

CLIMATE CHANGE, UNCERTAINTY, AND  
CONSEQUENT RISKS: OPPORTUNITIES FOR  
FOREST MANAGEMENT ADAPTATION IN BRITAIN

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**UNIVERSITY OF TWENTE.**

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CONSEQUENT RISKS: OPPORTUNITIES FOR  
FOREST MANAGEMENT ADAPTATION IN BRITAIN

DISSERTATION

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# **Chapter 1**

## **Introduction**

„Doubt is not a pleasant condition, but certainty is absurd“

Voltaire (1694 – 1778)

## **1.1 Background context and motivation**

Climate change is uncertain, in a sense that we do not know how global climate will emerge and how society will develop. Climate change data gathered from various climate models provide different views on the future represented by diverse model outcomes, which essentially show limited knowledge or uncertainty. This inherent uncertainty also influences, among others, forest managers and planners, as they should be using the information about future states of the environment together with a limited knowledge about society's development, to make decisions about forests. This uncertainty defined as "the situation in which there is not a unique and complete understanding of the system to be managed" (Brugnach et al. 2008) will affect decisions about climate change adaptation and can be a reason for not adapting. Previous research and policy documents (Defra 2007; Swart et al. 2009; Forestry Commission Scotland 2009) have stressed that a little is known about how uncertainty related to climate change and its impacts influences decision-making. Better knowledge about how decisions are made with this uncertainty should help, for example, forest management to sustain and even increase benefits from managed forests in the future. The following sections introduce background information for this thesis, starting with the climate change overview, following with climate change adaptation and impacts, then introducing new climate change projections and ecosystem services, and last summarising knowledge gaps.

### **CLIMATE CHANGE SCIENCE**

Since 2010, when this research started, new climate change impacts and adaptation research evolved, especially with many adaptation studies focusing on national level (European Environment Agency 2012; Blennow et al. 2012; Jones et al. 2012) and regional level (Seidl et al. 2011). Other changes involved the expansion of climate change modelling from single models to model ensembles – a collection of multiple models – to provide more robust climate data and also to reduce modelling uncertainty (Murphy et al. 2004; Van der Linden & Mitchell 2009). Furthermore, the first probabilistic climate change projections (UKCP09) (Murphy et al. 2009) were released in 2009 for the United Kingdom. The UKCP09 uses multiple climate models within a Bayesian framework to estimate for the first time subjective probabilities for climate variables. These probabilities are the essential information for the calculation of risk therefore it has allowed a new type of risk assessment. Additionally, the UKCP09 provides climate data for the UK at high spatial resolution, 25km and 5km, and at high temporal resolution, daily and monthly data for seven 30-year overlapping periods.

Other recent changes in climate change science in the last couple of years was a gradual shift from the widely used emissions scenarios introduced in the Special Report on Emissions Scenarios (SRES) by (Nakicenovic et al. 2000) to Representative Concentration Pathways (RCP) explained in (Moss et al. 2010). The RCPs are based on radiative forcing. Since then, the RCPs have been used, for example, in the latest IPCC fifth assessment (AR5) report for climate modelling (IPCC 2013). The latest evidence from the climate change science in the AR5 report did not reveal any completely new knowledge or facts about climate change compared to the IPCC's fourth assessment report. However, the AR5 report offered with more confidence a better understanding of climate change from detailed studies about human influence as being the dominant reason for climate change and also provided better climate change models.

### **CLIMATE CHANGE ADAPTATION**

Many studies have addressed and investigated climate change adaptation with emphasis, for example, on its barriers and beliefs (Moser & Ekstrom 2010; Blennow et al. 2012), on different levels from national to regional (Neil Adger et al. 2005; Swart et al. 2009; Seidl et al. 2011), on ecosystem-based adaptations (Jones et al. 2012), and also on forestry application (Bolte et al. 2009; Mason et al. 2012; Millar et al. 2007). Adaptation aims to minimise potential negative impacts on the ecosystem. Climate change studies focusing on social aspects of adaptation have identified limits to adaptation, such as ethics, knowledge or uncertainty, attitudes or perceptions of risks and culture (Adger et al. 2009). From the natural science point of view on climate change adaptation, the focus should be on more accurate impact models that can reduce uncertainty expressed as a limited knowledge. However, natural scientists also recognise that uncertainty is the main challenge for adaptation (Murphy et al. 2009). To be more explicit, not knowing what the future climate will be, and with a limited knowledge about its impacts to natural ecosystems, this can make the adaptation process hard and possibly expensive. For example, lacking information about the possible extreme drought impacts on forests will make it hard to choose the relevant adaptation measures in forest management.

