (500% increase by 2100), 2) Flood regulation (400% increase by 2100), 3) Carbon storage (300% increase by 2100), 4) Recreation (200% increase by 2100), 5) Employment (100% increase by 2100).

5.2.2 COMPARING BETWEEN VISIONS

The CRAFTY framework has previously been applied in a theoretical European context in order to assess the likelihood of meeting societal visions for the future (Brown et al., 2018). This previous application provided a starting point for establishing metrics which can be used to compare between the outputs of different visions, and to determine whether or not visions are on their way to being ‘met’ or not. Two of these metrics, ES diversity and land use diversity, were applied here. Both of these indices are based on Simpsons’s diversity index (Simpson, 1949). Usually ap-

plied to biodiversity, Simpson's index takes into account the number of species present, as well as the relative abundance of each species. As species richness and evenness increases, diversity increases. In this case, species are substituted for either ES or land manager type. So, the greater the number and evenness of ES provided, the greater the ES diversity, and the greater the number and evenness of different types of land managers, the greater the land use diversity. The equation for Simpson's diversity index is below, where n is the total number of each individual ES or land manager, and N is the total number of all ES or land managers:

$$D = 1 - \sum (n/N)^2$$

In addition, annual woodland cover was calculated by recording the percentage cover of woodland land managers plus timber producing non-woodland land managers, per time step. In order to compare between visions in terms of broad land use changes, land manager types were grouped into categories. To compare ES provision between visions, provision was summed per region, and per time step, in order to observe changes through time. All ES results were normalised to values between 0-1 (low-high provision), in order to facilitate comparison between the outputs resulting from varied indicators.

VISION THRESHOLDS: DIRECTIONAL NOT ABSOLUTE

In order to explore whether visions were being 'met' or not, thresholds had to be defined. Given the relative nature of the visions, exact desired values for service supply do not exist. Therefore, directional thresholds were used. The top five vision priorities identified by stakeholders in Chapter 3 were used. Thus, if results showed that supply of a priority service was increasing, this would be recorded as a positive step towards the vision being achieved. In contrast, if supply of a priority service decreased, this would be recorded as a negative step away from the vision.

5.3 RESULTS

In order to separate out distinctions in the results, they are presented by largely by region, with the exception of the following national metrics.

5.3.1 NATIONAL METRICS

Figure 5.2 shows a comparison of the national scale metrics generated for each vision. *Green Gold* shows the fastest increase in woodland cover, and along with *Woodland Culture* are the only visions which meet (and exceed) the 2032 target of 21% (23.8% and 21.8% respectively). These two visions continue to show rapid increases in land being managed for woodland later in the century, both exceeding the government target of 25% by 2050 (27.1% and 26.3% respectively). Rapid step changes happen when the model alterations to represent Land Reform occur - i.e. in both *Woodland Culture* and *Wild Woodlands* the change in attitudes towards woodland and forestry cause slight decreases in woodland cover around 2030 and 2050. By the end of the century, *Woodland Culture* (33.2%) and *Green Gold* (28%) have the highest woodland cover, followed by *Wild Woodlands* (26.9%), *Native Networks* (23.2%), and *Multiple Benefits* (22.7%). A full table of the metrics results can be found in Appendix D. There is an increase in ecosystem service diversity in all visions, except perhaps *Wild Woodlands*. *Woodland Culture* ends up with the highest ecosystem service diversity by the end of the century. *Green Gold* also shows a small initial drop in diversity, but this recovers and increases by the end of the century. *Multiple Benefits* shows the smallest increases in ecosystem service diversity. The services which decline to allow this increase in overall diversity tend to be floral species diversity, livestock, and recreation. Both *Woodland Culture* and *Wild Woodlands* illustrate that step changes in ecosystem service diversity can occur with modelled changes to represent Land Reform, but both visions show recovery and overall increases in diversity. This step change is of course dependent on how Land Reform is implemented in the model, but there is a clear response even if the size and or timing of this is variable.

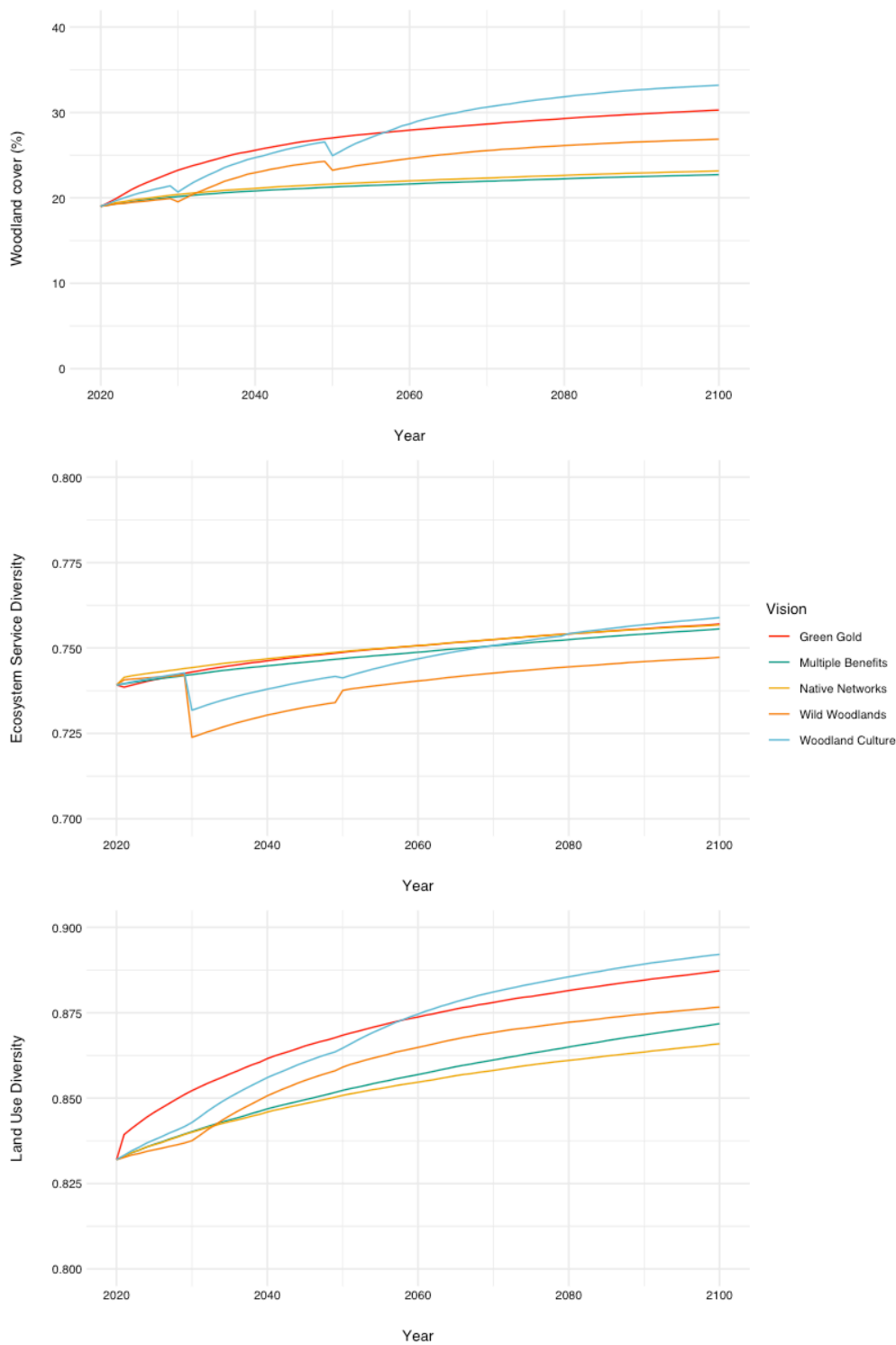


Figure 5.2: A comparison of national scale metrics (woodland cover, ES diversity and land use diversity) for each vision

In other words, the modelled change assumes an immediate impact, but real changes are likely to be more spread out as changes in ownership or management occur over time. Land use diversity also increases in all visions, especially in *Green Gold* and *Woodland Culture*, and least in *Native Networks*. This increase in diversity may represent movement towards achieving land reform goals.

5.3.2 INFLUENCE OF ESTATE MANAGER ATTITUDES TOWARDS DIVERSIFICATION

Figure 5.3 demonstrates a clear influence of the attitudes of estate managers towards diversification on potential achievement of woodland cover targets. If estate managers are less willing to diversify, then woodland cover targets are less likely to be met. If they are willing, then targets are met in more visions. In particular, when estates are willing to diversify, *Wild Woodlands* also meets the 2032 (21.9%) and 2050 (26.1%) targets. This suggests that estate manager attitudes are the main barrier to achieving the *Wild Woodlands* vision. *Native Networks* and *Multiple Benefits* meet the 2032 target if estates diversify, but never meet 2050 targets regardless of estate attitudes. This suggests that more extensive changes (represented within more extreme visions) are required to meet the 2050 target.

5.3.3 REGIONAL LAND USE CHANGE IMPLICATIONS

Scotland is made up of a number of distinct regions, which have their own characteristics and dominant land covers, and therefore different capacity to accommodate land cover change. Therefore, the results are considered at the regional level. Figure 5.4 demonstrates that woodland cover increases mainly at the expense of extensive agriculture in most visions and regions. Losses are in the range of 5-10% per region across most visions and regions. The greatest opportunity for increase in woodland cover (both native and non-native) appears to be in the Highlands and Islands, followed by Perth and Argyll and South Scotland. In visions with the

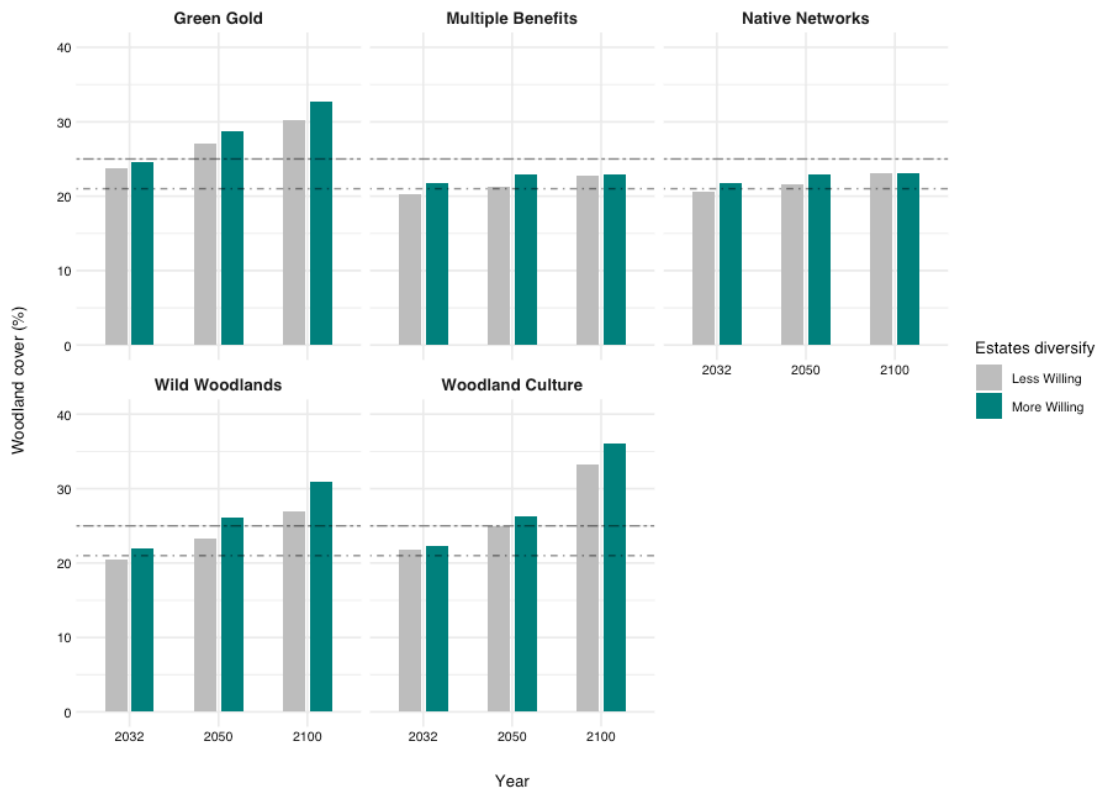


Figure 5.3: Effect of estate manager willingness to diversify on percentage woodland cover. The two Scottish Government targets of 21 percent by 2032 and 25 percent by 2050 are shown by the dashed lines

greatest increases in woodland cover, intensive agriculture is not strongly affected. It generally shows small increases (in the range of 1-2% per region) or no change in Grampian, Highlands, Perth & Argyll. It does decrease in Central for *Wild Woodlands* and *Woodland Culture*, and in South Scotland for *Green Gold*. In *Multiple Benefits*, intensive agriculture increases in all regions along with small increases in woodland cover. In *Native Networks* it increases in Grampian and Central Scotland. The amount of marginal land increases in most visions and regions. This is not marginal agricultural land, but areas of land which were assigned no agent-type during model set up - typically high montane areas which were assumed to have minimal management. Marginal land is expected to appear when agents ‘give-up’ i.e. they are no longer producing enough services to stay afloat, and where no new agent takes over the land they previously held.

5.3.4 ECOSYSTEM SERVICE RELATIONSHIPS

5.3.5 REGIONAL PATTERNS

Figure 5.5 illustrates the percentage change in ecosystem services observed in each vision. Across ES, the Highlands are shown to be an important supplier of carbon storage, flood regulation, floral species richness, recreation, and livestock compared to other regions. Crop provision is highest in Grampian, which aligns with Land Capability for Agriculture dataset. Land-based employment is highest in Perth & Argyll and Grampian, reflecting the high concentration of agriculture and timber focused forests in those regions. Ecosystem service provision is lowest overall in Central Scotland, reflecting its high urban density.

5.3.6 SYNERGIES

There is an increase in timber and land-based employment in all visions and regions. Crop production increases along with timber production and land-based employment in *Multiple Ben-*

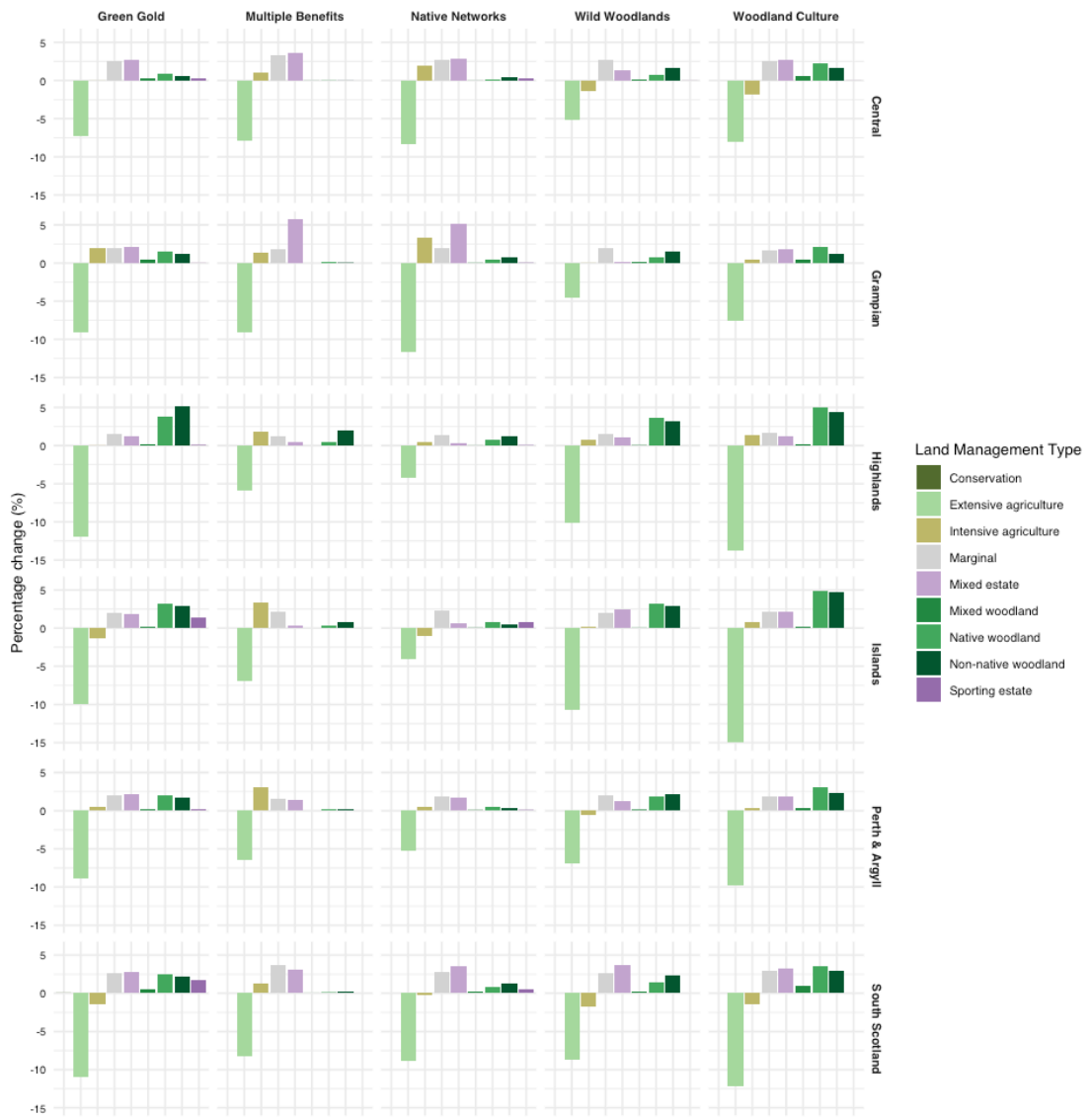


Figure 5.4: Percentage change in broad land use types compared to the baseline, for each vision and region

efits, *Native Networks* and *Woodland Culture*. Flood regulation shows small increases in all visions.

5.3.7 TRADE-OFFS

Negative effects on ecosystem service supply are most obvious for recreation, and livestock in some visions. Floral species richness shows small declines in most visions and regions, but losses are not large. Recreation declines over time in all visions. Trade-offs for crop production are not large, and are divergent depending on the vision. It decreases slightly in Grampian and Perth & Argyll in *Wild Woodlands*. In other visions it either stays fairly constant, or increases in some regions for *Native Networks*, *Multiple Benefits* and *Woodland Culture*. *Green Gold* shows minimal effect on crop production, with it staying constant or showing only slight increases or decreases. There are large decreases in livestock in *Woodland Culture* and *Wild Woodlands* except for Central and Grampian regions. Declines in livestock are particularly obvious in the Highlands in *Green Gold*, *Wild Woodlands*, *Woodland Culture*, as well as in the Islands, Perth & Argyll, and South Scotland. Carbon storage shows declines in *Wild Woodlands* and *Woodland Culture*, however this is thought to be a model artefact which will be explained further below.