To address future adaptation, many strategies have been developed such as “no-regret” strategy, reversible and flexible options strategy (Hallegatte 2009), and recently a new method of dynamic adaptive policy pathways (Haasnoot et al. 2013). This study builds upon the promising method of adaptive policy pathways and proposes a new modified solution for forestry, which can help to identify future pathways and options for adaptation depending on forestry management actions and uncertainty. The novelty is in assessing key forest ecosystem services, and using high resolution spatial and temporal probabilistic climate change data to define adaptation options. This method offers a new way

to support climate change adaptation with multiple options, incorporated knowledge and stochastic uncertainty about the future climate change impacts, and also uncertainty expressed by emissions scenarios.

## **CLIMATE CHANGE IMPACTS**

Our knowledge about climate change and its impacts is rapidly increasing through advanced climate modelling and a better understanding of natural systems. At a global scale, models predict changes in climate patterns with regional differences, such as changes in surface temperature or average precipitation (IPCC 2013). The main projected trends of climate change are increased temperature, frequency and severity of extreme climate events, such as drought and floods; and increased mean annual rainfall, e.g., in the north of Europe while a decrease is predicted for the south of Europe (Alcamo et al. 2007). Under all emissions scenarios, climate projections for Europe are showing an overall increase in temperature ranging from 1 to 5.5°C by the 2080s with a higher increase in winter compared with summer (Alcamo et al. 2007). At a global scale, projections estimate an increase in temperature ranging from 0.3 to 4.8°C for 2081-2100 relative to 1986-2005 (IPCC 2013). On the other hand, the expected precipitation trend has more seasonal character and noticeable changes between regions, mostly as a response to large-scale circulations and water vapour loading (Alcamo et al. 2007). In the case of extreme events, for example, the effects of warmer summers with lower rainfall will most likely cause more heatwaves and droughts resulting in a northward shift across Europe (Beniston et al. 2007). These extreme events will most likely cause damage to ecosystems as was the case of reduced crop yields due the European heatwave in 2003 (Ciais et al. 2005). Such climatic effects will most likely have serious impacts on forest health, productivity, and also on species composition.

In the United Kingdom, the projected climate change during the 21st century is following global trends with warmer climate and seasonal spatial rainfall patterns. These projections are reinforced by the latest UKCP09 climate change projections for the UK. According to the UKCP09, the expected changes in climate conditions show an increase in mean temperature from 1.2 to 6.8°C for the 2080s under the medium (A1B) emissions scenario with specific temperatures depending on the location in the UK (Murphy et al. 2009). Predicted precipitation indicates no simple trends but large differences between locations, especially between the west and the east coast. The predictions for the 2080s under the medium emissions scenario indicate wetter winters with 33% increase for mean central estimate but drier summers with 40% decrease for central estimate (Murphy et al. 2009). More extreme weather events are predicted for the UK, for instance, a major increase in the number of heatwaves

– defined as two days with daily maximum temperature above 29°C - for the 2080s under the medium emission scenario (Jones et al. 2009; Murphy et al. 2009). These estimated changes in the future climates combined with impact models can help to quantify, for example, the reduction or increase of forest ecosystem services. For instance, combining information from the previous climate change projections UKCIP02 and the impact model for tree growth, Broadmeadow et al. (2005) found a decrease in potential tree growth for broadleaves by the 2050s, especially in southern England.

### **NEW PROBABILISTIC CLIMATE CHANGE PROJECTIONS**

To get prepared for the climate change impacts, new knowledge from climate science and modelling has been incorporated into the development of new probabilistic climate change projections in the UK (UKCP09) (Murphy et al. 2009). These projections, however, still include a high level of uncertainty related mainly to natural climate variability, an incomplete understanding of Earth System processes, and of future emissions (Murphy et al. 2009). The UKCP09 climate change projections address and quantify these uncertainties, allowing decision-makers to assess with more confidence the potential severity and magnitude of climate impacts. For the first time in the UK, the UKCP09 quantifies climate change with subjective probabilities and provides climate information at a higher spatial and temporal resolution. The subjective probabilities of climate data mean that for each climate variable a future probability of occurrence is estimated based on climate change knowledge and expert judgments. The probability is calculated from a large ensemble of the Met Office HadCM3 model and twelve international climate models used in the IPCC 4th Assessment Report. Additionally, expert judgments, such as about climate model parameters were incorporated into subjective probabilities. Furthermore, the UKCP09 offers a higher temporal resolution compared with previous climate projections (UKCIP02) consisting of seven 30-year overlapping time periods representing individual decades, starting from the 2020s (2010-2039) until 2080s (2070-2099). The spatial resolution of climate data also increased from 50km in the UKCIP02 to either 25km or 5km resolution in the UKCP09, with the latter one available from the weather generator.