5.3.8 MOVEMENT TOWARDS VISION PRIORITIES

Figure 5.6 illustrates movement towards or away from vision priorities in the modelled results, based on current indicators. All visions included biodiversity as a primary objective, but only *Native Networks* sees some small increases (in some regions) in modelled biodiversity based on the floral species richness indicator used. Apart from floral species richness, *Green Gold* illustrates the most consistent positive movement towards its objectives, with softwood, hardwood timber, and carbon storage increasing in all regions, and potential rural employment increasing in all but two regions. *Wild Woodlands* shows the least positive movement towards its ob-

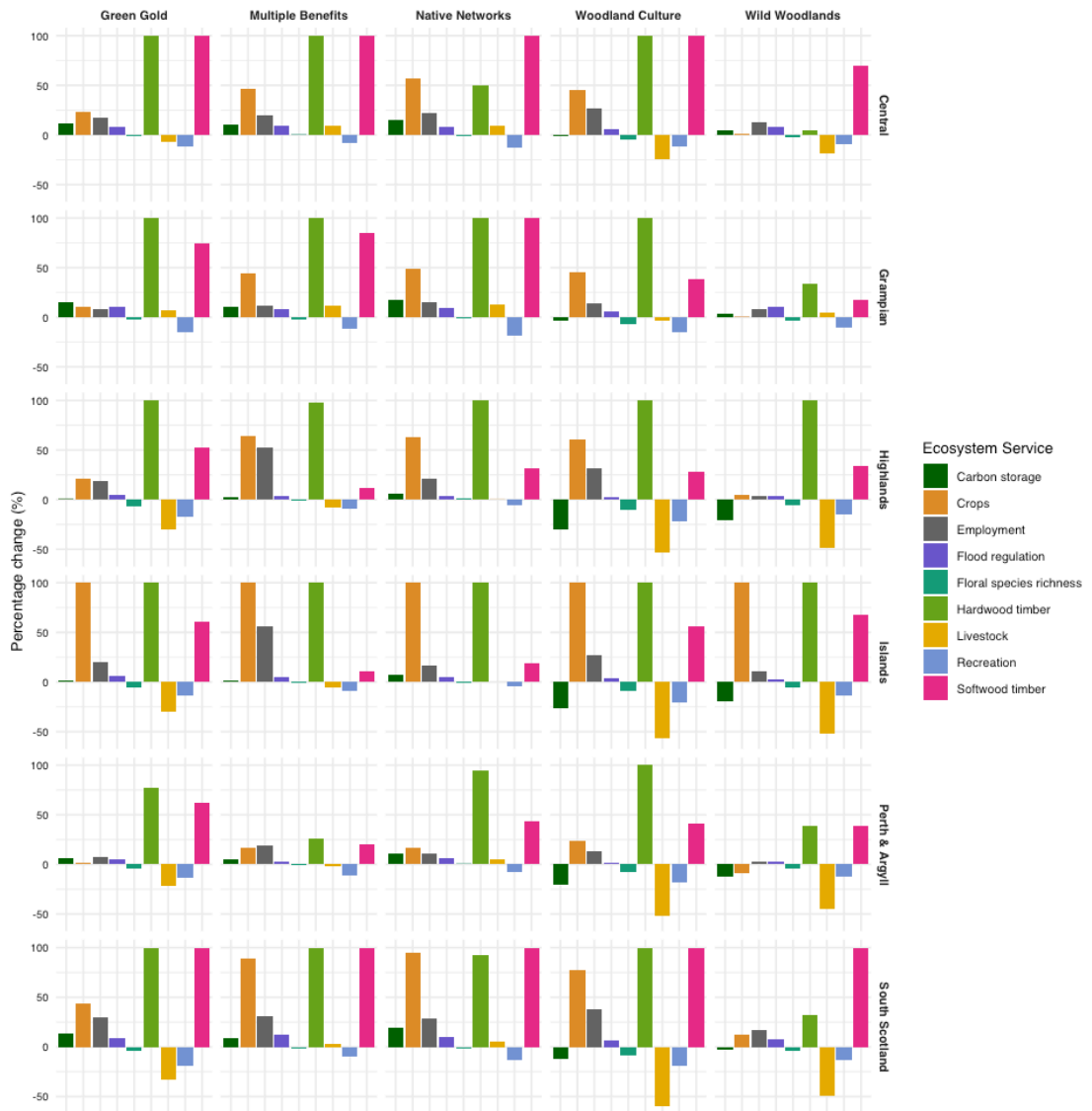


Figure 5.5: Change in ecosystem service provision over time, per region and vision

jectives, although there are increases in flood regulation and potential rural employment in all regions. Woodland Culture attempts to balance the largest number of objectives and shows positive movement towards some objectives (crop production, employment, hardwood timber, and softwood timber), with small trade-offs in floral species richness and recreation, and larger trade-offs in livestock decline. Although associated with the least land use change, *Multiple Benefits* and *Native Networks* also show positive movement towards three and four out of their six objectives respectively, in most regions.

5.4 DISCUSSION

This chapter has aimed to illustrate how qualitative scenarios of the future can be represented in a large-scale land use and ES model. The model is used to assess possible future changes in Scottish land use and ES provision under alternative stakeholder visions. The results suggest that there could be largely positive effects of woodland expansion on ES, across visions. There are synergies between timber production, land-based employment, and crop production in several regions and visions. Trade-offs are identified for livestock, recreation, and floral species diversity. However, all ES results are strongly dependent on the current data, knowledge, and modelling choices, and these will be discussed further. Willingness of estate managers to diversify land use has a strong influence on whether or not woodland cover targets are met. Key barriers to achieving targets appear to be the continuation of marginal agriculture and single-use management in the Highlands, especially to *Wild Woodlands*. Of the governance mechanisms represented within the model, the most successful appear to include: targeted annualised incentives for woodland, diversification of land use, and increased resources (human, social, financial, manufactured) for local communities. Together, these findings suggest that more significant changes may be required, in particular in relation to a change to highly valued ‘traditional’ Scottish upland landscapes, in order to meet targets for woodland expansion. Along with these attitude related changes, governance mechanisms have been identified which could further enable

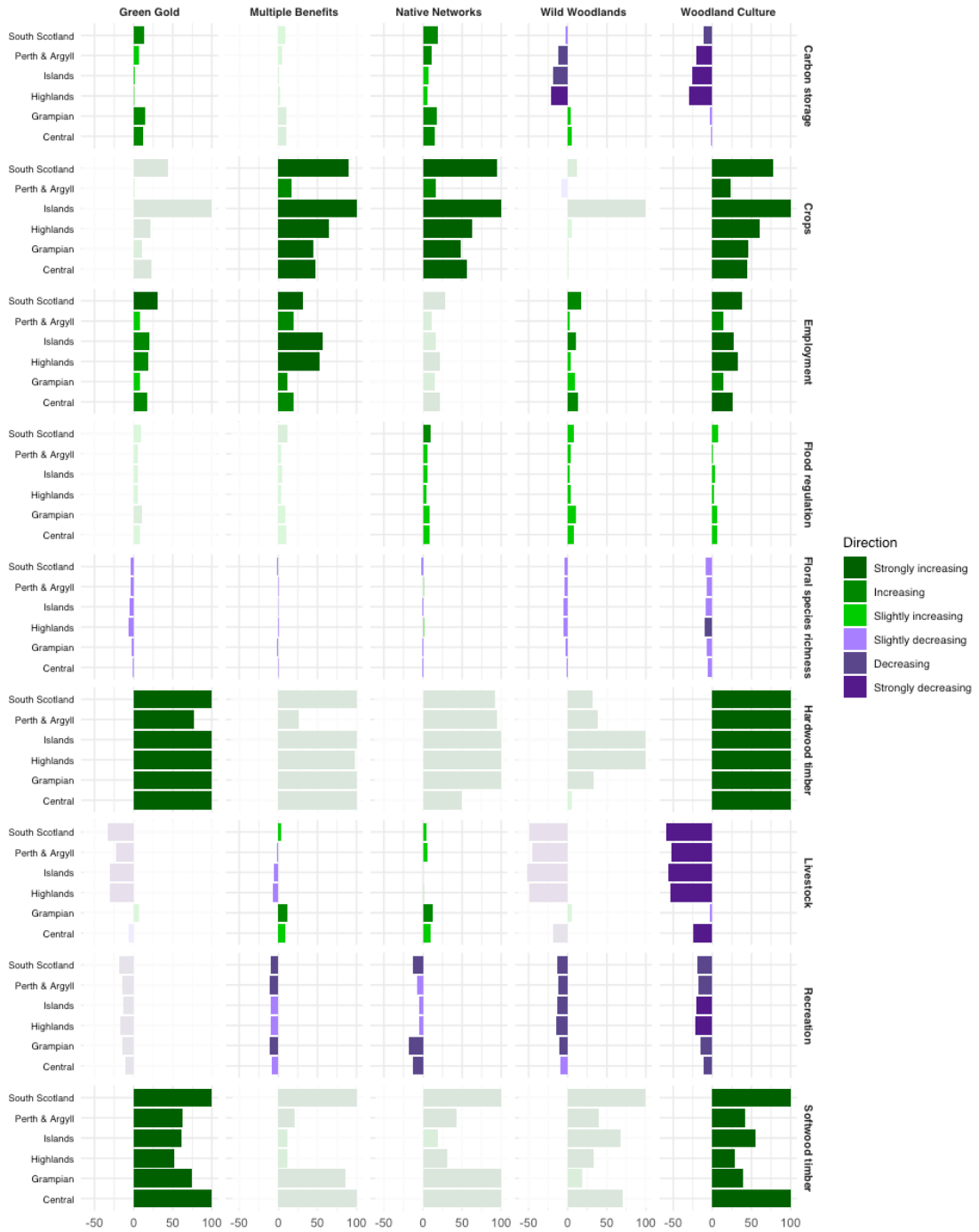


Figure 5.6: Direction of change in priority service provision for each vision. Where services were not priorities for that vision, they are faded out

woodland expansion. The following sections discuss these findings further by considering each research question in turn.

5.4.1 HOW MIGHT ALTERNATIVE VISIONS AFFECT ES PROVISION?

Multifunctional land use is a core objective of much of Scottish land use policy (Scottish Government, 2016) and these results suggest that an increase in woodland cover can increase both ES and land use diversity, both of which can provide indices of multi-functionality. Overall the visions represent different ambitions and therefore directions for woodlands and the benefits they provide, so ES diversity may initially decrease as demand changes, or develop slowly as visions shift in a particular direction. These findings confirm the current homogeneous nature of much of Scotland's landmass. Large areas of similar land cover and land use - predominantly extensive pastoral grassland and heather moorland - produce a particular perhaps narrow set of ES. Linking the concepts of ES and multi-functionality is recognised as a promising approach for landscape research and planning (Mastrangelo et al., 2014). On a continental scale, it has been found that there is high (but as yet unrealised) potential for win-win situations and increasing multi-functionality in European forests (Plas et al., 2017), and the results presented here suggest this could be the case for Scotland. Work on ES mapping in Scotland has also indicated that woodland creation may be best placed in multifunctional hotspots (Gimona & Van Der Horst, 2007). High ES diversity (and therefore multi-functionality) may indicate areas where trade-offs between ES are fewer and land management is meeting a greater diversity of human demands (Raudsepp-Hearne et al., 2010). Nonetheless, in comparison to using the Simpsons diversity index for biological diversity, where higher values are always assumed to be better, high values of ES diversity may only be considered better if the particular ES being measured are desired by society (Raudsepp-Hearne et al., 2010). As previously noted, the predominant view of upland open landscapes as 'wild' has considerable popular, cultural, and political resonance in Scotland (McMorran et al., 2008). Thus, any change to these habitats will have trade-offs and an increase

in ES diversity may not be desired, something that objectives for multi-functionality rarely make clear.

Previous research in Scotland has acknowledged that further work is required to identify mechanisms which balance trade-offs and attain the 'best' solutions for a range of stakeholders (Muñoz-Rojas et al., 2015; Nijnik et al., 2013; Thomas et al., 2015). Muñoz-Rojas et al. (2015) also explore conflicting policy priorities and to a certain extent this is reflected in the visions which, although agreeing on many elements, have important distinctions and different priorities. CRAFTY-Scotland offers a model which enables such trade-offs to be taken into account and several are illustrated by the results. The declines in floral species richness observed for most visions, especially in the Highlands and Perth & Argyll, are due to the replacement of some extensive grassland and heathland habitats - which are higher producers of floral species diversity - with woodland and, in some cases, more intensive agriculture. Thus the model goes some way towards quantifying any potential loss in these habitats and their associated biodiversity and cultural value. As highlighted in Chapter 2, a complete assessment of how woodland expansion may affect biodiversity is limited by data availability, but it is likely that any declines in floral species richness will be accompanied by benefits provided to biodiversity in other ways e.g. increases in woodland species richness or increased woodland connectivity (Burton et al., 2018b). Future work could also explore implications such as loss of open-ground breeding birds (e.g. waders) habitat as another indicator by which to explore trade-offs.

The decline in recreation value across most visions can be explained by the decline in the extent of extensive pastoral and traditional multifunctional estate managers who currently provide more recreation than other agents based on the photo density data used as an indicator. This finding reaffirms the high value placed on Scotland's 'wild' landscapes as they currently exist (McMorran et al., 2008; Stockdale & Barker, 2009). However, given the reliance of the indicator on photo data, it is important to question how much of the density is due to the current land cover, and how much may be attributed to other aspects such as topography, remoteness, or other tourist

attractions such as human artefacts, castles, lochs etc., which may coincide with these land cover types. It also does not account for how recreation or tourism values may change in the future. Research in a Scottish regional park has suggested that almost three quarters of respondents showed preference for either more forest, habitat restoration for nature, or landscape multifunctionality compared to more traditional open landscapes, illustrating that landscape change is acceptable amongst recreationalists and tourists, and that more heterogeneous landscapes are often preferred (Schmidt et al., 2017). It is also clear that despite the declines shown, the Highlands as a region remain critical for providing both floral species richness and recreation services for Scotland under all visions.

The decrease in carbon storage in *Wild Woodlands* is thought to be more an artefact of the model than a likely result. Although there may be some initial carbon release from afforestation on some land use types, this is not observed in other visions with similar land use changes. The productive potential of all land managers to produce ES was determined from relationships which were developed from correlations between the underlying datasets. The ability of agricultural and pastoral managers to produce carbon sequestration benefits was found to be sensitive to grassland productivity, as this often coincided with high soil carbon values. Service production in CRAFTY depends on a production function, which is calculated using the amount of capital available to the land manager, and the demand for services which that land manager produces. The modelled decrease in grassland productivity in *Wild Woodlands*, intended to simulate a loss of support for marginal agriculture, means that the remaining extensive agricultural, mixed estate and traditional sporting land managers are not able to produce as much carbon storage. This 'loss' may not occur in reality, as although coverage of extensive agricultural land may decline, that which remains would continue to store the same amount of carbon as it did previously, while any loss (actual or simulated) begins to be compensated for by woodland agents as time goes on. The largest losses in livestock occur in *Wild Woodlands* and *Woodland Culture* in most regions. This aligns with the vision storylines, which envisage a decline in monetary support for

marginal agriculture and illustrates that the modelled decline in support is effective when also combined with a decline in societal demand for livestock.

In terms of positive effects on ES, there is clearly potential for increased timber production (both softwood and hardwood) with this having potential benefits for rural employment, and generally positive results for carbon storage. Future uncertainties relating to climate change may affect this productive potential. Exploration of future climate projections on forest yield in the UK have shown that effects vary by species and scenario (Petr et al., 2014). There is a high likelihood of potential reduction in tree growth for three major species. There could be a growth reduction of up to 94% for total stand yield class in the lowlands and as much as 64% in the uplands (mainly in Eastern UK and in the 2080s) (Petr et al., 2014). Sitka spruce is expected to be most sensitive to drought, and given that potential productivity for Sitka is the basis of the capital for softwood timber, this should be considered carefully in relation to these results, especially in lowland areas. However, there could be potential increases for Scots pine and Pendunculate oak in upland areas and western UK, with recommendations that it may be preferable to establish forests on upland sites which tend to be less drought sensitive. Given that much of Scotland is upland in nature, and that the results here suggest that there could be larger increases in productive woodland in Highland regions under most visions, this could highlight a rare positive synergy in terms of timber productivity and woodland expansion under future climate change. Future work within CRAFTY-Scotland could use projected climate data to ‘update’ capitals through time, therefore taking account of both socio-economic and climate change and quantifying possible future effects further.

An unexpected synergy occurs for crop provision in the Highlands and Perth & Argyll in *Woodland Culture*, with it increasing significantly alongside other services including timber production and carbon storage. While research shows that the soil, climate and topographical characteristics of the Highlands and Islands constrain the biophysical possibilities for agricultural production, it is acknowledged that in theory there are opportunities for increasing production

in those regions thanks to a mixture of new technologies, widespread adoption of best-practice, improved marketing, and efforts to close gaps between high and low performing farms (Moxey & Thomson, 2018). However this potential increase is highly dependent upon support payments post-Brexit (Moxey & Thomson, 2018), and thus the possibility for significant increases in crop production alongside increasing woodland cover in the Highlands, Islands, Perth & Argyll remains uncertain.

Overall these results suggest that woodland cover can increase with limited trade-offs against existing land uses and ES. There are slight declines in crops and livestock, in some regions and visions, and the negative effects on floral species richness and recreation reflect the indicators used as much as any actual loss, and may also be compensated for by other aspects not represented in this model, for example: woodland species diversity and new forms of recreation. Thus, the results illustrate that woodland expansion has the potential be a broadly positive process, under a range of pathways with different priorities, but it is important to consider whether the modelled visions are feasible in reality.

5.4.2 ARE AREA-BASED WOODLAND TARGETS FEASIBLE?

The Scottish Government aims to achieve Net-Zero carbon emissions by 2045 (Committee on Climate Change, 2020). The Committee on Climate Change argues that Scotland can achieve net-zero emissions ahead of the rest of the UK due to its ability to use its significant land area to remove CO₂ from the atmosphere. This relies on an immediate and sustained increase in tree planting rates to 15,000 hectares per year between now and 2045 (Committee on Climate Change, 2019). Only two visions - *Green Gold* and *Woodland Culture* - meet the Scottish Government targets of 21% woodland cover by 2032 and 25% by 2050. Both visions emphasise use of new and existing woodlands for production. The ‘productivist’s’ position (where economic objectives are highly valued) remains strong in Scotland (Nijnik et al., 2016), and it is clear from recent policy that there is strong support for elements of the *Green Gold* vision from the Scot-

tish Government. The Climate Change Plan includes aims to increase woodland cover, use more sustainably sourced wood fibre and encourage use of timber in the construction industry, as well as restoring peatlands (Scottish Government, 2018). The recent Forestry Strategy reiterates these objectives for forestry, aiming to increase the use of Scottish wood products in construction, as well as improving the condition and extent of native woodland (Scottish Government, 2019). There is emphasis on the role of productive timber species in the economy, and the role they - including harvested wood products - can play in climate change mitigation.

Research supports the carbon sequestration benefits of productive conifer forests managed for harvested wood products. Afforestation with relatively fast growing tree species (e.g. Sitka spruce) on low grade agricultural land (e.g. currently used for sheep grazing) has been found to be a cost-effective option compared to other species types (Nijnik et al., 2009, 2013). In another scenario study comparing low, medium and high ambition planting and forest management, a model taking into account the carbon stored in different tree components, as well as soil and litter, concluded that medium and high ambition scenarios could sequester 12-15 Mt carbon by 2030 (Thomson et al., 2018). The study showed that forests managed for harvested wood products made large contributions to that sequestration, compared to forests managed for fuel and natural broadleaved forest, although those forests also had important roles to play.

If estates are willing to diversify, *Wild Woodlands* also meets both targets, offering a pathway more focused on native woodland regeneration. Recent research suggests that natural forests (both newly naturally regenerated and protected old growth) may have more carbon storage potential than productive forests in the long term (Lewis et al., 2019b). For the carbon pool to significantly change in the long term the maintenance of slower growing old-growth stands, which also increase and protect soil organic carbon stocks, is expected to be more beneficial (Körner, 2017; Schwartz et al., 2017). Incentivising fast-growing productive species may be beneficial in the shorter term, but the model suggests that if the Scottish Government wants to meet (and exceed) 25% woodland cover, pathways with more dramatic societal changes may need to be

considered. This aligns with Scottish focused Net-Zero progress reports, which emphasise that any post-CAP framework should promote transformational land use change and measures for deep emissions reductions including afforestation and peat restoration (Committee on Climate Change, 2019).

Climate change policy for the land sector is challenged by complex biophysical and socioeconomic contexts (Brown, 2020). Socioeconomic factors act against wider uptake of incentive schemes, especially for new woodland on improved agricultural land, and this is expected to constrain long-term decarbonisation objectives unless tackled directly (Brown, 2020). Across visions, the main land use which loses out to increasing woodland cover is extensive agriculture. The UK's upland extensive grasslands and heathlands represent a 'cultural landscape', with a long history of agricultural land use meaning that agricultural objectives are strongly associated with social and environmental benefit (Brown et al., 2011). Agricultural activities on farms and crofts are a dominant form of land use in Scotland and represent an important component of the economic, social and environmental fabric of the country (Moxey & Thomson, 2018). Barriers to woodland expansion in the past have included cultural resistance, with a dichotomous view of farming and forestry as being competing land uses predominating (Hardaker, 2018). Bowditch et al. (2019) argue that habitat management for deer stalking and grouse shooting has perpetuated a marginalised environment for forests in the Highlands, suppressing a timber production culture. Private land managers are often unwilling to see sporting use, the economic staple of the estate compromised by tree planting (Bowditch et al., 2019). This is illustrated within these results where high 'giving-in' thresholds assigned to estate managers prevent larger scale changes in *Wild Woodlands* and *Native Networks*. Land degradation is perceived radically differently by different people, depending on their worldview and relationship with land (Willemen et al., 2020). Thus, the reduction in extensive agriculture could translate as a loss of culture and established livelihoods to some. On the other hand, others view upland extensive grasslands and heathlands as a 'devastated terrain' or 'wet desert' (Mather, 1992) and many view woodland

restoration as an essential process to restore habitats which have been lost (Armstrong, 2015).