### **ECOSYSTEM SERVICES**

Forests represent important ecosystems as they offer multiple goods and services, e.g. sustainable timber resource, biodiversity, and places for wellbeing. Previously, forests were seen as providers of forest functions, which de Groot (2006) defined as regulation, habitat, production, information, and carrier. However, the recent shift in terminology and understanding from functions to ecosystem goods and services has been introduced by Millennium

Ecosystem Assessment (Millennium Ecosystem Assessment 2005) and in the UK by the National Ecosystem Assessment (NEA) (UK National Ecosystem Assessment 2011). The UK NEA stresses the benefits of ecosystems to societal well-being and classifies them into four key categories: provisioning, regulating, cultural, and supporting (UK National Ecosystem Assessment 2011). Forests have been traditionally seen as sources of services such as forest production and contribution to the local economy but recently new services emerged such as carbon sequestration and recreation (Quine et al. 2011). A little is known about these new services, especially how much service they can provide now and in the future. The main drivers changing provision of forest ecosystem services in the UK will be, for example, land use, pollution, and climate change causing both positive and negative impacts (Quine et al. 2011). Hence, to support climate change adaptation in forestry, not one but multiple ecosystem services under climate change have to be assessed, as Bateman et al. (2013) concluded that assessment of multiple services should help a better decision making in environmental management and policy.

#### **KNOWLEDGE GAPS**

In the uncertainty and risk domain related to climate change, the previous limitations included mainly the lack of probabilistic climate data and their low spatial and temporal resolutions. To quantify risk with a traditional approach, the probability of a hazard along with its impacts is crucial. Only since 2009 the first probabilistic climate change projections for the UK have made it possible to undertake a new type of risk assessment, providing a hazard's subjective probability and contributing to a new understanding of climate change uncertainty. Additionally, these projections introduced a higher spatial and temporal resolution, which in combination with assessed risks can lead to more focused decision-making. The release of the probabilistic climate change projections not only brings a new way of thinking about risk but also poses new questions, such as how the results from the new risk assessment can be used and understood by decision makers.

Even in the climate change adaptation and forestry domain many limitations and knowledge gaps exist. At the national and regional scale assessments of climate change impacts addressing specific questions are lacking in contrast, for example, to global mega-assessments such as the IPCC. These mega-assessments are published on five or more year cycles, hence are mostly outdated compared with more frequent regional studies. Furthermore, practical and concrete information about climate change impacts on forests are unavailable for decision makers at the required detail, or are not communicated in suitable form. In the British conditions a lot is known about forest related hazards such as wind (Gardiner & Quine 2000), but knowledge and information is lacking with

regard to drought impacts, which are expected to become more frequent and harmful to forests in the future. Finally, for climate change adaptation to be successful, information is needed about actual adaptation measures or options while currently “potential” measures are mostly available in the literature.

Therefore, this research explores the role of uncertainty in forest planning and management with an emphasis on climate change adaptation. This study focuses on the public forest estate in Britain because these forests cover about 812,000 ha (Forestry Commission 2012b) and are managed for delivering public goods and services. Therefore, forests planners should try to maximise future forest benefits even under uncertainty and climate change. The latest climate change projections for the UK were used to assess potential impacts on the public forest estate and delivery of the key forest ecosystem services. The fundamental issues this study addresses are, first to understand how forest planners understand and manage uncertainty, and what their perception of climate change risks are. Secondly, to estimate potential drought impacts across Great Britain followed by an assessment of four key forest ecosystem services under climate change in Scotland. Finally, to explore how planners can conceptualise and decide about forests with new climate change information and with inherent uncertainty.

## **1.2 Uncertainty**

The main theoretical concept of this thesis is uncertainty. Uncertainty helps us to narrow down the main problems associated with climate change adaptation and forestry, and to identify type of uncertainty with its sources. This section explains what uncertainty is, how it has been previously understood, and how it relates to climate change and societal problems. First, I introduce the quantified uncertainty as risk and its meaning in environmental assessments; followed by the broader explanation of uncertainty and its sources with different perspectives; then I describe uncertainty within a climate change science; then place uncertainty within the societal problems; and last, elaborate how this research contributes to the new understanding of uncertainty and risk.