Previous research has concluded that despite their cultural value, many upland areas will need to be prepared for a reduction in grazing and prescribed burning due to trends in subsidies for upland farming and agricultural abandonment (Reed et al., 2009b). Given this likelihood, and the fact that these results suggest that the loss in grazing area is relatively small even when targets for woodland are met (in the range of 2-6% depending on the region), it seems that there is room for both increasing woodland cover and maintaining valued cultural landscapes if desired by society. The development of new incentives for diversification are assumed by many stakeholders regarding the future of rural land use in the UK uplands as a whole (Reed et al., 2009b), and previous research demonstrates significant agreement between diverse interviewees about the desired future of land use in Scotland, with common aims including multifunctional land use, meeting climate change targets, coherent long term policies and funding mechanisms, more collaboration, and diverse resilient local communities (Valluri-Nitsch et al., 2018). Many land managers may consider new options if woodland expansion could demonstrate greater economic return early-on and throughout the life-cycle, as well as recognising the contributions to climate change, landscape, and ecosystem services (Bowditch et al., 2019). In particular, for sporting focused managers, linking forest expansion aims with deer shelter-belt design and enhancement could shift perception and increase interest in diverse silvicultural approaches, which produce higher quality timber alongside healthier deer habitat (Bowditch et al., 2019). Simulating payment for woodlands via increasing woodland capitals in targeted areas appears to be effective within CRAFTY-Scotland. The way this has been modelled assumes that any such payment would be annual and long-term, suggesting that regular support and compensation for the public benefits provided by maintaining and increasing woodland cover is required for significant change. The results presented here illustrate that models like this have the potential to be used with stakeholders to help quantify trade-offs, explore how exactly wider common aims can be met, and where policies and long-term funding could best be applied.

5.4.3 CAN NOVEL GOVERNANCE MECHANISMS INFLUENCE LAND MANAGER BEHAVIOUR TO PROMOTE PATHWAYS TO VISIONS?

Given the potential need for greater changes in order to achieve the targets for woodland cover discussed above, this final section aims to discuss how achievable these changes might be in reality. Given that *Woodland Culture* - which encompasses the most dramatic simulated changes - has the strongest effect on increasing both woodland cover and ES diversity, it is important to consider how achievable the modelled changes are. Both Land Reform and Community Empowerment are Scottish Government agendas, and thus there is significant interest in exploring how they could be achieved, and what their effects may be. Land ownership in particular is a complex and sensitive issue, which requires time and facilitated dialogue (Valluri-Nitsch et al., 2018). Most of the advantages associated with the current pattern of landownership are related to the economies of scale generated by large land holdings (Glass et al., 2013). In some parts of Scotland, disadvantages are associated with this highly concentrated land ownership, which can be an impediment to economic development if communities are excluded from the decision making process or investment activities are imposed upon them, thus causing significant and long-term harm to the communities affected (Glass et al., 2013, 2019). The recent diversification in terms of increasing public, NGO, and community land ownership has produced a number of social, economic and environmental benefits including changing emphasis in deer management, new opportunities for crofters, and development of strategic partnerships to deliver landscape scale approaches (Skerratt et al., 2016). As a result, continued increasing diversity and reduced concentration of ownership is expected to increase rural resilience in the future (Glass et al., 2019). Local community control in particular is expected to be beneficial, with case study findings demonstrating that community landownership can function as a powerful catalyst and positive agent for reconstructing rural development (McMorran & Scott, 2013). Of course, any change generated by communities will be set within 'locally prescribed narratives of sustainability' (McMorran & Scott, 2013).

A similar divergence in stakeholder visions has been found by (Valluri-Nitsch et al., 2018), with ‘My Land’ emphasising community ownership versus ‘Your Land’ which maintains the status quo in terms of concentrated land ownership. This highlights a debate around land ownership and community involvement in decision making. Depending on the perspectives of those involved, participation could be seen to be either counter-productive for decision-making, or an essential principle of sustainable development, with participatory decision making being seen as inherently beneficial. Due to different interpretations of sustainability and what that means to local communities, community ownership can’t always be assumed to be beneficial. If visions such as ‘My Land’ or *Woodland Culture* are prioritised, land management objectives will depend on the values of the community, and if woodland expansion is desired on a national level then some form of incentive for woodland and its continued maintenance and management may be required. Alternatively, if large areas of land continue to be managed by private, public or NGO bodies, as envisaged in ‘Your Land’, and visions here including *Green Gold* and *Multiple Benefits*, this could mean that either land use changes are minimal, or that there are the potential for large-scale, top-down land use changes e.g. either forest plantations being established or native woodland restoration over larger areas.

The model results suggest that the status quo (large proportions of extensive grassland and heathland) is only maintained if land managers have external resources to maintain that, and that otherwise more diverse land use emerges and is beneficial for ecosystem service production. This may be undesirable to some stakeholders. However, the way Land Reform has been represented in the model can be interpreted not as extensive estates or farms being replaced or out-competed, but instead adapting and choosing to manage some of their land in a different way i.e. diversifying. The disadvantages associated with concentration of ownership are not purely associated with private landownership, and smaller scale private ownership could be a valuable new mechanism for providing new sources of capital for rural development (Glass et al., 2013). Private estates can provide many benefits where community involvement is done well, with job

creation, direct spend in the local economy and indirect economic impacts (Hindle et al., 2014). They can also provide social benefits in the form of housing, public access and interpretation, and community facilities.

There are wider comparisons to be made to international research linking small and medium forest enterprises (SMFEs) to prosperity. This has mostly been explored in low and middle income countries, but could equally be applied to Scotland, where rural development is a key aim of Scottish Government policy. Similarly to sustainability, prosperity is subject to a range of interpretations, but has been defined as ‘our ability to flourish as human beings – within the ecological limits of a finite planet’ (Jackson, 2009). Forests may contribute to more widely shared and enduring prosperity (Miller & Hajjar, 2019). Locally controlled forest enterprises can deliver a wide variety of benefits to forest-reliant communities, and economic viability is necessary for SMFEs to generate broader benefits for the communities in which they operate (Humphries et al., 2018; Miller & Hajjar, 2019). This links to the holistic Forest and Landscape Restoration (FLR) approach with strategies which emphasise social outcomes and give local communities ownership of restoration having far more chance of success (Mansourian et al., 2017). At the same time, there is a relative paucity of evidence on the relationship between forests and broader prosperity and this is a clear direction for future work (Miller & Hajjar, 2019). Rural development budgets are uncertain post-Brexit, and woodland is currently under-monetised given its potential environmental benefits (Hardaker, 2018), so there remains a significant opportunity to give new emphasis to rural funding.

5.5 IMPLICATIONS

The approach taken here has explored some of the implications of benefits which are desired by Scottish policy - more woodland cover and multi-functionality - highlighting potential trade-offs and complexities within these aims. It shows that national scale modelling of multiple ES and objectives is important to reveal the full consequences of policy objectives. Possible implications

are highlighted here for major stakeholder groups:

RESEARCH

- Wider issues remain in terms of representing ES valuation and provision, and these determine the strength of any synergies or trade-offs observed within the modelling process. CRAFTY-Scotland shows the potential for models which can represent intrinsic attitudes and values in a spatial way, and there are opportunities to develop this further.
- It is acknowledged that vision pathways such as those explored here will not exist in static conditions. Climate change in particular is expected to have significant implications for habitats and species, and future models should account for the effect of climate change on capitals, for example changes in the spatial range of suitability for different tree species and the likely productivity of different crops.
- There is also an opportunity to explore the effect of conflicting policy drivers, i.e. for different sectors, beyond visions focused on woodlands, in order to explore how different objectives can be reconciled.
- Modelled outputs are seductive in their power to reflect land system change and are too often mistaken for the 'truth' (Rounsevell et al., 2012b). Ideally, model outputs should be evaluated in cooperation with stakeholders, so that erroneous interpretations and conclusions are not drawn. This highlights an important opportunity to 'close the loop' through discussing the results with stakeholders initially involved in vision development. Future applications could design a research process aiming for a more participatory process from beginning to end, with potential for regional or landscape scale applications of the model used to explore context specific land use visions with as many stakeholders as possible.

- Instead of focusing solely on technical mapping and aiming to optimise land use, more land use models should focus on the processes and governance within the land use system. There is value in considering non-economic values and societal demand for ES, in order to explore the trade-offs between land uses and more realistic pathways to desired futures. Fully participatory approaches undertaken with stakeholders, where they can tweak model implementation, could be particularly valuable

PUBLIC SECTOR

- The results suggest that there is considerable synergy between government policies relating to woodland expansion, ES multi-functionality, increasing diversity of land management, and empowering local communities. As highlighted in Chapter 3, spelling out the how's of achieving a vision is expected to be particularly beneficial for sustainable land use planning (Metzger et al., 2018; Shipley & Michela, 2006), and the results presented here go some way towards illustrating these at a national level for Scotland.
- Given the apparent success of modelling incentives for public goods within some visions, explorations of public support mechanisms after Brexit should take this into account.
- The modelling process identified key barriers to achieving woodland expansion targets. These included subsidised marginal agriculture in Less Favoured Areas (LFAs) and the attitudes of some land managers where large areas of single-use management are maintained. To achieve targets, policies could aim to address these aspects, encouraging diversification of land management and looking into alternative forms of support for land managers in LFAs

NGO SECTOR

- Environmental NGOs have been strong advocates of landscape approaches and collaboration between different stakeholders. There is potential for modelling approaches such as CRAFTY-Scotland to provide a tool within these platforms by which to assess the effects of different management options at the landscape scale.

PRIVATE SECTOR

- The potential increase in timber production in the two most “successful” visions, *Green Gold* and *Woodland Culture* suggests that there is potential to significantly expand the Scottish timber market, in particular for smaller-scale ventures and hardwood timber.
- There could be innovative links to be made between new small and medium forest enterprises (SMFEs) and prosperity as woodland cover increases

LAND MANAGERS

- There are many potential benefits in increasing land use diversity, managing for more woodland, and providing ES which provide public services.
- Diversifying land use has the potential to increase ES diversity and resilience in the face of future challenges.

5.6 CONCLUSIONS

CRAFTY-Scotland has facilitated an exploration of how land managers may adapt to changes in policy and incentives for agriculture, woodlands, and forestry. The modelling framework allows for the inclusion of multiple ES and trade-offs between them. The potential and method

of implementation for increased woodland cover in Scotland depends strongly on land manager and societal attitudes to changes to ‘traditional’ or currently widespread forms of land use. Stakeholders consulted by Burton et al. (2018a) saw a role for some form of payment for public goods in order to encourage woodland expansion, and there was success in simulating this within CRAFTY-Scotland. Well-designed approaches which engage with multiple stakeholders and aim to provide targeted annualised support could be effective in supporting woodland expansion objectives. As social norms have been identified as the most significant obstacles to the implementation of landscape approaches, future strategies need to engender wider societal understanding and support, and regional to local poly-centric and participatory governance approaches may be essential to achieve this. The results suggest that different modelled pathways affect the ability to reach targets for woodland expansion and the extent to which ecosystem service synergies and trade-offs occur.

Continuing to manage large areas of land for the status quo, often facilitated by external resources, means that long-term targets for woodland expansion are less likely to be met. Governance strategies which could facilitate success include: funding for the development of smaller-scale markets for both softwood and hardwood timber; regular or annualised payments for the public goods provided by woodlands; and efforts to diversify land management (whether this comes through Land Reform or diversification within large estates) combined with empowering local communities with increased access to funding and resources. There are potentially powerful positive synergies between a number of core Scottish Government aims including woodland expansion, Land Reform, and Community Empowerment. This highlights potentially exciting research avenues in linking woodland expansion to small forest enterprises and prosperity. By exploring a number of normative positive futures in a quantitative land use model, this interdisciplinary approach has provided an example of how future research could support and even drive transformational land use decisions.

Overall the process has highlighted the connection of aims for woodland expansion to wider

issues - including cultural perceptions of land use, participation in policy and planning, Land Reform and Community Empowerment - and the significant interventions which will have to be grappled with in order to achieve the changes captured within the visions on this scale. This represents a major challenge for politicians as well as society as a whole. Given the urgent need to move towards sustainable land use in the face of multiple challenges, linking societal visions to models in research approaches which engage society with science and encourage futures thinking have great potential, and should be built upon in future applications.

6

Discussion

This thesis has addressed the feasibility of aims for woodland expansion in Scotland, exploring alternative stakeholder visions for how this might ideally unfold, as well as the potential for ABM as a tool by which to simulate these visions, and the resulting land use changes, ES relationships, and implications for multifunctional land use. The four previous chapters have explored the research questions posed in Chapter 1. This final chapter critically discusses the key contributions to knowledge (highlighted by each sub-heading), outlining limitations and opportunities for future research where appropriate.

RESEARCH FOR WOODLAND EXPANSION NEEDS TO TACKLE EVIDENCE GAPS AND EXAMINE
NORMATIVE BIASES: THINKING ON LONG TIMESCALES AND NEW IDEAS ARE REQUIRED TO
TACKLE GLOBAL CHALLENGES

Chapter 2 found that currently the largest body of evidence in the UK exists for the effects of conifer plantations, and in particular effects on broader societal benefits such as carbon sequestration and flood regulation. The focus on public benefits is to be expected given the global challenges and calls to action outlined in Chapter 1. In particular, the potential for woodland expansion to play a key role as a ‘natural climate solution’ is acknowledged and debated by a large body of international and global research (Bastin et al., 2019; Grainger et al., 2019; Griscom et al., 2017; Lewis et al., 2019a). The potential for woodland planting to mitigate flood events also relates to a global recognition of the need for adaptation and increasing resilience in the face of climate change. However, the UK picture for biodiversity and how woodland expansion might help to address the declines outlined in Chapter 1 is less clear.

The results from Chapter 2 suggest a need for a broader consideration of other taxa and metrics for biodiversity, in order to better understand the effects of woodland expansion. This is an unexpected finding given that more broadly forests are known to harbour most of global terrestrial biodiversity (Aerts & Honnay, 2011; Liang et al., 2016; Perera et al., 2018) and forest restoration - in particular approaches which link biodiversity to ecosystem functions - is expected to increase biodiversity in human-altered ecosystems (Aerts & Honnay, 2011). Past human exploitation has led to substantial changes in forest extent, dynamics, structure and species composition (Halme et al., 2013), and this has been acknowledged in both a UK (Quine et al., 2011) and Scottish context (Hobbs, 2009; Holl & Smith, 2007). Taking into account this historical loss, there is a need to think on much longer timescales. As illustrated in Chapter 5, woodland expansion may result in some loss of particular aspects of open habitat biodiversity, but it is likely that this will have replaced other aspects of woodland biodiversity in the past. Land use history in the UK and Scotland has clearly been a major driver in what research has been carried out over the last

century, and therefore what we currently know. The concept of “shifting baselines” describes a phenomena where society values ecosystems in a state with which they grew up (Papworth & Rist, 2009; Pauly, 1995). Therefore, people value what they are used to, regardless of the fact that the ecosystem state may have been depleted or damaged over longer time scales. Taking into account historical perspectives is essential, and more broadly land system science needs to discuss the normative questions, values, perspectives and assumptions relating to its research questions (Nielsen et al., 2019).

Looking to the future and taking into the account the need for transformations for sustainability, the current bias towards conifer monocultures in research (Chapter 2) and practice should be challenged. Recent research has argued that a focus on clear-cutting, monocultures and production to meet the demands of a large-scale timber industry makes it more difficult to transition to truly multifunctional forestry systems (Jonsson et al., 2019). Mixed coniferous–deciduous forests are better able to support the most commonly prioritised ES, timber, as well as several — although not all — other services, compared to monoculture systems that are currently in use, and this highlights the need for further research into the management of mixed forest stands (Jonsson et al., 2019). Recent research confirms that mixed species stands can produce more ES, over-yielding in 35% of cases compared to monoculture stands, and providing multiple other ES (Jonsson et al., 2019). This diversity is also important for other ecosystem functions such as litter decomposition, and higher structural complexity is expected to increase functionality (Mori et al., 2017). Thus, despite the evidence for rapid and cost effective carbon sequestration (Nijnik et al., 2016), novel exotic tree species are not always the rational response to rapid environmental change, especially where there are conservation objectives (Ennos et al., 2019). Liang et al. (2016) have also highlighted the negative effect of biodiversity loss on forest productivity and the potential benefits from the transition of monocultures to mixed-species stands in forestry practices. Previous research in a UK context has concluded that diversifying forestry, including increased use of continuous cover management is likely to improve resilience and meet targets for both

biomass and biodiversity (Ray et al., 2017). Given that this research demonstrates that Scottish stakeholders want a broad range of benefits from woodland expansion, and all see sustainability as a central objective, future research should continue to explore novel ways in which this can be met.

SIGNIFICANT EVIDENCE GAPS REMAIN FOR TOPICS WHICH HAVE THE MOST POTENTIAL TO ADDRESS BARRIERS TO WOODLAND EXPANSION

Chapter 2 also illustrated that there is a paucity of evidence for the effect of woodland expansion on cultural, provisioning, and multiple interacting ES, yet these are often the most important factors for stakeholders when considering options for land use change. It is suggested that locally nuanced, participatory and transdisciplinary approaches are necessary to move forward. Wider research supports this view. Although forest restoration is acknowledged as a mechanism to achieve multiple goals, including climate mitigation, biodiversity conservation, socio-economic benefits, food security, and ecosystem services (Chazdon & Brancalion, 2019), compared to forest degradation, knowledge concerning the responses of biodiversity and ES to forest restoration is relatively limited (Mori et al., 2017). In particular further research on the socio-ecological considerations including how to develop sustainable forest management, reconcile different objectives, and evaluate multi-functionality will further assist policy formation and decision-making (Mori et al., 2017).

The Forest and Landscape Restoration (FLR) research agenda is aiming to tackle these considerations (Bloomfield et al., 2019; Chazdon et al., 2017; Mansourian et al., 2017). A key feature of FLR is its aim to combine both forest and non-forest ecosystems, accommodating multiple actors, sustainable food production, ES provision, and biodiversity conservation (Chazdon et al., 2017). Key policy-driven research needs to include explorations of where small-holders and communities have derived economic returns from restoration, which measures of human wellbeing can be easily and consistently monitored to demonstrate response to FLR, and how

landowners can benefit in terms of payments for ES, harvesting of forest products, or added value via certification (Chazdon et al., 2017). It is acknowledged that across Europe, different landscape histories, land ownership structures, and value chains based on different ES mean that regionally adapted landscape approaches engaging multiple stakeholders and actors through evidence-based landscape governance are needed (Lazdinis et al., 2019). These transdisciplinary approaches should be transformed from one-off ‘projects’ to longer-term ‘platforms’ which can adapt and evolve over time (Grove & Pickett, 2019).

AT A HIGH LEVEL, THERE IS COMMON GROUND BETWEEN DIVERSE STAKEHOLDERS

As the visions are presented at the moment, they could have a valuable role as communication tools, through describing and visualising alternative aims and objectives for woodland expansion. However, given the focus of this research on positive visions of the future, this may skew attitudes compared to previous research. At a UK level, it has been noted that there has previously been a low level of interest and management activity in woodlands, and generally negative attitudes to woodland creation amongst private landowners, as well as a strong dichotomy between forestry and farming (Lawrence & Dandy, 2013). More recently, an analysis of farmers in Scotland found that the proportion of farmers not intending to increase the area of woodland or forestry on their land outnumbered those who did intend to plant by six to one, although they also identified certain characteristics which made farmers more likely to be willing to plant (Hopkins et al., 2017). Analysis of public preferences regarding woodlands in Scotland has shown they are complex, but that woodlands are acknowledged as having a role to play in ecological, aesthetic and socio-economic aspects of land use and land management (Nijnik & Mather, 2008).

More recent research has demonstrated comparability between public and expert preferences in support of the multifunctional future of forestry in Scotland, and public support for proper integration of woodlands in the Scottish countryside. Although some people in Scotland are in favour of native woodland conservation and extensive regeneration and others are more con-

cerned with the socioeconomic aspects of forestry development (e.g. new employment opportunities) there is likely an agreement across various attitudinal groups regarding the necessity of multifunctional forestry development (Nijnik et al., 2016). Chapter 3 has demonstrated similar broad divisions in terms of productionist vs. conservationist views (e.g. *Green Gold* and *Woodland Culture* vs. *Wild Woodlands* and *Native Networks*) but also high level agreement in terms of the public benefits available from woodland. On one hand, this high level agreement could be due to the increasing awareness of the potential for shifts in land use to contribute to climate goals and sustainability. Alternatively, as acknowledged in Chapter 3, the framing of the research (i.e. positive visions) and the types of stakeholders involved (i.e. the ‘usual suspects’) could have an effect. At the same time, linking the visions to the ABM provided an alternative approach, with the model to some extent representing a proportion of negative attitudes of farmers and estate owners based on previous research. It is important to note that opinions may have changed since the survey data was collected. The attitudinal survey data which informed the model may now have altered among some respondents due to significant recent changes including Brexit and increased awareness of the climate emergency.