### **RISK**

Every decision-making always involves risk, either with consciously or unconsciously knowing about it. In the literature two diverse views or understandings of risk exist. The first one defines risk quantitatively, which is a traditional approach established by Blaikie (1994), and the other one defines risk non-quantitatively mainly with its perception introduced by Slovic (1987). From a traditional perspective risk is defined as “a function of both hazard and vulnerability” (Blaikie 1994), where hazard occurs with a certain probability and

vulnerability relates to the impact of a hazard. Probability, related to hazard, is understood as a statistical likelihood of a natural hazard derived from long records, which occurred in the past. This probability can be called a classical or frequentist probability. Additionally, as Blaikie (1994) pointed out “knowledge of physical causal mechanisms is incomplete”, even with quantified probability still imperfect knowledge about a system remains. Vulnerability described by Blaikie (1994) is understood as being able to cope with, resist, and recover from adverse impacts. Other definitions in the climate change context define risk as “a combination of the chance or probability of an event occurring, and the impact or consequence associated with that event” (Willows & Connell 2003) and by the IPCC as combining the magnitude of the impact with the probability of its occurrence (Schneider et al. 2007). These risk definitions suggest that once risk is quantified, it provides a sense of ‘certainty’. I believe this is a faulty understanding of risk because even when quantified, still uncertainty about a system and its processes remains. These shortcomings of risk need to be communicated to the end-users of risk assessment outputs.

The other literature on risk investigates risk non-quantitatively with non-technical view related to “intuitive judgments” or risk perceptions (Slovic 1987). Risk perception can be described as people’s understanding or feeling about a hazard. Many studies have explored risk perceptions in the context of climate change (Etkin & Ho 2007), climate change adaptation (Adger et al. 2009), and also in forestry (Blennow et al. 2013). The consequences of risk perception can, among others, result in a delay or no response to a potential risk, or in the policy domain particular risks can be excluded from policies if they are perceived too low. Hence, risk perception is a crucial factor influencing how decisions are made. To illustrate both understandings of quantified and non-quantified risk, imagine, for example, a situation where a forest manager has to decide about a forest in a windy area. The manager has information about risk from a wind model at his/her disposal but also has his/her own feelings, expertise, and observations about the wind in the area from the past years. The question arises which risk understanding is more dominant and will then guide his/her decision about the forest.

Large knowledge exists from these two diverse perspectives on risk, however there is still a lack of understanding how risk is placed or dealt with within the uncertainty. Essentially, risk is a quantified representation of uncertainty (van Asselt 2005), or as a metaphor, risk is a “controllable island in the sea of uncertainty” (Nowotny et al. 2001). This research study explores these two perspectives and offers new insight into thinking and understanding of risk within uncertainty, forestry and climate change domain, which to my knowledge has not been investigated before.

## UNCERTAINTY OVERVIEW

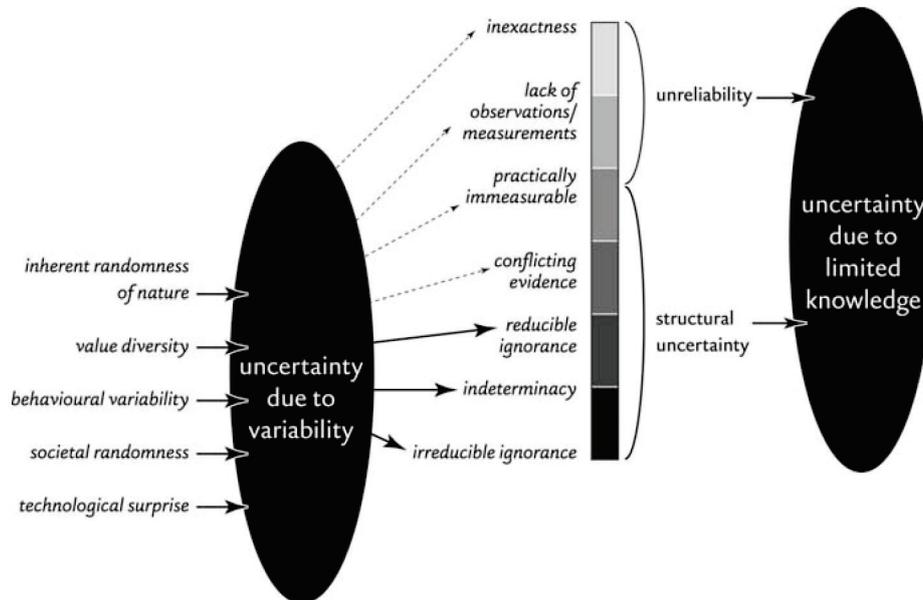
Now, our understanding expands from the 'risk island' to the 'sea of uncertainty', which covers different types of risk. The society is continuously interested in knowing more about uncertainty because of a desire to have a complete picture about a studied problem or a system. This is exaggerated by the demand from society, and policy and decision makers aiming to reduce and minimise uncertainty. Therefore, research is thought to be a source and supply of certainty (Borchers 2005) while using e.g. models to provide 'certain' knowledge about reality (van Asselt & Rotmans 2002). However, in situations when new knowledge about processes is available, e.g. from climate change models, this can potentially reveal new information which might decrease or even increase uncertainty, thus making decisions more complex (van Asselt & Rotmans 2002). Hence, the desire for reducing uncertainty can be counterproductive and can lead to more uncertainty. To better understand the complexity of uncertainty I first define, then place uncertainty within a framework, and finally explain uncertainty within the context of this research inquiry in the following sub-sections.

Uncertainty has many definitions and typologies, which vary across scientific disciplines with diverse understandings. To illustrate these diverse views on uncertainty, it is worth presenting several definitions from environmental, climate, and social sciences. Starting with an example in environmental science, uncertainty has been defined as "any departure from the unachievable ideal of complete determinism" (Walker et al. 2003). The next two definitions of uncertainty are within climate change science, one from the British perspective defining uncertainty as "a characteristic of a system or decision where the probabilities that certain states or outcomes have occurred or may occur is not precisely known" (Willows & Connell 2003). The other one is from global perspective by the IPCC defining uncertainty as "an expression of the degree to which a value (e.g. the future state of the climate system) is unknown" (IPCC 2007) highlighting the degree of unknown predicted change. In social science uncertainty has been defined as "a certain situation a person does not dispose about information which quantitatively and qualitatively is appropriate to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristics" (Zimmermann 2000). These definitions of uncertainty have their limitations, for example the definition by Willows & Connell (2003) which defines uncertainty only in a sense that the knowing of probabilities of different states results in a 'certain' knowledge, while omitting or acknowledging other uncertainties such as behavioural variability. The reasons for many uncertainty definitions among scholars are probably due to the complexity and difficulty to describe what uncertainty actually means in a coherent way.

## UNCERTAINTY TYPOLOGY AND SOURCES

No uniform or widely accepted typology of uncertainty exists. Therefore, to identify and classify different types of uncertainty, this research builds upon typologies proposed by (Walker et al. 2003; van Asselt & Rotmans 2002), especially focusing on different uncertainty sources. Two uncertainty typologies by Walker et al. (2003) and van Asselt & Rotmans (2002) differ with a dissimilar classification hierarchy of uncertainty either with three dimensions or with two sources, respectively. The three dimensions by Walker et al. (2003) consists of model, level, and nature of uncertainty describing uncertainty from different views. The nature of uncertainty represents two uncertainty sources where similarities exist with the sources as defined by van Asselt & Rotmans (2002). These typologies can help to better organize and clearly communicate uncertainties to policy and decision makers as well to scientists. Many scholars have identified and classified uncertainty types to different categories such as structural, metrical, and translational uncertainty (Rowe 1994), or to different dimensions of location, nature, and level of uncertainty (Walker et al. 2003). However, to provide more consistent typology and at higher hierarchical level, my focus has been on uncertainty sources.

The two main sources of uncertainty are variability of a system and limited knowledge, see Figure 1-1. The terminology for these two sources varies, with the variability of uncertainty previously referred to, for example, 'stochastic uncertainty', 'objective uncertainty', and 'external uncertainty'; and the limited knowledge was referred to 'subjective uncertainty', 'informative uncertainty', and 'internal uncertainty' (cf (van Asselt & Rotmans 2002) and (Koch et al. 2009)). Variability, referred in this thesis to *stochastic uncertainty*, is described as a situation when a system or a process behaves in an unpredictable way (van Asselt & Rotmans 2002) or as the inherent variability of a human or natural system (Walker et al. 2003). Limited knowledge, referred in this thesis to *epistemic uncertainty*, is described as a situation when an analyst does not have a complete understanding of a system (van Asselt & Rotmans 2002) or as the consequence of imperfect knowledge (Walker et al. 2003). To further distinguish between understandings of these two sources, new information or knowledge can reduce epistemic uncertainty but it cannot reduce stochastic uncertainty. Comparing two uncertainty sources in Figure 1-1, sub-categories of variability/stochastic uncertainty are drivers and reasons for the limited knowledge uncertainty. Essentially, without variability of the system limited knowledge about the system will be smaller. In an extreme case when we can measure and understand the whole or closed system under investigation, then limited knowledge might not exist.