FUNDING PUBLIC GOODS

Regarding the widely shared view amongst the stakeholders consulted in Chapter 3 that funding for public goods could be helpful in achieving many of the visions and the apparent success in simulating this funding within the ABM, it is important to consider how this may be achieved. There has been a great deal of research on Payment of Ecosystem Services (PES) schemes which aim to translate external, non-market values of the environment into real financial incentives for local land managers to provide ES (Engel et al., 2008). PES schemes have proliferated in recent years, with a number of projects piloted within the UK (DEFRA, 2016), but challenges remain (Reed et al., 2017) and PES have also been the subject of wider concern in terms of their ethics and promotion of economic values over non-economic justifications for conservation (Redford

& Adams, 2009). Markets are certainly not a panacea, and PES schemes need to be designed well and monitored in order to be successful (Kinzig et al., 2011). PES schemes have a number of key principles (DEFRA, 2016). They should be voluntary, and ensure that the beneficiary pays directly to the provider of the ES. They should demonstrate additionality i.e. that they provide benefit to the land manager providing the ES over and above what would normally be expected of them. Payments should also be conditional on the delivery of the ES. Ideally, management actions to provide the ES should be permanent, and actions in one location should not lead to the loss or degradation of ES elsewhere (leakage).

The different emphases in each vision would require alternative foci for PES schemes, and in theory any number of schemes with different focus could be developed to fund a diverse mix of woodlands providing multiple benefits. For example, *Green Gold* might most likely develop a PES scheme for carbon. Carbon focused schemes should learn from the Woodland Carbon Code, which has run in the UK since 2011. Landowners registered for the code can sell carbon units from new woodlands to companies wanting to offset their greenhouse gas emissions, based on robust carbon prediction tools and monitoring. This has experienced issues given the volatile price of carbon on the market and government awareness of the potential dip in timber supply in 20 to 40 yrs, which has influenced and limited the grants available. The scheme is currently under revision and shows the potential for private funding to drive woodland creation and provision of public goods. Any such schemes could learn from other pilot projects which have been run and assessed in recent years. Best practice guidance has developed from lessons learnt from these pilots (Smith et al., 2015). A phased approach is suggested, moving through steps 1) identifying saleable ES, sellers and buyers, 2) establishing scheme principles and resolving technical issues, 3) negotiating and implementing agreements, 4) monitoring, evaluation and review, and finally 5) considering opportunities for multi-benefit PES schemes (Smith et al., 2015). Place-based PES approaches have been found to mitigate trade-offs, provide a chance to better account for cultural ecosystem services, and engage with and empower diverse stakeholders (Reed et al.,

2017).

For other visions, where the objectives may be less marketable, funding may need to come from public sources. Since the exit of the UK from the EU, the replacement of the CAP is a devolved issue. In England, the Environmental Land Management Scheme (ELMS) is currently under consultation, with increased emphasis on providing public money for public goods. In Scotland, the Agriculture (Retained EU Law and Data) (Scotland) Bill has given Scottish ministers powers to retain the basic framework of the CAP but to better adapt it for Scottish conditions. It is likely that this will also involve increased focus on diversification and provision of wider services, and the findings of this theses support the value of giving these themes greater emphasis. The 2020 UK Government budget has confirmed £640m for a new Nature for Climate Fund. In addition, £200 million has been pledged for developing flood resilience, which could include natural flood management and appropriate woodland creation projects under this banner.

Wild Woodlands would likely prioritise funding for natural regeneration. It is already recognised that in cases where the major limitations to natural regeneration are socio-economic rather than biophysical, innovations in policies and economic incentives at multiple levels will be needed (Chazdon et al., 2020). Chazdon et al. (2020) have suggested a number of interventions, including; encouraging landowners in areas suitable for natural regeneration to wait 1–2 years prior to planting trees to assess whether the rate of natural regeneration is sufficient, and applying the same value in PES programs for natural regeneration as for tree plantations. Other visions might develop schemes for funding woodlands which link up existing native woodlands and enhance connectivity (*Native Networks*), or incentivise farmers to plant more small farm woodlands and linear features such as hedgerows (*Multiple Benefits*). An important consideration will be how to operate multiple funding schemes (likely supporting different habitats and associated ES) alongside one another to move towards wider land management benefits. If truly diverse and multifunctional landscape are desired, then maintaining an overview of all funding schemes (public and private) will be required to ensure that certain ES or habitat types do not

dominate.

LINKING SOCIETAL VISIONS TO MODELS

Stakeholders are often unclear whether their ideal futures are actually achievable, and thus linking visionary ideas with quantitative models can assist with understanding (Trutnevyte et al., 2012). This research has made steps towards this in a Scottish context. However, similarly to Verkerk et al. (2016) it would be beneficial to link the modelling steps and the elicitation of the visions more tightly, with fewer assumptions being made by the modeller when identifying ways to represent the visions. Participation is a key principle of sustainable development, and previous research has suggested that long-term, iterative approaches which involve stakeholders as well as modelling or analysis cycles appear particularly promising (if practically challenging) for future vision development (Brown et al., 2018). This links to the idea of moving from research projects to long-term participatory platforms (Grove & Pickett, 2019). Participatory decision making is not without conflict, but the method outlined here provides a way with which different options could be assessed. This is a key area for future research.

ABM AS A TOOL FOR LAND SYSTEM SCIENCE

ES research has increasingly highlighted the need to include multiple ES in models in order to assess synergies and trade-offs that may occur between them. Making trade-offs between ES explicit is a core aim of ecosystem assessments, and yet these have often been explored using economic assessments, with decisions being made based on market values, which on principle many ES do not have (having an intrinsic, or non-monetary value to society) (Carpenter et al., 2009). The true social value of non-marketed ES depends on the ways that services are used by different stakeholders. Brown et al. (2016) have argued that bottom-up models are much better suited to understanding land use change, as the social processes which are behind land

use decisions are determined mainly by individual intentions and social norms such as language, culture and intentions, as opposed to by general and predictable ‘laws’, particularly economic ones. Thus, the land use system is a social one as much as an environmental one. The omission of behavioural processes from scenario modelling has constrained understanding of how we can develop more sustainable land use systems (Brown et al., 2018) and applications to real-world contexts are particularly needed (Brown et al., 2016). CRAFTY-Scotland has demonstrated that an ABM applied to a real-world situation can take account of societal demand for non-marketed services (e.g. recreation, biodiversity, flood regulation) and this research has demonstrated that ABM could be a promising method for negotiating trade-offs between services which have non-economic values. External societal demand is shown to have strong effect within CRAFTY-Scotland. Despite increasing research interest in ES demand, most ES assessments to date have focused on studying the stocks and spatial distribution of ES supply, and have only recently begun to explore ES demand (Wolff et al., 2015). The impact of demands for multiple ES on land use change needs to be investigated, as do attempts which capture spatial and temporal dynamics (Wolff et al., 2015). ABMs such as CRAFTY-Scotland can provide a fuller exploration of likely land use changes as, in contrast to purely economic approaches, they can incorporate other non-economic values. The stakeholders consulted in Chapter 3 identified non-monetary demand for non-monetary services, and CRAFTY provided a framework through which these could be included in an assessment of future land use change and implications for ES provision. By representing different land managers as well as their objectives and attitudes (Chapter 4), this research has attempted to reconcile the high-level stakeholder visions representing large amounts of consensus together with diverse land managers and the likelihood of them managing land in a way which would help to move towards those visions.

REGIONAL DISTINCTIONS AND NEGOTIATING TRADE-OFFS

Given the need for locally nuanced approaches outlined above, the results illustrate the potential for the CRAFTY framework to be applied in regional or local contexts. Distinctions in ES provision over time appear more clearly in the regional results, with certain regions more suited to provision of certain ES. For example, the Highlands remain a consistently important supply of floral biodiversity, while South Scotland shows the most potential for changes in hardwood timber provision. Regional applications could offer a chance for more detailed analysis of potential land use change, especially in regional partnerships where land ownership and objectives are transparent. This potential was highlighted by workshop participants in Chapter 3, with discussions recognising that perhaps not one single vision is realistic for the whole of Scotland, but that particular visions may be more applicable to particular regions. Future research could present the results of the model to stakeholders and policy makers to refine visions, combine elements of different visions, and identify preferred pathways. There would be great value in exploring broader societal visions for land use as a whole, with input from all land use sectors.

CULTURAL VALUES REMAIN, AND IT IS BEYOND MODELLING (ALONE) TO TACKLE THIS

Brown et al. (2018) found that the extent to which trade-offs are acceptable amongst stakeholders were a major factor in influencing vision feasibility. The results from Chapter 5 clearly indicate that the land uses which bear the brunt of woodland expansion are the extensive grasslands and heather moorlands which currently hold high cultural value. Wider research has acknowledged that the loss of old-growth grassy biomes is a risk from forest expansion, and that there is a need to consider the ecology and ES provided by these ecosystems (Veldman et al., 2015). The UK and Scotland were not highlighted as ‘at risk’ areas in previous analysis (Veldman et al., 2015), probably due to these ecosystems not being defined as ‘old-growth’, but nevertheless there is the need for further integration of open habitats and their associated ES in future fine-scale analysis.

DIFFERENT MODELLED PATHWAYS AFFECT THE ABILITY TO REACH TARGETS AND THE EXTENT TO WHICH TRADE-OFFS OCCUR

This study is amongst the first which has taken an approach of linking societal visions to quantitative models, with previous examples undertaking this in applied and theoretical European contexts (Brown et al., 2018; Verkerk et al., 2016). The results from Chapter 5 suggest that not all visions can meet area based targets for woodland expansion. This is similar to Verkerk et al. (2016) who observed limited pathways to two of their three visions and none to the third, and to Brown et al. (2018), who found that the consolidated land use visions they modelled were neither fully coherent or achievable, with there being a fundamental tension between small scale land system multi-functionality and large-scale efficiency. Within the results presented here, there are very different emphases between the visions which are shown to have the most potential to meet targets. As discussed in Chapter 5, there is a significant difference between the bottom-up community control envisaged in *Woodland Culture*, versus the top-down change in *Green Gold*. Forest transitions around the world have occurred for a variety of different reasons including; passively due to agricultural abandonment, after large scale crises to restore degraded lands, or by centralised power with clearly articulated goals (Rudel et al., 2019). As a result, there is no single ‘right’ way to achieve change, but the need to accelerate forest transitions to slow climate change, stem biodiversity loss and prevent deterioration in ES is globally recognised (Rudel et al., 2019).

SOCIETAL DEMAND FOR ES IS ESPECIALLY IMPORTANT TO DRIVE LAND USE CHANGE

Chapter 5 illustrates that simulating increasing societal demand for ES was important for driving woodland expansion. Therefore, longer term strategies which communicate the urgent need for forest transitions to engender societal support are likely to be critical. Realising sustainable forest management in Europe is unlikely to be driven by centralised mechanisms, but instead

poly-centric governance, which will be strongly linked to different land ownership patterns at operational levels (Lazdinis et al., 2019). Taking this into account, regionally adapted landscape approaches which engage multiple stakeholders through evidence based landscape governance are required. It is acknowledged that both climate and socio-economic change will also affect the extent to which visions can be achieved (Brown et al., 2018), although the effect of climate change may be less than either socio-economic change or behavioural differences between land managers (Blanco et al., 2017b). The omission of the effects of climate and socio-economic changes in this study is a key limitation, and is a priority for future research.

SMALL CHANGES IN ATTITUDES COMBINED WITH AN INCREASE IN LOCAL RESOURCES HAS POTENTIAL TO HAVE A STRONG EFFECT

One of the most interesting outcomes of Chapter 5 was the representation of both Land Reform and Community Empowerment within the *Woodland Culture* vision. These are both hugely complex and sensitive processes and therefore not easily modelled, but there was a seeming success in representing them simply within the ABM, with the *Woodland Culture* vision showing the greatest positive changes in woodland cover and ES supply. Given that together these policies aim to diversify land management and empower local communities, there are wider comparisons to be made to international research linking small and medium forest enterprises (SMFEs) to prosperity. This has mostly been explored in low and middle income countries, but could equally be applied to Scotland, where rural development is a key aim of Scottish government policy. Similarly to sustainability, prosperity is subject to a range of interpretations, but has been defined as “our ability to flourish as human beings – within the ecological limits of a finite planet” (Jackson, 2009). Forests may contribute to more widely shared and enduring prosperity (Miller & Hajjar, 2019). Locally controlled forest enterprises can deliver a wide variety of benefits to forest-reliant communities, and economic viability is necessary for SMFEs to generate broader benefits for the communities in which they operate (Humphries et al., 2018; Miller &

Hajjar, 2019). Once again, this links to the holistic FLR approach with approaches which emphasise social outcomes and give local communities ownership of restoration having far more chance of success (Mansourian et al., 2017). At the same time, there is a relative paucity of evidence on the relationship between forests and broader prosperity and this is a clear direction for future work (Miller & Hajjar, 2019).

INTERACTION WITH OTHER LAND USE CHANGE DRIVERS

Scotland is currently undergoing an energy transition due to its significant potential for renewable energy, mostly in rural and remote regions (Munro, 2019). The UK Climate Change Act (2008) set out aims for an 80% reduction in greenhouse gas emissions by 2050 based on 1990 levels. The Climate Change (Scotland) Act 2009 set the same target, with the addition of 100% of electricity demand to be met from renewable resources by 2020. This has resulted in a proliferation of schemes, and community energy initiatives in particular are flourishing due to Land Reform and Community Empowerment legislation (Munro, 2019). Energy developments including onshore wind, hydroelectric, and solar require large amounts of infrastructure both on site and to transfer captured energy from areas where it can be generated to centres where the energy is primarily consumed (Munro, 2019). This suggests that there is, and will continue to be land use competition, or at least that careful land use planning is required to balance the need to both meet woodland expansion and renewable energy targets. Research has suggested that farmer participation in agri-environment schemes is associated with increased participation in both recent and anticipated future afforestation and renewable energy production (Sutherland et al., 2016), so these major targets may not need to be seen as conflicting. In addition, it is acknowledged that there is an existing synergy between forestry and renewable energy production: the intention to adopt renewable heat production from wood biomass (Sutherland et al., 2016). This detail was acknowledged by stakeholders involved in discussing the *Green Gold* vision, with linkages between community heating initiatives and woodland creation projects proposed.

FUTURE THREATS TO TREES AND WOODLANDS

As already noted, future land use change will not take place in static conditions and climate change is expected to have a significant effects on woodland growth, species survival and distributions. Forests will have to adapt not only to changes in mean climate variables but also to increased variability with greater risk of extreme weather events, such as prolonged drought, storms and flood (Lindner et al., 2010). There is also growing incidence of new tree pest and disease epidemics, linked to increased global trade in recent decades (Potter & Urquhart, 2017). Current disease threats include: Ash dieback, *Dothistroma* needle blight (affecting conifer species including Corsican pine, lodgepole pine and Scots pine), Dutch elm disease, *Phytophthora austrocedri* (affecting Juniper), and *Ramorum* (mainly affecting larch). In terms of pests, the Great spruce bark beetle is currently affecting spruce species and occasionally pine, in addition to the Large pine weevil and Pine tree lappet moth. Climate change may also influence the susceptibility of trees to pests and disease (Freer-Smith & Webber, 2017). Future anticipated threats include the Asian longhorn beetle, Bronze birch borer, Emerald ash borer, and *Xylella*. Current and future threats are the subject of a great deal of research as well as monitoring and regulation via Scottish Forestry. Full consideration of these was beyond the scope of this thesis, but there are exciting research avenues to be highlighted in terms of combining Individual Based Models (IBMs) of pest or disease spread with ABMs of land use change such as the one presented here. Model combinations such as these could assist with explorations of the land use change and ecosystem service implications of pest and disease outbreaks, as well as how adaptive management may help to minimise risk of such outbreaks.

SOCIO-ECOLOGICAL TRANSFORMATIONS

The grand challenges outlined in Chapter 1 clearly state the case for sustainability science to help inform transformative decisions, and land system science efforts to tackle sustainability issues so

far have laid bare many temporal, spatial, human, and biophysical trade-offs, including which communities and interests are affected by land use change (Nielsen et al., 2019). It is essential to ensure that models such as the one developed here are not interpreted as being able to predict the future. However, models do have a role in surprising people, and breaking the illusions of understanding that we have about particular systems. Values around land use and society's place in managing it are deeply held, and despite the calls for action, downward trends continue. Instead of trying to communicate why, approaches which show people how things could change could be powerful. Combining positive visions of the future and non-economic modelling approaches could have a valuable role in this.

Conclusions

This thesis has conducted an exploration of the synergies and trade-offs between ES generated by woodland expansion in Scotland, focussing latterly on how governance could influence targets for woodland expansion and resulting ES provision from Scottish landscapes. Through a process of stakeholder engagement and development of an ABM representing suitability for woodland expansion, multiple ES, and diverse land managers with different objectives, the research process has shed light on how ES might change under alternative stakeholder visions of the future.

Much emphasis is placed on the potential for woodland expansion to tackle grand challenges including climate change and biodiversity loss. In terms of climate change mitigation and resilience, evidence from both existing research (Chapter 2) and modelling (Chapter 5) supports this. For biodiversity, further research and a shift in focus (to thinking on longer timescales and with new metrics) is required to gain a fuller picture of the likely dynamics under woodland expansion. Aligning future research within the FLR framework will also allow research, policy, and practice to gain improved understanding of socio-cultural views and benefits around woodland expansion. By better understanding both economic and non-economic values around woodland expansion and land use change, future action will be better able to understand different motivations and how to influence change in a way that will benefit as many stakeholders as possible.

Stakeholders consulted in Chapter 3 saw a role for some form of payment for public goods in order to encourage woodland expansion, and there was some success in simulating this within CRAFTY-Scotland in Chapter 5. Well-designed approaches which engage with multiple stakeholders and aim to provide annualised support could be effective in supporting woodland expansion objectives, and there is a significant opportunity over the next few years to give new diversified emphasis to public funding, perhaps combined with novel private funding schemes such as PES. As social norms have been identified as the most significant obstacles to the implementation of landscape approaches, future strategies need to engender wider societal understanding and support, and regional to local poly-centric and participatory governance approaches may be essential to achieve this.

The results in Chapter 5 suggest that alternative modelled pathways affect the ability to reach targets for woodland expansion and the extent to which ES synergies and trade-offs occur. There are potentially powerful positive synergies between a number of core Scottish government aims including woodland expansion, Land Reform, and Community Empowerment. This highlights potentially exciting research avenues in linking woodland expansion to small forest enterprises and prosperity. By exploring a number of normative positive futures in a quantitative land use model, this interdisciplinary approach has provided an example of how future research could support and even drive transformational land use decisions.

ABM is a powerful tool in the sustainability science toolbox and whilst being spatially explicit, there is less focus on technical mapping and more on the processes and governance within the land use system. In particular, CRAFTY-Scotland has demonstrated the value of taking into account non-economic values and societal demand, and this has assisted exploration of the potential synergies and trade-offs between ES - something that previous research has struggled to do. The reliance on existing data to parameterise the model meant that similar limitations in ES indicators to other work were found, and research needs to continue to be aware of these limitations to address them further.

Given the urgent need to move towards sustainable land use in the face of multiple challenges, linking societal visions to models in research approaches which engage society with science and encourage futures thinking have great potential. All the methods used in the thesis are under-utilised or under-developed, and it is important they are built upon in future applications.