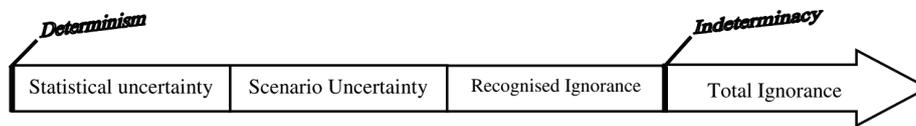
**Figure 1-1 The sources of uncertainty (source: (van Asselt & Rotmans 2002))**

The stochastic uncertainty consists of many individual sources as specified in Figure 1-1, which are: inherent randomness of nature (behaviour of natural system in non-linear manner), value diversity (variability of people's views due to their perceptions and values), behavioural variability (the variation from behavioural patterns), societal variability (chaotic societal processes at different institutional levels), and technological surprises (new technological developments and innovations) (Morgan et al. 1990; van Asselt & Rotmans 2002; Walker et al. 2003). This list is not exhaustive but it provides a guidance to identify which sources relate to stochastic uncertainty. Such uncertainties are due to the natural behaviour of studied phenomena, which are hard to measure or accurately predict such as air temperature in 2020 in the UK. Each of these individual sources addresses the specific component of system unpredictability either related to human or to natural systems. Therefore, when investigating a problem, knowing about a type of uncertainty can help to identify suitable methods and also help to clearly communicate uncertainty. For instance, addressing a problem of what tree species to plant, the main uncertainty sources that will influence the final decisions are then inherent randomness of nature, i.e. future climate, and value diversity, i.e. how stakeholders or public value different forest ecosystem services.

A system behaves unpredictably but in addition a limited knowledge or epistemic uncertainty about a system exists, which creates a second source of uncertainty. As Figure 1-1 shows, epistemic uncertainty can be described by a

degree of knowledge, starting from small uncertainty (inexactness), followed by lack of observations (missing easily obtainable data), practically immeasurable (lacking knowledge of hard to measure data), conflicting evidence (interpretation of data in different ways), reducible ignorance (processes not yet observable), indeterminacy (understanding principle laws but will never manage to understand the whole system), and up to large uncertainty (irreducible ignorance representing what cannot be known) (van Asselt & Rotmans 2002). All these types highlight that depending on the problem under investigation, from a simple problem of acquiring more measurements to a complex or a societal problem of not knowing what we do not know new relevant information can provide a better understanding and this can help to answer the problem. In some cases this might not be possible, especially when our imperfect knowledge is too large, as is the case of reducible ignorance and beyond it. This implies that the research focus should be on problems and processes where uncertainty is possible to reduce, for example through additional research or new technological advances. Scientists and decision makers should recognise that a high degree of epistemic uncertainty, as stressed above, occurs and this can actually be a reason for not finding solutions to complex problems.

As Walker et al. (2003) mentioned, uncertainty is “a grey area between well-known and what is not known” relevant to decision making. Therefore, this degree of knowledge needs an attention. The continuum of knowledge extends from unachievable determinism to total ignorance – unknown unknowns. This knowledge determines the level of uncertainty a decision maker has to consider in solving a problem situation while taking into account a limited understanding of what the future outcomes of his/her decisions are. Various degrees of knowledge indicate a level of uncertainty a decision maker will have to deal with, as depicted in Figure 1-2. The degree of uncertainty starts from the complete understanding of a situation (determinism), through statistical uncertainty (measurable deviation from the “truth” value), scenario uncertainty (indication of possible future outcomes), recognized ignorance (limited scientific knowledge about functional relationships), to not knowing what we might even not know (total ignorance) (Walker et al. 2003). In addition I believe, that this continuum of uncertainty is not only directional but also shows an increase of uncertainty the further we go. This is not recognized either by (van Asselt & Rotmans 2002) in Figure 1-1 or by (Walker et al. 2003) in the description of levels of uncertainty in Figure 1-2.