A

Appendix A

A.1 SEARCH TERMS USED FOR THE SYSTEMATIC REVIEW

Table A.1: Search terms used for each database

Date	Database	Search Terms	Search Settings	Timespan	Hits
02/02/2016	Web of Science	<p>TS = ((woodland expansion OR "woodland restoration" OR "woodland planting" OR "forest expansion" OR "forest restoration" OR "afforestation" OR "woodland creation") AND (network OR corridor OR connect* OR buffer OR dispersal OR forag* OR "adjacent habitat*" OR "tree plant*" OR "tree species composition" OR "species composition" OR "stocking densit*" OR "planting method" OR size OR edge OR design OR "open space" OR glade OR ride OR soil OR management OR "post-planting" OR treat* OR weed* OR prun* OR thin* OR coppic* OR structur* OR spacing OR fell* OR "dead wood" OR (wet* OR water)) AND (change* OR effect* OR impact* OR benefit* OR establish* OR succes* OR fail* OR increas* OR declin* OR neutral OR "no effect*" OR function* OR service* OR synerg* OR "trade-off*" OR provisioning OR supporting OR regulating OR cultural OR scale OR time) AND (biodivers* OR species OR population* OR communit* OR ecosystem OR habitat* OR site* OR stand OR region* OR landscape* OR "ecosystem function" OR "ecosystem service" OR vegetation OR soil* OR nutrient* OR climate OR "carbon sequestration" OR "carbon storage" OR flood* OR "water quality" OR timber OR farm* OR agricultur* OR agro* OR crop* OR peat* OR recreation* OR aesthetic* OR health OR hunt* OR shoot*) AND (open habitat* OR habitat* OR bog OR heath* OR grassland OR gras* OR forest* OR wood**))</p>	<p>Refined to: Web of Science Core Collection and BIOSIS Collection. Region refined to UK, United Kingdom, England, Scotland, Wales, Ireland, North Ireland. Sorted by relevance</p>	All years (1864-2016)	725

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
02/02/2016	Scopus	<p>((woodland expansion OR "woodland restoration" OR "woodland planting" OR "forest expansion" OR "forest restoration" OR "afforestation" OR "woodland creation") AND (network OR corridor OR connect* OR buffer OR dispersal OR forag* OR "adjacent habitat*" OR "tree plant*" OR "tree species composition" OR "species composition" OR "stocking densit*" OR "planting method" OR size OR edge OR design OR "open space" OR glade OR ride OR soil OR management OR "post-planting" OR treat* OR weed* OR prun* OR thin* OR coppic* OR structur* OR spacing OR fell* OR "dead wood" OR (wet* OR water)) AND (change* OR effect* OR impact* OR benefit* OR establish* OR succes* OR fail* OR increas* OR declin* OR neutral OR "no effect*" OR function* OR service* OR synerg* OR "trade-off" OR provisioning OR supporting OR regulating OR cultural OR scale OR time) AND (biodivers* OR species OR population* OR communit* OR ecosystem OR habitat* OR site* OR stand OR region* OR landscape* OR "ecosystem function*" OR "ecosystem service*" OR vegetation OR soil* OR nutrient* OR climate OR "carbon sequestration" OR "carbon storage" OR flood* OR "water quality" OR timber OR farm* OR agricultur* OR agro* OR crop* OR peat* OR recreation* OR aesthetic* OR health OR hunt* OR shoot*) AND (open habitat* OR habitat* OR bog OR heath* OR grassland OR grass* OR forest* OR wood*) AND AFFILCOUNTRY (united kingdom OR ireland))</p>	Region limited to United Kingdom and Ireland	All years (1976 - 2016)	505

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
22/01/2016	Google Scholar	with the exact phrase: "woodland expansion" afforestation "woodland creation" "forest expansion". With any of the words:biodiversity species population community habitat ecosystem landscape "ecosystem function" "ecosystem service"	Advanced search	Any time	31
22/01/2016	Google Scholar	with the exact phrase: "woodland expansion" afforestation. With any of the words: biodiversity species population community habitat ecosystem landscape "ecosystem function" "ecosystem service"	Advanced search. Sorted by relevance	Any time	312 (take first 100 hits)
03/02/2016	Google	with the exact phrase: "woodland expansion" afforestation. With any of the words:biodiversity species population community habitat ecosystem landscape "ecosystem function" "ecosystem service"	Advanced search. Only pdfs. Sorted by relevance	Any time	1,280 results, take first 100
02/02/2016	Forestry Commission	woodland expansion, afforestation, effect, biodiversity, ecosystem services	Advanced search. Sorted by relevance. PDFs only	Any time	279 (take first 25 hits)
02/02/2016	Forest Commission (publications) - no specific search available for FR	3 separate searches: woodland expansion, biodiversity (returned 2) and woodland expansion, ecosystem services (returned 0) and just woodland expansion (returned 8)	Advanced search. All of the words.	Any time	2, took all, 0, took none, 8, took 4

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
02/02/2016	UK Govt. Website (DEFRA, Environment Agency, Natural England Natural Resources Wales	"woodland expansion, afforestation, biodiversity, ecosystem services"	Sorted by relevance	Any time	148 (take first 25 hits)
02/02/2016	Scottish Natural Heritage	woodland expansion	No advanced options for sorting in any way, basic search	Any time	Took first 25 hits
02/02/2016	James Hutton Institute	woodland expansion			
03/02/2016	SEPA	woodland expansion, forestry, biodiversity, ecosystem services	Library/Document search	Any time	13 (took all)
03/02/2016	The Wildlife Trusts	tried variations of the SEPA search			
03/02/2016	The Woodland Trust	woodland creation	Filtered to document		4 (took all)

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
03/02/2016	RSPB	Manual search through document library section	Topic: forestry, all years, anywhere.		Took all results from briefings, information sheets, other documents and reports, then filled up to 25 hits with first results from consultation re-sponses

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
03/02/2016	JNCC	Manual search in publications catalogue.	Publications catalogue > Habitats > Woodland		16 results
03/02/2016	National Trust	woodland expansion			
03/02/2016	English Heritage	woodland expansion			
03/02/2016	Campaign to Protect Rural England	woodland expansion			3 results
03/02/2016	SRUC	With the exact phrase "woodland expansion" "afforestation" "woodland creation". With at least one of the words: biodiversity, ecosystem services	Advanced search. Documents only.		0 results
03/02/2016	Confor	woodland expansion			
03/02/2016	CEH	woodland expansion	Advanced search > Content		3 results, 1 paper down- loaded
03/02/2016	NERC	woodland expansion			
03/02/2016	EU LIFE				
03/02/2016	United Utilities	woodland expansion			4 results, took all
03/02/2016	Yorkshire Water	woodland expansion			0 results
03/02/2016	Severn Trent	woodland expansion			0 results

Table A.1: Search terms used for each database (*continued*)

Date	Database	Search Terms	Search Settings	Timespan	Hits
03/02/2016	Game and Wildlife Conservation Trust	woodland expansion	Downloads		3
07/04/2017	Web of Science	(TS = ((woodland expansion OR "woodland restoration" OR "woodland planting" OR "forest expansion" OR "forest restoration" OR "afforestation" OR "woodland creation")) AND (network OR corridor OR connect* OR buffer OR dispersal OR forag* OR "adjacent habitat*" OR "tree plant*" OR "tree species composition" OR "species composition" OR "stocking densit*" OR "planting method" OR size OR edge OR design OR "open space" OR glade OR ride OR soil OR management OR "post-planting" OR treat* OR weed* OR prun* OR thin* OR coppic* OR structur* OR spacing OR fell* OR "dead wood" OR (wet* OR water)) AND (change* OR effect* OR impact* OR benefit* OR establish* OR succes* OR fail* OR increas* OR declin* OR neutral OR "no effect" OR function* OR service* OR synerg* OR "trade-off" OR provisioning OR supporting OR regulating OR cultural OR scale OR time) AND (biodivers* OR species OR population* OR communit* OR ecosystem OR habitat* OR site* OR stand OR region* OR landscape* OR "ecosystem function*" OR "ecosystem service*" OR vegetation OR soil* OR nutrient* OR climate OR "carbon sequestration" OR "carbon storage" OR flood* OR "water quality" OR timber OR farm* OR agricultur* OR agro* OR crop* OR peat* OR recreation* OR aesthetic* OR health OR hunt* OR shoot*) AND (open habitat* OR habitat* OR bog OR heath* OR grassland OR grass* OR forest* OR wood*)) AND LANGUAGE: (English)	Refined by:COUNTRIES/TERRITORIES:(ENGLAND OR WALES OR SCOTLAND OR NORTH IRELAND OR IRELAND) Timespan: 2016- 2017. Indexes: SCI- EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.	2016-2017	51 results, took all

A.2 INCLUSION/EXCLUSION PROCESS USED FOR THE SYSTEMATIC REVIEW

Systematic reviews revolved around selecting studies based on predefined criteria. These criteria relate directly to the key elements of the research questions, in a PICO format (population, intervention, comparator, outcome).

The following criteria were used to select suitable studies:

1. *Population*: any species, population, community, habitat, or ecosystem service
2. *Intervention*: any woodland/forest expansion, creation, restoration
3. *Comparator(s)*: any other habitat, either pre-afforestation, or studies in comparison to an established woodland habitat
4. *Outcome*: any change, effect, impact
5. *Type of study*: any
6. *Setting*: UK

The process also excluded documents with a policy or guidance focus (e.g. research on constraints to new woodland, advice for best practice, or strategic objectives). Studies which were included had to consider the impact/effect of new woodland or assess the effect of established woodland in comparison to other habitats. Some documents could not be accessed due to restrictions or were book chapters which could not be sourced online.

Study inclusion assessments were performed and fully recorded in a spreadsheet. This can be found as electronic supplementary material: <https://www.sciencedirect.com/science/article/pii/S0378112718306662?via%3Dihub#moos5>

The entire database of papers included in the final review can also be found as electronic supplementary material at the same link.

B

Appendix B

- B.1 THE MAIN CODED THEMES WITHIN EACH STEEP CATEGORY
- B.2 HOW EACH CODED THEME WITHIN EACH STEEP CATEGORY WAS POSITIONED ON THE 2X2 MATRIX
- B.3 A FULL LIST OF THE DOCUMENTS USED FOR CODING TO PRODUCE THE VISIONS

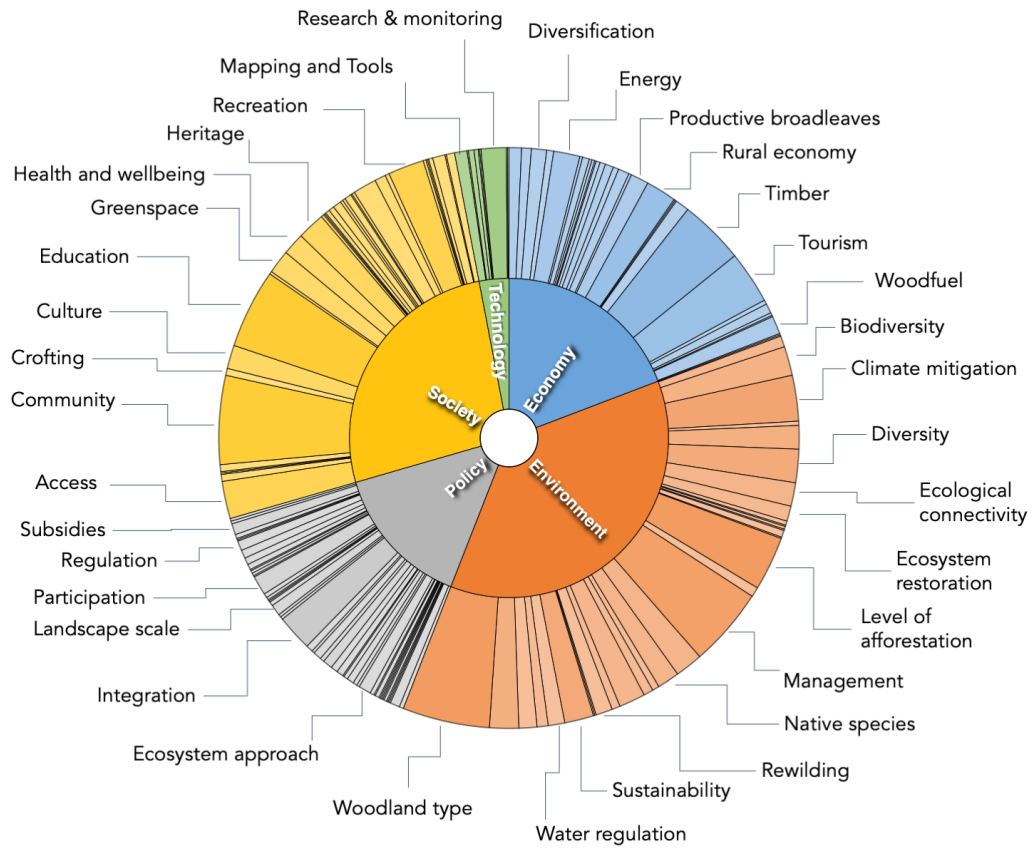


Figure B.1: A sunburst chart illustrating the main coded themes within each STEEP category (Society, Technology, Economy, Environment, Policy and Governance). The size of each section represents the number of times a piece of text was coded to that theme. The colour shading represents the number of source documents coded to each theme, with darker shading equating to more documents.

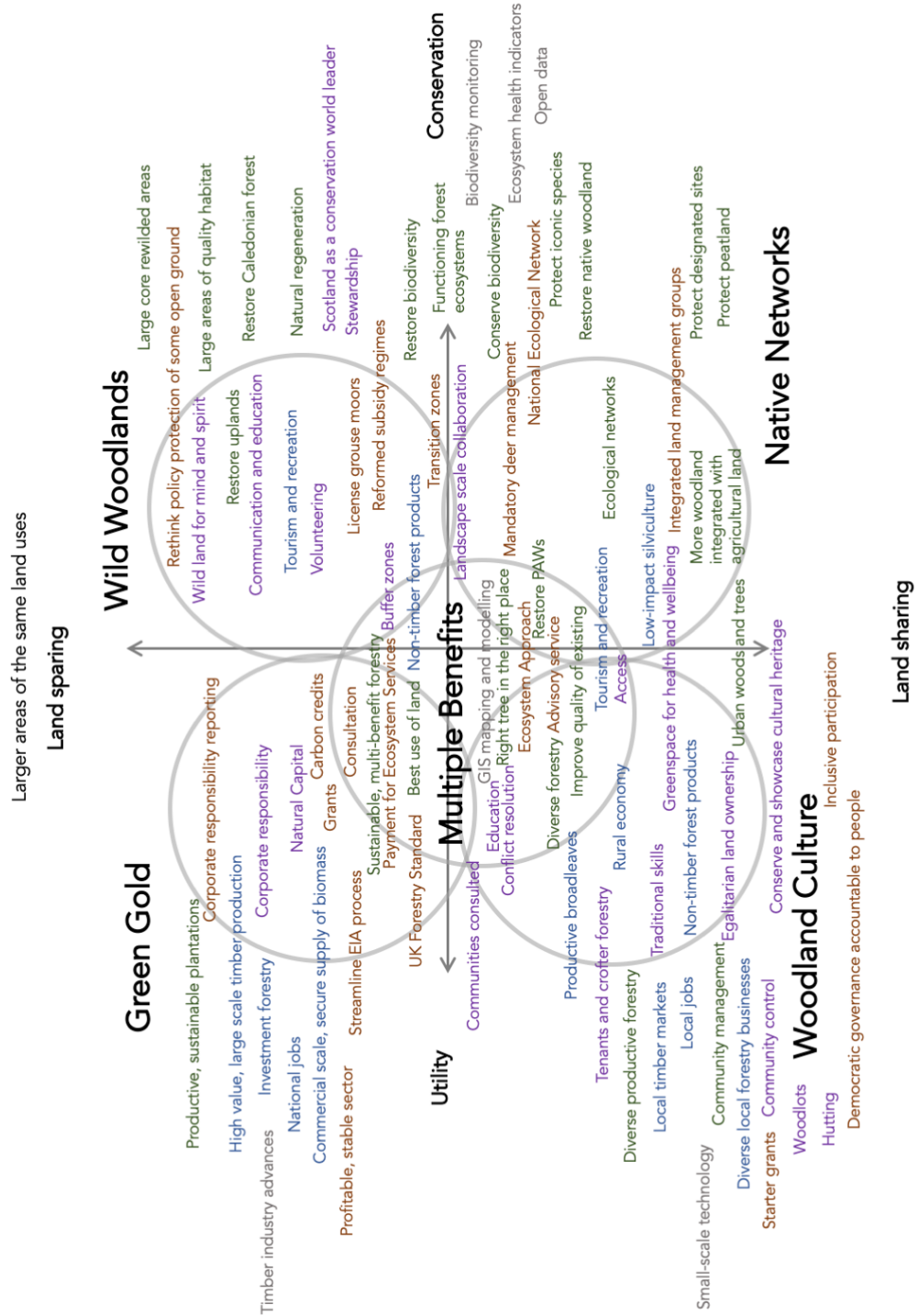


Figure B.2: The visions axes, showing how the coded themes were mapped onto, and clustered within the four identified critical elements (utility > conservation, land sharing > land sparring). The colours of the themes relate to their STEEP category S (Society) = purple, T (Technology) = grey, E (Environment) = green, E (Economy) = blue, P (Policy) = Red

Table B.1: The documents used for coding vision elements

Document	Date	Stakeholder	Category	Type	Level
Cairngorms National Park Partnership Plan 2012-2017	2012	Cairngorms National Park	Government	Document	Regional
CALL Programme Plan 2011-2015	2011	Coigach- Assynt Living Landscape	NGO	Document	Regional
Climate Change (Scotland) Act 2009	2009	Scottish Government	Government	Policy	National
Community Woodland Association Response to Woodland Expansion Rationale	N/A	Community Woodlands Association	NGO	Consultation	National
Confor's Vision	2016	Confor	NGO	Webpage	National
Cowal and Trossachs District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
Crown Estate Forest for the Future	2011	Crown Estate	Government	Document	National
Dumfries and Borders District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
Forest Policy Group Vision	2016	Forest Policy Group	Think-tank	Webpage	National
Forestry Vision	2016	University of Edinburgh	Research	Document	National
Galloway District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
Great Trossachs Forest	2016	Great Trossachs Forest	NGO	Webpage	Regional

Table B.1: The documents used for coding vision elements (*continued*)

Document	Date	Stakeholder	Category	Type	Level
Inverness Ross and Skye District Plan	2014	Forestry Commission	Government	Document	Regional
Land Use Strategy	2016	Scottish Government	Government	Policy	National
Living Landscapes for the Scottish Uplands	2016	Scottish Wildlife Trust	NGO	Policy	National
Loch Lomond and Trossachs National Park Partnership Plan 2012-2017	2012	Loch Lomond and Trossachs National Park	Government	Document	Regional
Lochaber District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
Moray and Aberdeenshire District Plan	2014	Forestry Commission	Government	Document	Regional
North Highland District Strategic Plan	2015	Forestry Commission	Government	Document	Regional
Our Essential Wildness	N/A	John Muir Trust	NGO	Document	National
Reforestation Scotland Vision	2016	Reforestation Scotland	NGO	Webpage	National
RSPB Our Vision for Scottish Forestry	2016	RSPB	NGO	Webpage	National
Rural Scotland in Focus 2016 SRUC	2016	SRUC	Research	Document	National
Scottish Biodiversity Strategy	2004	Scottish Government	Government	Policy	National

Table B.1: The documents used for coding vision elements (*continued*)

Document	Date	Stakeholder	Category	Type	Level
Scottish Forestry Strategy 2006	2006	Scottish Government	Government	Policy	National
Scottish Forum on Natural Capital	2016	Scottish Forum on Natural Capital	NGO	Webpage	National
Scottish Government Rationale for Woodland Expansion	2009	Scottish Government	Government	Document	National
Scottish Land & Estates WEAG Consultation Response	2011	Scottish Land and Estates	Private	Consultation	National
Scottish Land and Estates A Vision for the Uplands	2016	Scottish Land and Estates	Private	Blog	National
Scottish Land and Es- tates Consultation Response Opportunities for Woodland Expansion	2013	Scottish Land and Estates	Private	Consultation	National
Scottish Land and Estates Forestry Page	2016	Scottish Land and Estates	Private	Webpage	National
Scottish Lowlands District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
SEPA Forests	2016	SEPA	Government	Webpage	National
SFA Creating Woodlands for Wildlife and People in Scotland	N/A	Scottish Forest Alliance	NGO	Document	National

Table B.1: The documents used for coding vision elements (*continued*)

Document	Date	Stakeholder	Category	Type	Level
SNH Natural Heritage Futures Forests	2002	Scottish Natural Heritage	Government	Document	National
SNH Natural Heritage Futures Forests Update	2009	Scottish Natural Heritage	Government	Document	National
SNH Natural Heritage Futures Hills and Moors	2002	Scottish Natural Heritage	Government	Document	National
SNH Natural Heritage Futures Hills and Moors Update	2009	Scottish Natural Heritage	Government	Document	National
Tay District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
The Crown Estate	2016	Crown Estate	Government	Webpage	National
The Future of Forestry in Scotland 2016	2016	Scottish Government	Government	Consultation	National
The Future of Forestry in Scotland LINK Response November 2016	2016	Scottish En- vironment Link	NGO	Consultation	National
Thriving Forestry and Timber in a post-Brexit world	2016	Confor	NGO	Document	National
Tilhill Company Brochure 2016	2016	Tilhill	Private	Document	National
Trees for Life's Vision	2016	Trees for Life	NGO	Webpage	Regional
UK Forestry Standard	2011	Forestry Commission	Government	Document	National

Table B.1: The documents used for coding vision elements (*continued*)

Document	Date	Stakeholder	Category	Type	Level
Vision for Rewilding Britain - Aug 2014	2014	Rewilding Britain	NGO	Document	National
Woodland Expansion Advisory Group (WEAG) Final Report	2012	Woodland Expansion Advisory Group	Government	Document	National
West Argyll District Strategic Plan	2014	Forestry Commission	Government	Document	Regional
WIAT Strategic Framework 2015 - 2020	2015	Scottish Government	Government	Document	National
Woodland Trust Growing the Future	2016	Woodland Trust	NGO	Policy	National
Woodland Trust Life's Better With Trees	2016	Woodland Trust	NGO	Policy	National
WWF RSPB Wildlife Trusts A New Policy for our Countryside	2016	Wildlife Trusts, RSPB, National Trust, WWF	NGO	Document	National
Wild Land Management Standards: Biodiversity and Woodland	NA	John Muir Trust	NGO	Document	National