**Figure 1-2 The continuous transition of uncertainty from determinism to total ignorance (source: (Walker et al. 2003))**

A new element in the understanding of uncertainty is ambiguity, coming from decision-making science. Ambiguity is recognised as the third type or source of uncertainty relevant to this study. Ambiguity essentially means the presence of multiple frames or interpretations of a problem or a situation among stakeholders (Dewulf et al. 2005), with frames representing or interpreting reality (Brugnach et al. 2008). In the context of previous uncertainty typologies, ambiguity is similar to the value diversity previously introduced as a part of stochastic uncertainty but new understanding highlights the multiple values of decision makers. Ambiguity, as discussed by Brugnach et al. (2008), can be then seen as another source or a kind of uncertainty in addition to epistemic and stochastic uncertainties. Furthermore, ambiguity between stakeholders can on the one hand be a result of incomplete knowledge about a problem and on the other hand can be a result of completely different views of a problem due to its variability. When multiple stakeholders or decision makers try to come up with a solution to a problem, they hardly have a consensus about a problem's definition and even about a possible solution. This can be one of the reasons why many problems are not solved, such as plans for new wind farms. Ambiguity is a useful concept for describing the decision-making processes when more opinions or interpretations exist. Additionally, not only new uncertainties can emerge from new knowledge or information, but indeed another concern is how different decision or policy makers interpret and frame a decision problem using new information. These frames can potentially lead to ambiguity in the decision-making process (Dewulf et al. 2005).

All three sources of uncertainty were described above but one question remains: how do they relate and complement each other? Hence, a three-dimensional uncertainty space was proposed; see Figure 1-3, which consolidates all uncertainties by their sources into one framework. This framework is not complete and universal but provides a useful way to consolidate diverse sources of uncertainty. The uncertainty space is inspired by research in the area of water management, specifically in the NeWater project (Brugnach et al. 2009). Each axis represents one of the three uncertainty sources and consists of all uncertainty types previously described. Uncertainties in the space are not mutually exclusive with some overlaps, especially between ambiguity and stochastic uncertainty. This space also highlights that more than

one type of uncertainty can be present when evaluating either a decision problem or a situation, which two circles represent in Figure 1-3. This simple visualization of uncertainty should help any decision or policy maker to identify, compare, and communicate uncertainty types. Additionally, when a decision maker addresses a problem all uncertainties related to this problem should be found within this space.

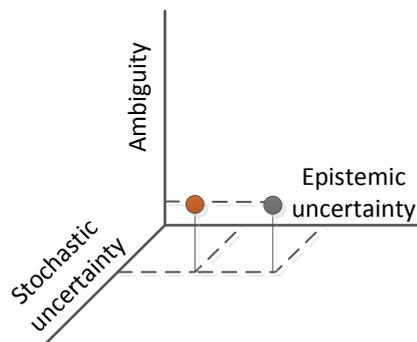


Figure 1-3 Uncertainty space

### UNCERTAINTY PERSPECTIVES

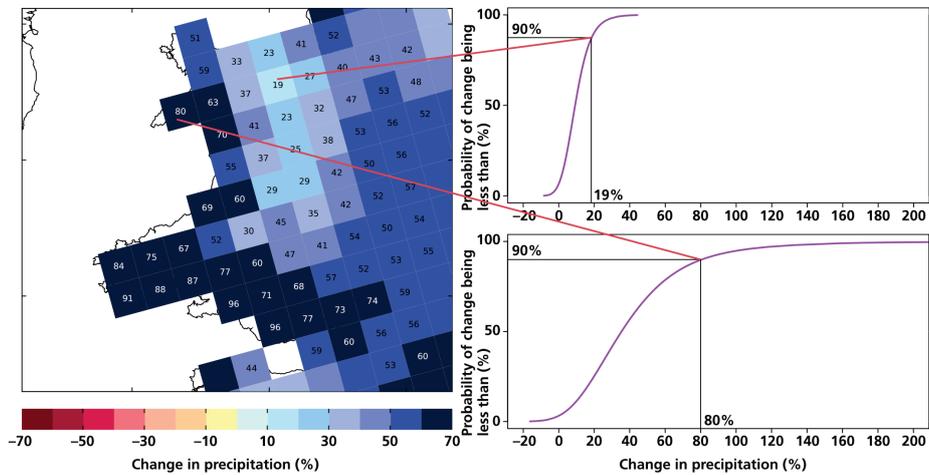
Differences between three uncertainty sources and previous typologies can be better explained by taking two uncertainty perspectives. Hence, a possible view on uncertainty is from two main perspectives: a decision-maker's perspective and a modeller's perspective (Walker et al. 2003). A decision-maker's uncertainty perspective focuses more on the value of outcomes set by the goals linked to desired objectives and priorities. On the other hand, accumulated uncertainty of model outcomes is a key for a modeller's perspective. Identifying uncertainties and their sources within two perspectives, we think that stochastic and epistemic sources relate mainly to a modeller's perspective, while in addition to those two sources ambiguity relates to a decision maker's perspective. Many definitions of uncertainty exist from a decision-maker's perspective due to its complexity, the range of diverse views, and understanding by scholars. Therefore, only definitions for two types of uncertainty that decision makers face are presented here. First, they face normative uncertainty, i.e. "an actor may be in doubt as to what goal to pursue and what actions to take in order to achieve these goals" (Newig et al. 2005). Second, they deal with informational uncertainty, i.e. "the knowledge deficits of the decision-maker" (Newig et al. 2005). Van Asselt and Rotmans (2002) call this uncertainty 'limited knowledge'. In summary, decision makers are uncertain about what they want, the information they have and need, and their beliefs and doubts across time, i.e. when and where to take actions. Therefore, their decisions are subjective because of uncertainty.