B.4 MATERIALS USED IN THE STAKEHOLDER WORKSHOP AND INTERVIEWS

B.5 FINAL VISIONS ILLUSTRATIONS

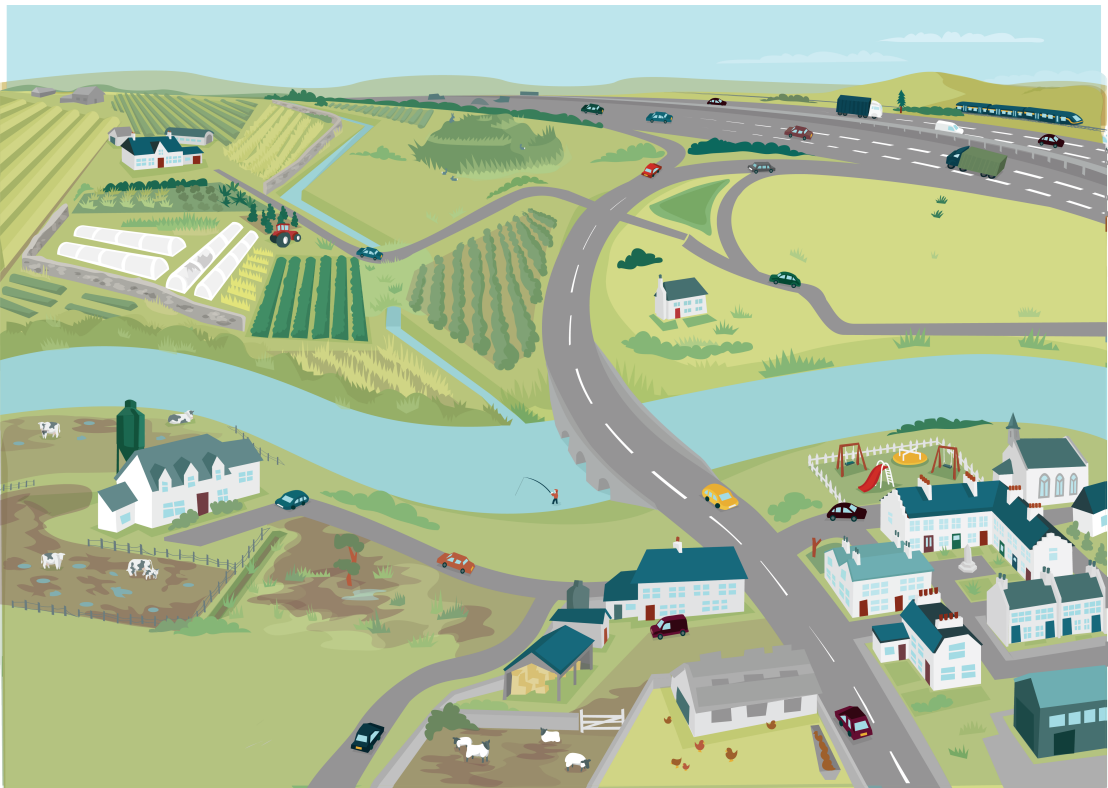


Figure B.3: The lowland landscape used in the stakeholder workshop and interviews



Figure B.4: The upland landscape used in the stakeholder workshop and interviews

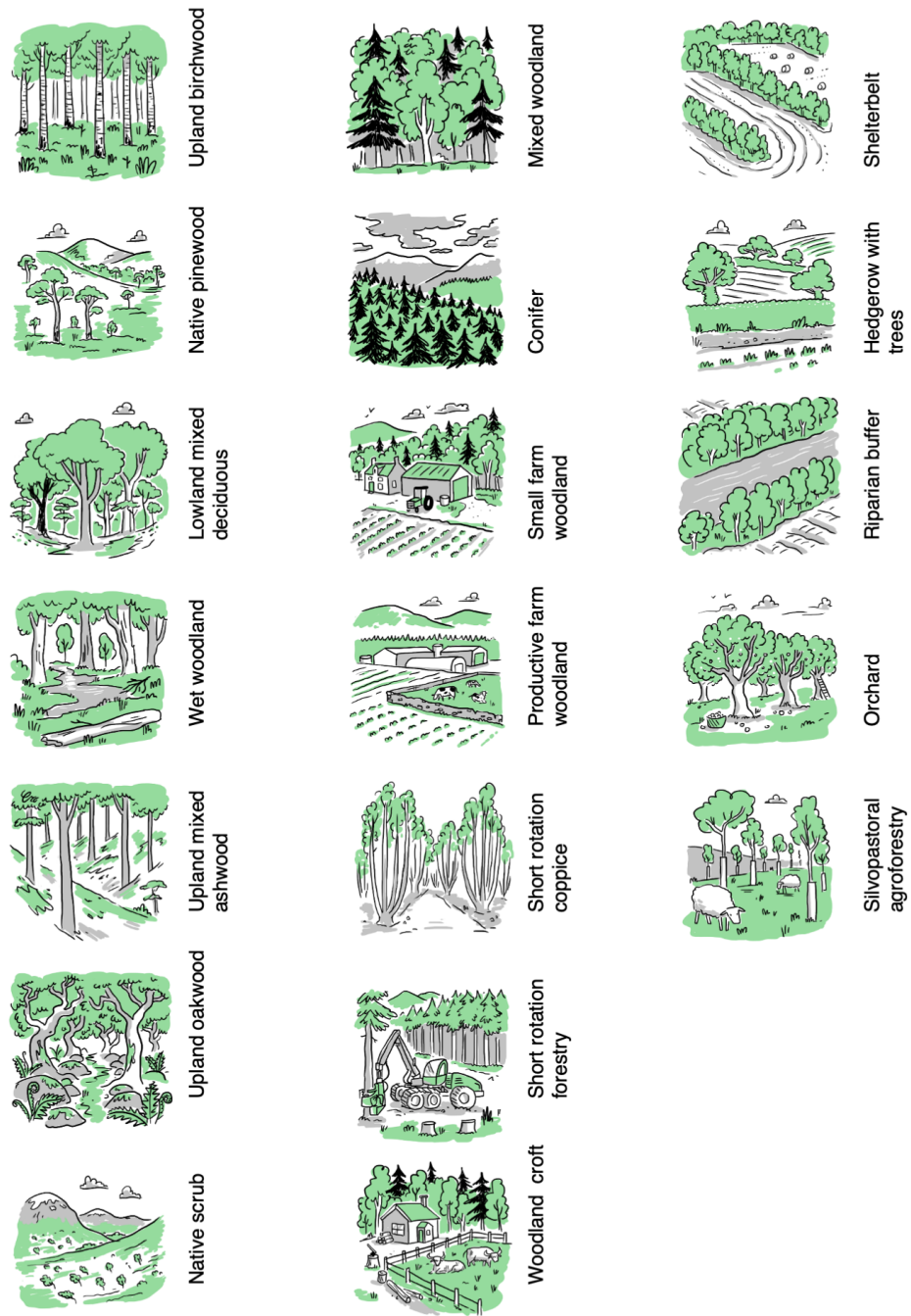


Figure B.5: The woodland type tiles used in the stakeholder workshop and interviews



Figure B.6: The ecosystem service type tiles used in the stakeholder workshop and interviews

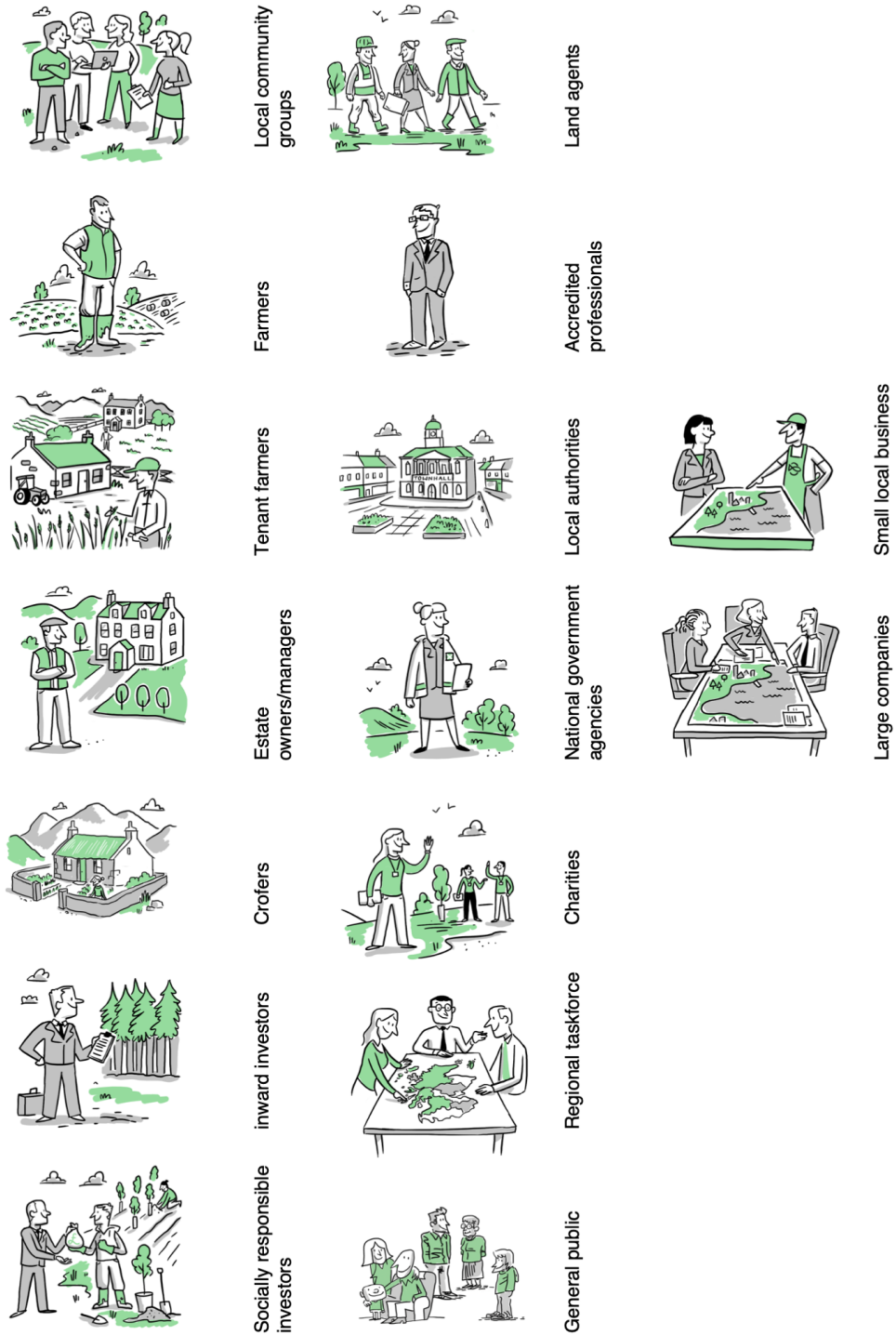


Figure B.7: The actor type tiles used in the stakeholder workshop and interviews

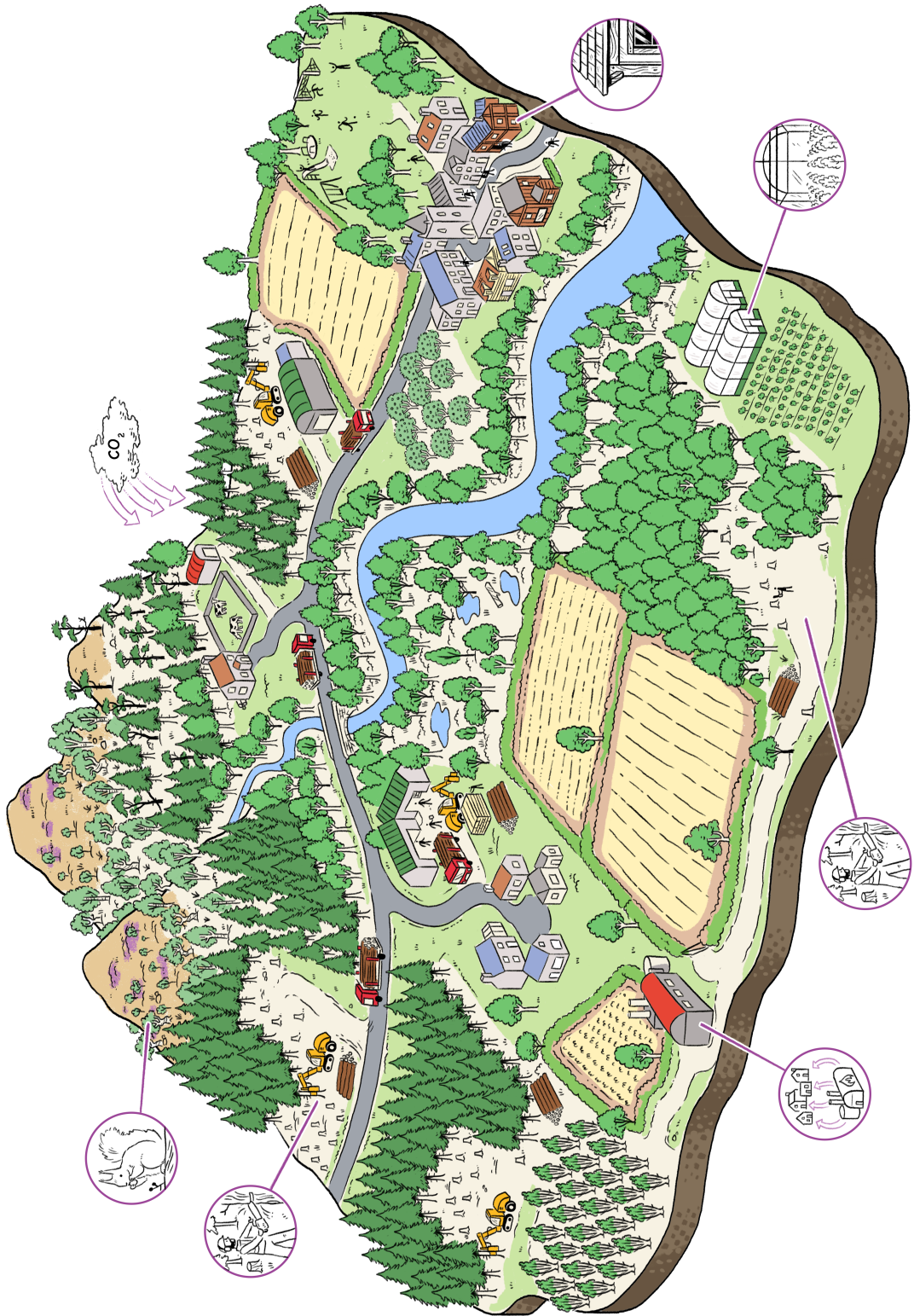


Figure B.8: Green Gold



Figure B.9: Multiple Benefits

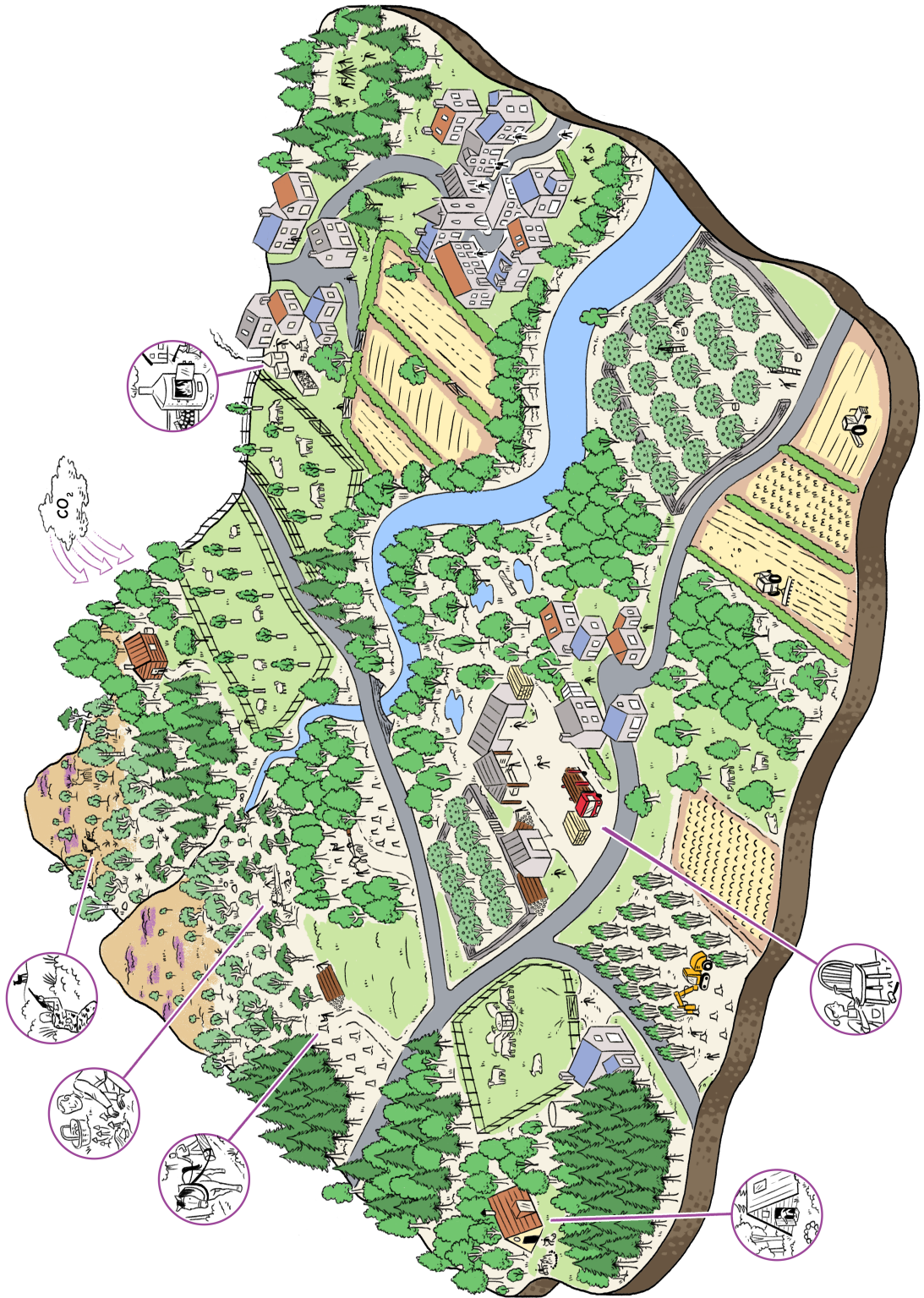


Figure B.11: Woodland Culture

C

Appendix C

C.1 ALL AGENT FILES, DESCRIBING THEIR SERVICE PRODUCTION CAPABILITIES AND SENSITIVITY TO RELEVANT CAPITALS

Table C.1: All agent files with parameters for service production and capital sensitivity

	deep.peat	lessNAT	moreNAT	lessF	moreF	lessNW	moreNW	financial	manufactured	social	human	water.runoff	grassland	crop.productivity	mixed.yc	agro.yc	n.broad.consv	n.broad.yc	n.conifer.yc	nn.broad.yc	nn.conifer.yc	region	Production	Service
Productive non-native conifer																								
Softwood timber	1	0	0	1	1	0	0	0.930	0.018	0.260	0.160	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	1.000	0	0.940	
Hardwood timber	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.094	0	0.770	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.810	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.900	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.040	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.005	0	0.075	
Livestock	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Crops	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Employment	1	0	0	1	1	0	0	0.070	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.240	
Productive non-native broadleaf																								
Softwood timber	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Hardwood timber	1	0	0	1	1	0	0	0.000	0.240	0.000	0.030	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.830	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.490	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.640	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.790	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.170	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.010	
Livestock	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Crops	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Employment	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.240	
Productive native conifer																								
Softwood timber	1	0	0	1	1	0	0	0.260	0.230	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	1.000	0	0.960	
Hardwood timber	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.590	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.710	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.900	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.040	0.060	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.022	

Table C.r: All agent files with parameters for service production and capital sensitivity (*continued*)

	Production	region	nn.conifer.yc	nn.broad.yc	n.conifer.yc	n.broad.yc	n.broad.consv	agro.yc	mixed.yc	crop.productivity	grassland	water.runoff	human	social	manufactured	financial	moreNW	lessNW	moreF	lessF	moreNAT	lessNAT	deep.peat	
Service	Livestock	0	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Crops	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Employment	0.240	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.270	0.0000	0.0000	0	0	1	1	0	0	1	
Production	Productive native broadleaf																							
	Softwood timber	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Hardwood timber	0.9990	0.0000	0.00	1.0000	0.0000	0.00	0.00	0.00	0.0000	0.0000	0	0.030	0.0000	0.160	0.0000	0	0	1	1	0	0	1	
	Biodiversity	0.740	0.0000	0.00	0.0000	0.140	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Carbon	0.620	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Flood regulation	0.790	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Recreation	0.110	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.070	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Livestock	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Crops	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0	0	1	1	0	0	1	
	Employment	0.240	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	0.110	0	0	1	1	0	0	1
	Production	Conservationis: native woodland																						
		Softwood timber	0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1
Hardwood timber		0.0000	0.0000	0.00	0.0000	0.0000	0.490	0.00	0.00	0.0000	0.0000	0	0.130	0.0000	0.080	0.230	1	1	0	0	1	1	1	
Biodiversity		0.680	0.0000	0.00	0.0000	0.0000	0.070	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Carbon		0.720	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Flood regulation		0.800	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	1	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Recreation		0.080	0.0000	0.00	0.0000	0.0000	0.028	0.00	0.00	0.0000	0.0000	0	0.030	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Livestock		0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Crops		0.0000	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	0	0	1	1	1	
Employment		0.160	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.035	0.0000	0.050	0.0000	1	1	0	0	1	1	1	
Production		Multifunctional mixed woodland																						
		Softwood timber	0.450	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.40	0.0000	0.0000	0	0.060	0.0000	0.070	0.160	1	1	1	1	0	0	1
	Hardwood timber	0.470	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.40	0.0000	0.0000	0	0.060	0.0000	0.070	0.160	1	1	1	1	0	0	1	
	Biodiversity	0.730	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.11	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	1	1	0	0	1	
	Carbon	0.660	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.00	0.0000	0.0000	0	0.0000	0.0000	0.0000	0.0000	1	1	1	1	0	0	1	

Table C.r: All agent files with parameters for service production and capital sensitivity (*continued*)

	Production	region	nn.conifer.yc	nn.broad.yc	n.conifer.yc	n.broad.yc	n.broad.consv	agro.yc	mixed.yc	crop.productivity	grassland	water.runoff	human	social	manufactured	financial	moreNW	lessNW	moreF	lessF	moreNAT	lessNAT	deep.peat
Flood regulation	0.800	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1	0.000	0.000	0.000	0.000	1	1	1	1	0	0	1
Recreation	0.093	0	0.000	0.000	0.000	0.000	0.000	0.000	0.04	0.000	0.000	0	0.095	0.001	0.000	0.000	1	1	1	1	0	0	1
Livestock	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	1	1	1	1	0	0	1
Crops	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	1	1	1	1	0	0	1
Employment	0.160	0	0.000	0.000	0.000	0.000	0.000	0.000	0.12	0.000	0.000	0	0.130	0.200	0.300	0.110	1	1	1	1	0	0	1
Multifunctional non-native conifer																							
Softwood timber	0.450	0	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.160	0.260	0.018	0.030	0	0	1	1	0	0	1
Hardwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Biodiversity	0.770	0	0.094	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Carbon	0.810	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Flood regulation	0.900	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Recreation	0.075	0	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.040	0.000	0.000	0.000	0	0	1	1	0	0	1
Livestock	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Crops	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Employment	0.240	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.070	0	0	1	1	0	0	1
Multifunctional native conifer																							
Softwood timber	0.450	0	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.230	0.260	0	0	1	1	0	0	1
Hardwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Biodiversity	0.590	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Carbon	0.710	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Flood regulation	0.900	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Recreation	0.022	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.060	0.040	0.000	0.000	0	0	1	1	0	0	1
Livestock	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Crops	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Employment	0.240	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.270	0.000	0.000	0	0	1	1	0	0	1
Multifunctional non-native broadleaf																							
Softwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	1	1	0	0	1
Hardwood timber	0.400	0	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0.020	0.000	0.240	0.000	0	0	1	1	0	0	1

Table C.r: All agent files with parameters for service production and capital sensitivity (continued)

	deep.peat	lessNAT	moreNAT	lessF	moreF	lessNW	moreNW	financial	manufactured	social	human	water.runoff	grassland	crop.productivity	mixed.yc	agro.yc	n.broad.consv	n.broad.yc	n.conifer.yc	nn.broad.yc	nn.conifer.yc	region	Production	Service	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.21	0.000	0	0.490	Biodiversity	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.640	Carbon	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.700	Flood regulation	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.770	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.24	0.000	0	0.010	Recreation	
Livestock	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Livestock	
Crops	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Crops	
Employment	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.240	Employment	
Multifunctional native broadleaf																									
Softwood timber	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Softwood timber	
Hardwood timber	1	0	0	1	1	0	0	0.000	0.160	0.000	0.030	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.990	Hardwood timber	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.140	0.000	0.00	0.000	0	0.740	Biodiversity	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.620	Carbon	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.700	Flood regulation	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.070	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.10	Recreation	
Livestock	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Livestock	
Crops	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Crops	
Employment	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.240	Employment	
Agroforestry																									
Softwood timber	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	Softwood timber	
Hardwood timber	1	0	0	1	1	0	0	0.000	0.190	0.000	0.080	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.910	Hardwood timber	
Biodiversity	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.700	Biodiversity	
Carbon	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.860	Carbon	
Flood regulation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.600	Flood regulation	
Recreation	1	0	0	1	1	0	0	0.000	0.000	0.000	0.026	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.046	Recreation	
Livestock	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.098	Livestock	
Crops	1	0	0	1	1	0	0	0.000	0.000	0.000	0.100	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.710	Crops	
Employment	1	0	0	1	1	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.290	Employment	
Intensive arable																									

Table C.r: All agent files with parameters for service production and capital sensitivity (*continued*)

	deep.peat	lessNAT	moreNAT	lessF	moreF	lessNW	moreNW	financial	manufactured	social	human	water.runoff	grassland	crop.productivity	mixed.yc	agro.yc	n.broad.consv	n.broad.yc	n.conifer.yc	nn.broad.yc	nn.conifer.yc	region	Production	Service	
Softwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Softwood timber
Hardwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Hardwood timber
Biodiversity	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.710	Biodiversity
Carbon	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.220	Carbon
Flood regulation	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.300	Flood regulation
Recreation	1	0	0	0	0	0	0	0.000	0.100	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.062	Recreation
Livestock	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Livestock
Crops	1	0	0	0	0	0	0	0.000	0.170	0.000	0.400	0	0.000	1.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.920	Crops
Employment	1	0	0	0	0	0	0	0.370	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.470	Employment
Extensive arable																									
Softwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Softwood timber
Hardwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Hardwood timber
Biodiversity	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.750	Biodiversity
Carbon	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.370	Carbon
Flood regulation	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.400	Flood regulation
Recreation	1	0	0	0	0	0	0	0.000	0.100	0.000	0.030	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.082	Recreation
Livestock	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Livestock
Crops	1	0	0	0	0	0	0	0.000	0.150	0.000	0.250	0	0.000	1.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.910	Crops
Employment	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.990	Employment
Intensive pastoral																									
Softwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Softwood timber
Hardwood timber	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Hardwood timber
Biodiversity	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.850	Biodiversity
Carbon	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.430	Carbon
Flood regulation	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	1	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.600	Flood regulation
Recreation	1	0	0	0	0	0	0	0.000	0.000	0.000	0.035	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.120	Recreation
Livestock	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	1.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.066	Livestock
Crops	1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0	0.000	0.000	0.00	0.00	0.000	0.000	0.000	0.00	0.000	0	0.000	0.000	Crops

Table C.r: All agent files with parameters for service production and capital sensitivity (*continued*)

	Production	region	nn.conifer.yc	nn.broad.yc	n.conifer.yc	n.broad.yc	n.broad.consv	agro.yc	mixed.yc	crop.productivity	grassland	water.runoff	human	social	manufactured	financial	moreNW	lessNW	moreF	lessF	moreNAT	lessNAT	deep.peat
Livestock	0.058	0	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.000	0.100	0	0.007	0.000	0.060	0.000	0	0	0	0	0	0	1
Crops	0.030	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.100	0.000	0	0.040	0.003	0.000	0.000	0	0	0	0	0	0	1
Employment	0.077	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.006	0.050	0	0.000	0.000	0.100	0.100	0	0	0	0	0	0	1
Conservation estate																							
Softwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Hardwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Biodiversity	0.770	0	0.000	0.280	0.280	0.000	0.000	0.00	0.3	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Carbon	0.680	0	0.000	0.000	0.000	0.280	0.000	0.00	0.50	0.000	0.280	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Flood regulation	0.600	0	0.000	0.000	0.000	0.000	0.000	0.00	0.50	0.000	0.290	1	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Recreation	0.160	0	0.000	0.000	0.020	0.004	0.050	0.00	0.00	0.000	0.000	0	0.050	0.000	0.000	0.000	0	0	0	0	1	1	1
Livestock	0.091	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Crops	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	1	1	1
Employment	0.049	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.290	0	0.010	0.160	0.000	0.210	0	0	0	0	1	1	1
Marginal																							
Softwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Hardwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Biodiversity	0.790	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Carbon	0.700	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Flood regulation	0.300	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Recreation	0.230	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Livestock	0.056	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Crops	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Employment	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
Waterbodies and urban areas																							
Softwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	1
Hardwood timber	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	1
Biodiversity	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	1
Carbon	0.000	0	0.000	0.000	0.000	0.000	0.000	0.00	0.00	0.000	0.000	0	0.000	0.000	0.000	0.000	0	0	0	0	0	0	1

Table C.r: All agent files with parameters for service production and capital sensitivity (*continued*)

deep.peat	1	1	1	1	1
lessNAT	0	0	0	0	0
moreNAT	0	0	0	0	0
lessF	0	0	0	0	0
moreF	0	0	0	0	0
lessNW	0	0	0	0	0
moreNW	0	0	0	0	0
financial	0.000	0.000	0.000	0.000	0.000
manufactured	0.000	0.000	0.000	0.000	0.000
social	0.000	0.000	0.000	0.000	0.000
human	0.000	0.000	0.000	0.000	0.000
water.runoff	0	0	0	0	0
grassland	0.000	0.000	0.000	0.000	0.000
crop.productivity	0.000	0.000	0.000	0.000	0.000
mixed.yc	0.00	0.00	0.00	0.00	0.00
agro.yc	0.00	0.00	0.00	0.00	0.00
n.broad.consv	0.000	0.000	0.000	0.000	0.000
n.broad.yc	0.000	0.000	0.000	0.000	0.000
n.conifer.yc	0.000	0.000	0.000	0.000	0.000
nn.broad.yc	0.00	0.00	0.00	0.00	0.00
nn.conifer.yc	0.000	0.000	0.000	0.000	0.000
region	0	0	0	0	0
Production	0.000	0.000	0.000	0.000	0.000
Flood regulation					
Recreation					
Livestock					
Crops					
Employment					
Service					

C.2 LAND USE AND WOODLAND CATEGORY RECLASSIFICATION

C.3 TIMBER PRODUCTION LOOK-UP TABLE PER AGENT

Table C.3: Timber service assigned to each agent

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SS_soil_yc_1990	1	AFT	prod.nn.conifer	timber.service	10.2292968
SS_soil_yc_1990	2	AFT	prod.nn.conifer	timber.service	17.2643736
SS_soil_yc_1990	3	AFT	prod.nn.conifer	timber.service	24.9918103
SS_soil_yc_1990	4	AFT	prod.nn.conifer	timber.service	32.7283935
SS_soil_yc_1990	5	AFT	prod.nn.conifer	timber.service	40.0470246
SS_soil_yc_1990	6	AFT	prod.nn.conifer	timber.service	50.5102174
SS_soil_yc_1990	7	AFT	prod.nn.conifer	timber.service	56.2735849
SS_soil_yc_1990	8	AFT	prod.nn.conifer	timber.service	61.3043770
SS_soil_yc_1990	9	AFT	prod.nn.conifer	timber.service	62.6039425
SS_soil_yc_1990	10	AFT	prod.nn.conifer	timber.service	66.6369038
SS_soil_yc_1990	11	AFT	prod.nn.conifer	timber.service	70.1523048
SS_soil_yc_1990	12	AFT	prod.nn.conifer	timber.service	73.2175144
SS_soil_yc_1990	13	AFT	prod.nn.conifer	timber.service	75.8938655
SS_soil_yc_1990	14	AFT	prod.nn.conifer	timber.service	78.2355456
SS_soil_yc_1990	15	AFT	prod.nn.conifer	timber.service	80.2895835
SS_soil_yc_1990	16	AFT	prod.nn.conifer	timber.service	82.0963638
SS_soil_yc_1990	17	AFT	prod.nn.conifer	timber.service	83.6903546
SS_soil_yc_1990	18	AFT	prod.nn.conifer	timber.service	85.1008805
SS_soil_yc_1990	19	AFT	prod.nn.conifer	timber.service	86.3528600
SS_soil_yc_1990	20	AFT	prod.nn.conifer	timber.service	87.4674706
SS_soil_yc_1990	21	AFT	prod.nn.conifer	timber.service	88.4627290
SS_soil_yc_1990	22	AFT	prod.nn.conifer	timber.service	89.3539890

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SS_soil_yc_1990	23	AFT	prod.nn.conifer	timber.service	90.1543631
SS_soil_yc_1990	24	AFT	prod.nn.conifer	timber.service	90.8750767
SS_soil_yc_1990	25	AFT	prod.nn.conifer	timber.service	91.5257648
SS_soil_yc_1990	26	AFT	prod.nn.conifer	timber.service	92.1147203
SS_soil_yc_1990	27	AFT	prod.nn.conifer	timber.service	92.6491006
SS_soil_yc_1990	28	AFT	prod.nn.conifer	timber.service	93.1351008
BE_soil_yc_1990	1	AFT	prod.nn.broad	timber.service	0.0638582
BE_soil_yc_1990	2	AFT	prod.nn.broad	timber.service	6.9373666
BE_soil_yc_1990	3	AFT	prod.nn.broad	timber.service	32.3800429
BE_soil_yc_1990	4	AFT	prod.nn.broad	timber.service	58.6596645
BE_soil_yc_1990	5	AFT	prod.nn.broad	timber.service	75.9450912
BE_soil_yc_1990	6	AFT	prod.nn.broad	timber.service	85.8968809
BE_soil_yc_1990	7	AFT	prod.nn.broad	timber.service	91.5024554
BE_soil_yc_1990	8	AFT	prod.nn.broad	timber.service	94.7123720
BE_soil_yc_1990	9	AFT	prod.nn.broad	timber.service	96.6040152
BE_soil_yc_1990	10	AFT	prod.nn.broad	timber.service	97.7542296
SP_soil_yc_1990	1	AFT	prod.n.conifer	timber.service	10.3599794
SP_soil_yc_1990	2	AFT	prod.n.conifer	timber.service	27.0432547
SP_soil_yc_1990	3	AFT	prod.n.conifer	timber.service	45.0503892
SP_soil_yc_1990	4	AFT	prod.n.conifer	timber.service	60.1236278
SP_soil_yc_1990	5	AFT	prod.n.conifer	timber.service	71.3839047
SP_soil_yc_1990	6	AFT	prod.n.conifer	timber.service	79.4065243
SP_soil_yc_1990	7	AFT	prod.n.conifer	timber.service	85.0357407
SP_soil_yc_1990	8	AFT	prod.n.conifer	timber.service	88.9873122
SP_soil_yc_1990	9	AFT	prod.n.conifer	timber.service	91.7836949
SP_soil_yc_1990	10	AFT	prod.n.conifer	timber.service	93.7856780

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SP_soil_yc_1990	11	AFT	prod.n.conifer	timber.service	95.2376919
SP_soil_yc_1990	12	AFT	prod.n.conifer	timber.service	96.3049174
SP_soil_yc_1990	13	AFT	prod.n.conifer	timber.service	97.0996065
SP_soil_yc_1990	14	AFT	prod.n.conifer	timber.service	97.6987792
POK_soil_yc_1990	1	AFT	prod.n.broad	timber.service	18.9888864
POK_soil_yc_1990	2	AFT	prod.n.broad	timber.service	54.4196329
POK_soil_yc_1990	3	AFT	prod.n.broad	timber.service	77.0835276
POK_soil_yc_1990	4	AFT	prod.n.broad	timber.service	88.2722572
POK_soil_yc_1990	5	AFT	prod.n.broad	timber.service	93.6873822
POK_soil_yc_1990	6	AFT	prod.n.broad	timber.service	96.4158203
POK_soil_yc_1990	7	AFT	prod.n.broad	timber.service	97.8637149
POK_soil_yc_1990	8	AFT	prod.n.broad	timber.service	98.6715548
SBI_soil_yc_1990	1	AFT	consv.native	timber.service	36.5124252
SBI_soil_yc_1990	2	AFT	consv.native	timber.service	55.9694246
SBI_soil_yc_1990	3	AFT	consv.native	timber.service	70.6822852
SBI_soil_yc_1990	4	AFT	consv.native	timber.service	80.7113212
SBI_soil_yc_1990	5	AFT	consv.native	timber.service	87.2677479
SBI_soil_yc_1990	6	AFT	consv.native	timber.service	91.5046242
SBI_soil_yc_1990	7	AFT	consv.native	timber.service	94.2513402
SBI_soil_yc_1990	8	AFT	consv.native	timber.service	96.0504301
SBI_soil_yc_1990	9	AFT	consv.native	timber.service	97.2448306
SBI_soil_yc_1990	10	AFT	consv.native	timber.service	98.0495041
SS_soil_yc_1990	1	AFT	multi.nnc	timber.service	38.0796422
SS_soil_yc_1990	2	AFT	multi.nnc	timber.service	48.3250344
SS_soil_yc_1990	3	AFT	multi.nnc	timber.service	56.9160865
SS_soil_yc_1990	4	AFT	multi.nnc	timber.service	63.9496277

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SS_soil_yc_1990	5	AFT	multi.nnc	timber.service	69.6568233
SS_soil_yc_1990	6	AFT	multi.nnc	timber.service	74.2833244
SS_soil_yc_1990	7	AFT	multi.nnc	timber.service	78.0461298
SS_soil_yc_1990	8	AFT	multi.nnc	timber.service	81.1234065
SS_soil_yc_1990	9	AFT	multi.nnc	timber.service	83.6567246
SS_soil_yc_1990	10	AFT	multi.nnc	timber.service	85.7569839
SS_soil_yc_1990	11	AFT	multi.nnc	timber.service	87.5106517
SS_soil_yc_1990	12	AFT	multi.nnc	timber.service	88.9851805
SS_soil_yc_1990	13	AFT	multi.nnc	timber.service	90.2333726
SS_soil_yc_1990	14	AFT	multi.nnc	timber.service	91.2967736
SS_soil_yc_1990	15	AFT	multi.nnc	timber.service	92.2082698
SS_soil_yc_1990	16	AFT	multi.nnc	timber.service	92.9940613
SS_soil_yc_1990	17	AFT	multi.nnc	timber.service	93.6751599
SS_soil_yc_1990	18	AFT	multi.nnc	timber.service	94.2685284
SS_soil_yc_1990	19	AFT	multi.nnc	timber.service	94.7879494
SS_soil_yc_1990	20	AFT	multi.nnc	timber.service	95.2446923
SS_soil_yc_1990	21	AFT	multi.nnc	timber.service	95.6480280
SS_soil_yc_1990	22	AFT	multi.nnc	timber.service	96.0056275
SS_soil_yc_1990	23	AFT	multi.nnc	timber.service	96.3238735
SS_soil_yc_1990	24	AFT	multi.nnc	timber.service	96.6081055
SS_soil_yc_1990	25	AFT	multi.nnc	timber.service	96.8628127
SS_soil_yc_1990	26	AFT	multi.nnc	timber.service	97.0917879
SS_soil_yc_1990	27	AFT	multi.nnc	timber.service	97.2982504
SS_soil_yc_1990	28	AFT	multi.nnc	timber.service	97.4849447
SP_soil_yc_1990	1	AFT	multi.nc	timber.service	37.0292557
SP_soil_yc_1990	2	AFT	multi.nc	timber.service	57.4208007

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SP_soil_yc_1990	3	AFT	multi.nc	timber.service	71.9227622
SP_soil_yc_1990	4	AFT	multi.nc	timber.service	81.3963736
SP_soil_yc_1990	5	AFT	multi.nc	timber.service	87.4615072
SP_soil_yc_1990	6	AFT	multi.nc	timber.service	91.3688874
SP_soil_yc_1990	7	AFT	multi.nc	timber.service	93.9286982
SP_soil_yc_1990	8	AFT	multi.nc	timber.service	95.6401811
SP_soil_yc_1990	9	AFT	multi.nc	timber.service	96.8086865
SP_soil_yc_1990	10	AFT	multi.nc	timber.service	97.6227596
SP_soil_yc_1990	11	AFT	multi.nc	timber.service	98.2007527
SP_soil_yc_1990	12	AFT	multi.nc	timber.service	98.6183816
SP_soil_yc_1990	13	AFT	multi.nc	timber.service	98.9250382
SP_soil_yc_1990	14	AFT	multi.nc	timber.service	99.1535602
BE_soil_yc_1990	1	AFT	multi.nnb	timber.service	0.9845858
BE_soil_yc_1990	2	AFT	multi.nnb	timber.service	18.7118582
BE_soil_yc_1990	3	AFT	multi.nnb	timber.service	49.2480937
BE_soil_yc_1990	4	AFT	multi.nnb	timber.service	71.5297327
BE_soil_yc_1990	5	AFT	multi.nnb	timber.service	84.1275043
BE_soil_yc_1990	6	AFT	multi.nnb	timber.service	90.8927133
BE_soil_yc_1990	7	AFT	multi.nnb	timber.service	94.5746326
BE_soil_yc_1990	8	AFT	multi.nnb	timber.service	96.6452012
BE_soil_yc_1990	9	AFT	multi.nnb	timber.service	97.8531896
BE_soil_yc_1990	10	AFT	multi.nnb	timber.service	98.5834074
SBI_soil_yc_1990	1	AFT	multi.nb	timber.service	25.6998509
SBI_soil_yc_1990	2	AFT	multi.nb	timber.service	45.7193253
SBI_soil_yc_1990	3	AFT	multi.nb	timber.service	62.6308357
SBI_soil_yc_1990	4	AFT	multi.nb	timber.service	74.9025704

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SBI_soil_yc_1990	5	AFT	multi.nb	timber.service	83.2220702
SBI_soil_yc_1990	6	AFT	multi.nb	timber.service	88.7164431
SBI_soil_yc_1990	7	AFT	multi.nb	timber.service	92.3263201
SBI_soil_yc_1990	8	AFT	multi.nb	timber.service	94.7107986
SBI_soil_yc_1990	9	AFT	multi.nb	timber.service	96.3024720
SBI_soil_yc_1990	10	AFT	multi.nb	timber.service	97.8018258
SY_soil_yc_1990	1	AFT	agroforestry	timber.service	0.3059405
SY_soil_yc_1990	2	AFT	agroforestry	timber.service	3.5615640
SY_soil_yc_1990	3	AFT	agroforestry	timber.service	13.6172032
SY_soil_yc_1990	4	AFT	agroforestry	timber.service	29.1886551
SY_soil_yc_1990	5	AFT	agroforestry	timber.service	45.7220675
SY_soil_yc_1990	6	AFT	agroforestry	timber.service	60.0397325
SY_soil_yc_1990	7	AFT	agroforestry	timber.service	71.1618980
SY_soil_yc_1990	8	AFT	agroforestry	timber.service	79.3295829
SY_soil_yc_1990	9	AFT	agroforestry	timber.service	85.1681015
SY_soil_yc_1990	10	AFT	agroforestry	timber.service	89.2981370
SY_soil_yc_1990	11	AFT	agroforestry	timber.service	92.2162382
SY_soil_yc_1990	12	AFT	agroforestry	timber.service	94.2864828
SS_soil_yc_1990	1	AFT	estate.multi	timber.service	4.7025647
SS_soil_yc_1990	2	AFT	estate.multi	timber.service	9.4868195
SS_soil_yc_1990	3	AFT	estate.multi	timber.service	15.5785404
SS_soil_yc_1990	4	AFT	estate.multi	timber.service	22.3654927
SS_soil_yc_1990	5	AFT	estate.multi	timber.service	29.3156500
SS_soil_yc_1990	6	AFT	estate.multi	timber.service	36.0577702
SS_soil_yc_1990	7	AFT	estate.multi	timber.service	42.3722530
SS_soil_yc_1990	8	AFT	estate.multi	timber.service	48.1526226

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
SS_soil_yc_1990	9	AFT	estate.multi	timber.service	53.3666435
SS_soil_yc_1990	10	AFT	estate.multi	timber.service	58.0263145
SS_soil_yc_1990	11	AFT	estate.multi	timber.service	62.1674005
SS_soil_yc_1990	12	AFT	estate.multi	timber.service	65.8364919
SS_soil_yc_1990	13	AFT	estate.multi	timber.service	69.0832991
SS_soil_yc_1990	14	AFT	estate.multi	timber.service	71.9563433
SS_soil_yc_1990	15	AFT	estate.multi	timber.service	74.5007533
SS_soil_yc_1990	16	AFT	estate.multi	timber.service	76.7573133
SS_soil_yc_1990	17	AFT	estate.multi	timber.service	78.7622290
SS_soil_yc_1990	18	AFT	estate.multi	timber.service	80.5472796
SS_soil_yc_1990	19	AFT	estate.multi	timber.service	82.1401626
SS_soil_yc_1990	20	AFT	estate.multi	timber.service	83.5649150
SS_soil_yc_1990	21	AFT	estate.multi	timber.service	84.8423485
SS_soil_yc_1990	22	AFT	estate.multi	timber.service	85.9904650
SS_soil_yc_1990	23	AFT	estate.multi	timber.service	87.0248360
SS_soil_yc_1990	24	AFT	estate.multi	timber.service	87.9589399
SS_soil_yc_1990	25	AFT	estate.multi	timber.service	88.8044575
SS_soil_yc_1990	26	AFT	estate.multi	timber.service	89.5715274
SS_soil_yc_1990	27	AFT	estate.multi	timber.service	90.2689657
SS_soil_yc_1990	28	AFT	estate.multi	timber.service	90.9044533
mixed	1		multi.mixed		17.3658615
mixed	2		multi.mixed		33.0121525
mixed	3		multi.mixed		52.8010123
mixed	4		multi.mixed		68.6686942
mixed	5		multi.mixed		78.9985303
mixed	6		multi.mixed		85.4191622

Table C.3: Timber service assigned to each agent (*continued*)

lookupVariable	lookupValue	lookupVariable2	lookupValue2	newVariable	newValue
mixed	7		multi.mixed		89.4705416
mixed	8		multi.mixed		92.1145311
mixed	9		multi.mixed		92.9146646
mixed	10		multi.mixed		94.3070194
mixed	11		multi.mixed		92.3673583
mixed	12		multi.mixed		93.4255510
mixed	13		multi.mixed		94.2857752
mixed	14		multi.mixed		94.9937019
mixed	15		multi.mixed		92.2082698
mixed	16		multi.mixed		92.9940613
mixed	17		multi.mixed		93.6751599
mixed	18		multi.mixed		94.2685284
mixed	19		multi.mixed		94.7879494
mixed	20		multi.mixed		95.2446923
mixed	21		multi.mixed		95.6480280
mixed	22		multi.mixed		96.0056275
mixed	23		multi.mixed		96.3238735
mixed	24		multi.mixed		96.6081055
mixed	25		multi.mixed		96.8628127
mixed	26		multi.mixed		97.0917879
mixed	27		multi.mixed		97.2982504
mixed	28		multi.mixed		97.4849447

C.4 FLOOD REGULATION CROP FACTOR LOOK-UP TABLE PER AGENT

C.5 POTENTIAL LAND-BASED EMPLOYMENT INDICATOR ASSIGNED TO EACH AGENT

Table C.2: The reclassification applied to the landcover and woodland datasets used

Dataset	Original Categories	Reclassification
LCM	Broadleaf woodland	Broadleaf
LCM	Coniferous woodland	Conifer
LCM	Arable and horticulture	Arable
LCM	Improved grassland	Intensive grassland
LCM	Neutral grassland; Calcareous grassland; Acid grassland; Heather grassland	Extensive grassland
LCM	Heather	Heather
LCM	Bog; Fen, marsh and swamp	Wetland
LCM	Freshwater; Saltwater	Waterbodies
LCM	Urban; Suburban	Artificial
LCM	Supralittoral rock; Supralittoral sediment; Littoral rock	Marginal
NFI	Broadleaved	Broadleaf
NFI	Conifer	Conifer
NFI	Mixed mainly broadleaved	Mixed mainly broadleaf
NFI	Mixed mainly conifer	Mixed mainly conifer
NFI	Assumed woodland	Assumed woodland
NFI	Felled; Failed; Ground preparation; Wind-blow	Felled, failed, prep
NFI	Young trees	Young trees
NFI	Shrub	Shrub
NFI	Low density	Low density
NFI	Coppice; Coppice with standards	Coppice
NFI	Agriculture land	Agriculture
NFI	Grassland	Grassland
NFI	Open water; River	Waterbodies
NFI	Urban; Powerline; Quarry; Road; Windfarm	Artificial
NFI	Bare area; Other vegetation; Cloud/shadow; Uncertain	Marginal
NWSS	Upland birchwood	Upland birchwood
NWSS	Upland mixed ashwood	Upland mixed ash
NWSS	Upland oakwood	Upland oak
NWSS	Native pinewood	Native pinewood
NWSS	Lowland mixed deciduous	Lowland mixed deciduous
NWSS	Wet woodland	Wet woodland
NWSS	Visible regeneration native	Native regeneration
NWSS	Native trees <20% canopy ER to veteran	Native low density
NWSS	Exotic trees <20% canopy ER to veteran	Non-native low density
NWSS	Juniper scrub; Blackthorn scrub; Montane willow scrub; Hawthorn scrub	Scrub
NWSS	Non-native; Scrub of exotic species; Clear fell non-native	Non-native trees/scrub
NWSS	Agriculture	Agriculture
NWSS	Improved grassland	Intensive grassland
NWSS	Acid grassland; Neutral grassland; Calcareous grassland; Bracken, Dwarf shrub heath	Extensive grassland
NWSS	Bog; Fen, marsh and swamp	Wetland
NWSS	Rivers and streams; Standing open water	Waterbodies
NWSS	Boundary/linear features	Linear features
NWSS	Built-up areas and gardens	Artificial
NWSS	Inland rock; Montane; Unidentifiable	Marginal

Table C.4: Crop factors assigned to each agent

Agent	CORINE Land Cover Class	Crop factor
Productive non-native conifer	Coniferous forest	0.90
Productive non-native broadleaf	Broadleaved forest	0.70
Productive native conifer	Coniferous forest	0.90
Productive native broadleaf	Broadleaved forest	0.70
Native woodland (conservation)	Mixed forest	0.80
Multifunctional mixed woodland	Mixed forest	0.80
Multifunctional non-native conifer	Mixed forest	0.80
Multifunctional native conifer	Mixed forest	0.80
Multifunctional non-native broadleaf	Mixed forest	0.80
Multifunctional native broadleaf	Mixed forest	0.80
Agroforestry	Agro-forestry areas	0.60
Intensive arable	Annual crops	0.30
Extensive arable	Land predominantly occupied by agriculture	0.40
Intensive pastoral	Pastures	0.50
Extensive pastoral	Pastures	0.50
Sporting estate	Moors and heathlands	0.45
Traditional multifunctional estate	Moors and heathlands	0.45
Conservation estate	Peat bogs	0.60
Marginal	Sparsely vegetated areas	0.30

Table C.5: Employment service

Agent	Full time equivalent (FTE)	Details	Source	Number of agents	Adjustment
Productive non-native conifer	9675	9675 is sum of direct employment for: forest owners, land agents, forest management, harvesting and sales, self-employment, haulage and transport, sawmilling, production of panels, production of chips and pellets	https://scotland.forestry.gov.uk/supporting/forest-industries/economic-contribution-report	6433 (all productive woodland agents)	150
Productive non-native broadleaf	9675	9676 is sum of direct employment for: forest owners, land agents, forest management, harvesting and sales, self-employment, haulage and transport, sawmilling, production of panels, production of chips and pellets	https://scotland.forestry.gov.uk/supporting/forest-industries/economic-contribution-report	6434 (all productive woodland agents)	150
Productive native conifer	9675	9677 is sum of direct employment for: forest owners, land agents, forest management, harvesting and sales, self-employment, haulage and transport, sawmilling, production of panels, production of chips and pellets	https://scotland.forestry.gov.uk/supporting/forest-industries/economic-contribution-report	6435 (all productive woodland agents)	150

Table C.5: Employment service (*continued*)

Agent	Full time equivalent (FTE)	Details	Source	Number of agents	Adjustment
Productive native broadleaf	9675	9678 is sum of direct employment for: forest owners, land agents, forest management, harvesting and sales, self-employment, haulage and transport, sawmilling, production of panels, production of chips and pellets	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	6436 (all productive woodland agents)	1.50
Native woodland (conservation)	117	Figure taken from direct employment in environmental protection and conservation	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	137	0.10
Multifunctional mixed woodland	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	2.90
Multifunctional non-native conifer	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	2.90

Table C.5: Employment service (*continued*)

Agent	Full time equivalent (FTE)	Details	Source	Number of agents	Adjustment
Multifunctional native conifer	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	2.90
Multifunctional non-native broadleaf	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	2.90
Multifunctional native broadleaf	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	2.90
Agroforestry	4838	Half 9675 (productive woodland jobs)	https://scotland.forestry.gov.uk/supporting/forestry-industries/economic-contribution-report	1670 (all multifunctional woodland agents)	5.08

Table C.5: Employment service (*continued*)

Agent	Full time equivalent (FTE)	Details	Source	Number of agents	Adjustment
Intensive arable	6660	10% of 66,600 people directly employed in agriculture in Scotland	Latest agricultural census data and https://www.nfus.org.uk/farming-facts.aspx	40840 (all agricultural agents)	2.92
Extensive arable	2330	34% of 66,600 people directly employed in agriculture in Scotland	Latest agricultural census data and https://www.nfus.org.uk/farming-facts.aspx	40840 (all agricultural agents)	6.07
Intensive pastoral	12654	19% of 66,600 people directly employed in agriculture in Scotland	Latest agricultural census data and https://www.nfus.org.uk/farming-facts.aspx	40840 (all agricultural agents)	1.95
Extensive pastoral	23976	36% of 66,600 people directly employed in agriculture in Scotland	Latest agricultural census data and https://www.nfus.org.uk/farming-facts.aspx	40840 (all agricultural agents)	0.88
Sporting estate	336	Figure given for direct employment in sporting activities	https://landcommission.gov.scot/wp-content/uploads/2019/03/Research-Review-Concentrated-Ownership-FINAL-20190320.pdf	3327	0.10
Traditional multifunctional estate	5232	Figure given for direct employment, aggregated to full Scottish Land and Estates membership size	https://landcommission.gov.scot/wp-content/uploads/2019/03/Research-Review-Concentrated-Ownership-FINAL-20190320.pdf	1125	0.47
Conservation estate	2100	Paid staff in environment and animal charities	https://sevo.org.uk/projects-campaigns/t-love-charity/sector-stats	7079	0.30
Marginal	NA	Assumed no employment	NA	NA	NA

D

Appendix D

D.1 ALL METRICS RESULTS FROM CRAFTY-SCOTLAND VISION RUNS

Table D.1: All metrics outputs for each vision

Year	Woodland Cover (%)	Total ES Diversity	Total LU Diversity	Native woodland extent (%)	Conservation extent (%)	Intensive agriculture extent (%)	Intensive timber extent (%)	Estates extent (%)	Extensive agriculture extent (%)	Vision
2020	19.02148	0.7391837	0.8320119	1.682635	10.14328	10.76287	7.947235	27.83406	38.24466	Multiple Benefits
2021	19.15765	0.7395120	0.8329834	1.682635	10.14328	10.79035	7.973468	27.85530	38.10226	Multiple Benefits
2022	19.32310	0.7398935	0.8340097	1.682635	10.14328	10.81409	8.005946	27.88777	37.94861	Multiple Benefits
2023	19.40455	0.7401949	0.8347812	1.683884	10.14453	10.83032	8.040923	27.91401	37.82994	Multiple Benefits
2024	19.54963	0.7404997	0.8357129	1.683884	10.14453	10.86031	8.070903	27.93274	37.69128	Multiple Benefits
2025	19.69345	0.7408196	0.8365157	1.686383	10.14703	10.88029	8.087142	27.95648	37.57636	Multiple Benefits
2026	19.80035	0.7411192	0.8371998	1.686383	10.14703	10.86780	8.108378	27.97771	37.47892	Multiple Benefits
2027	19.89453	0.7413858	0.8380176	1.686383	10.14703	10.89903	8.127116	27.99895	37.35900	Multiple Benefits
2028	19.98107	0.7416289	0.8387180	1.686383	10.14703	10.92151	8.148352	28.01519	37.25657	Multiple Benefits
2029	20.08034	0.7419613	0.8394873	1.688881	10.14953	10.93775	8.169588	28.04767	37.13665	Multiple Benefits
2030	20.15161	0.7422171	0.8402237	1.688881	10.14953	10.97148	8.185827	28.07265	37.02297	Multiple Benefits
2031	20.23178	0.7425006	0.8409289	1.690130	10.15078	11.00271	8.200817	28.10138	36.91305	Multiple Benefits
2032	20.31324	0.7428059	0.8416472	1.690130	10.15078	11.02145	8.222053	28.13136	36.80312	Multiple Benefits

Table D.1: All metrics outputs for each vision (*continued*)

Year	Woodland Cover (%)	Total ES Diversity	Total LU Diversity	Native woodland extent (%)	Conservation extent (%)	Intensive agriculture extent (%)	Intensive timber extent (%)	Estates extent (%)	Extensive agriculture extent (%)	Vision
2033	20.39469	0.7431181	0.8423367	1.690130	10.15078	11.03894	8.232046	28.16384	36.69194	Multiple Benefits
2034	20.46468	0.7434109	0.8430130	1.691380	10.15202	11.06642	8.249535	28.19507	36.58326	Multiple Benefits
2035	20.52195	0.7436427	0.8436407	1.691380	10.15202	11.09515	8.259528	28.22505	36.47459	Multiple Benefits
2036	20.60850	0.7439075	0.8442102	1.691380	10.15202	11.09890	8.274518	28.25003	36.38340	Multiple Benefits
2037	20.65940	0.7441230	0.8448595	1.692629	10.15327	11.12513	8.284512	28.26877	36.28221	Multiple Benefits
2038	20.72049	0.7443728	0.8455748	1.692629	10.15327	11.16136	8.293256	28.29126	36.17354	Multiple Benefits
2039	20.76885	0.7445581	0.8461804	1.693878	10.15452	11.19633	8.297003	28.31374	36.06985	Multiple Benefits
2040	20.81212	0.7447961	0.8468717	1.695127	10.15577	11.24880	8.305747	28.33997	35.95493	Multiple Benefits
2041	20.87448	0.7449955	0.8474393	1.696376	10.15702	11.28253	8.315741	28.36246	35.85250	Multiple Benefits
2042	20.92412	0.7452179	0.8479832	1.696376	10.15702	11.30751	8.321987	28.38619	35.77005	Multiple Benefits
2043	20.96866	0.7454602	0.8484964	1.696376	10.15702	11.31500	8.329482	28.40993	35.69135	Multiple Benefits
2044	21.00684	0.7456377	0.8490101	1.696376	10.15702	11.3123	8.339475	28.42492	35.60016	Multiple Benefits
2045	21.05393	0.7458480	0.8495424	1.697625	10.15827	11.37746	8.351967	28.45115	35.50523	Multiple Benefits

Table D.1: All metrics outputs for each vision (*continued*)

Year	Woodland Cover (%)	Total ES Diversity	Total LU Diversity	Native woodland extent (%)	Conservation extent (%)	Intensive agriculture extent (%)	Intensive timber extent (%)	Estates extent (%)	Extensive agriculture extent (%)	Vision
2046	21.08702	0.7460434	0.8500502	1.697625	10.15827	11.39870	8.358213	28.47114	35.42028	Multiple Benefits
2047	21.13156	0.7462403	0.8505978	1.698875	10.15952	11.43368	8.365708	28.49112	35.32660	Multiple Benefits
2048	21.18629	0.7464955	0.8511200	1.701373	10.16202	11.44742	8.371954	28.52235	35.23915	Multiple Benefits
2049	21.23465	0.7467002	0.8516943	1.702622	10.16327	11.47989	8.373203	28.54859	35.13797	Multiple Benefits
2050	21.27028	0.7468939	0.8522826	1.702622	10.16327	11.52986	8.380698	28.57107	35.03304	Multiple Benefits
2051	21.32374	0.7471431	0.8528050	1.702622	10.16327	11.53985	8.389442	28.59730	34.95309	Multiple Benefits
2052	21.35937	0.7473144	0.8532333	1.702622	10.16327	11.55984	8.394439	28.61604	34.88064	Multiple Benefits
2053	21.38864	0.7474775	0.8537164	1.702622	10.16327	11.58857	8.398186	28.63353	34.79320	Multiple Benefits
2054	21.42937	0.7476977	0.8542423	1.703871	10.16452	11.61605	8.401934	28.65851	34.70326	Multiple Benefits
2055	21.45991	0.7478645	0.8547127	1.705120	10.16577	11.65478	8.408180	28.67850	34.61707	Multiple Benefits
2056	21.48664	0.7480309	0.8551152	1.705120	10.16577	11.67477	8.414425	28.69474	34.54711	Multiple Benefits
2057	21.52609	0.7482154	0.8556331	1.706370	10.16701	11.70974	8.418173	28.71722	34.45592	Multiple Benefits
2058	21.55536	0.7483925	0.8560666	1.706370	10.16701	11.73098	8.421921	28.73596	34.38347	Multiple Benefits
2059	21.59100	0.7485929	0.8564904	1.707619	10.16826	11.75721	8.425668	28.76095	34.30602	Multiple Benefits

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