A modeller's perspective on uncertainty associates with uncertainty typology of (Walker et al. 2003). From a modeller's perspective, the main uncertainty's understanding relates to the knowledge about a complex model, or as Walker et al. (2003) describe it as "location of uncertainty". The core aspects of this type of uncertainty then relate to the identification of a system's boundaries, a model structure – either conceptual or computer, inputs to the model, data and used methods, and accumulated model's uncertainty (Walker et al. 2003). A modeller can control some of the model components such as its structure whereas some components such as input data cannot be always fully controlled, hence leaving some unknowns. Therefore, a modeller has to ensure that each type of uncertainty is assessed in the modelling exercise, offering more robust model or model outcome. Also, the identification of uncertainty's type emphasises how each part of a model contributes to the overall accumulated uncertainty. Then, the accumulated uncertainty indicates how well a model can generalise or predict a studied system, and can be used to compare different models. Finally, information about uncertainty addressed during modelling can be, or should be, communicated to end-users.

#### **CLIMATE CHANGE UNCERTAINTY**

New uncertainty understanding in climate change science with improved climate models contributed to the new probabilistic climate change projections introduced in the United Kingdom (UKCP09). Probability of future climate change outcomes in the UKCP09 projections reflects the quantification of climate change uncertainty (Murphy et al. 2009). These projections address three main types of uncertainty, which are due to the natural variability of internal and external factors like solar radiation and El Nino, incomplete knowledge about the climate system represented in climatic models, and future emissions that are dependent on many factors such as GDP and energy use. Hence, the UKCP09 projections cover both epistemic and stochastic uncertainties and incorporate them into probabilities of climate variables, but treat emissions scenarios separately. The reason for keeping emissions scenarios outside probabilities is due to the large uncertainties about the future socio-economic development caused by human behaviour (Dessai & Hulme 2004). Better handling of these three main uncertainties with new methods resulted in probabilistic climate data, with probability defined as "a relative degree to which each possible climate outcome is supported by the evidence available, taking into account our current understanding of climate science and observations" (Murphy et al. 2009). The probabilities of climate variables allow us to specify how likely each variable will be in the future. The UKCP09 probabilistic projections are based on the best achievable current knowledge about physics, chemistry, biology, observational evidence, and also using expert judgments.

The nature of UKCP09 probabilistic projections with modelling uncertainty was driven by: expert judgments on specifying model parameters and their distributions, weighted HadCM3 multiple climate model run outputs by how well they can simulate historical observations, and the use of twelve international climate models, in addition to the HadCM3 model. These allowed construction of ensemble runs with sampling across uncertainties and with combination of multi-model runs forming a basis for probabilistic projections. The probability used in the UKCP09 is called Bayesian probability and can also be termed “subjective probability” corresponding to the degree of evidence from the observations but based, among others, on expert judgments (Murphy et al. 2009). This expert judgment relates to epistemic uncertainty and ambiguity. As Dessai & Hulme (2004) specify “probabilities of climate change will remain subjective”, acknowledging the role of limited knowledge and expert judgments about climate change components. Essentially, subjective probability describes the likelihood of an event using the latest knowledge based on the information or evidence available. They are similar to a case of betting on horse racing where probabilities define chances for horses to win depending on their performance, but not having an equal probability. Probabilities in the UKCP09 are expressed either by a Probability Density Function (PDF) or by a Cumulative Distribution Function (CDF). The CDF defines a probability or a likelihood of climate change, such a 20% chance of temperature change below 1.5°C in the future. UKCP09 projections not only offer probabilities for climate variables but they are also space and time sensitive, which can help decision makers to be more confident about the future climate. Figure 1-4 shows on an example how well climate models can predict rainfall, illustrated with different probability distributions (CDFs) for two locations in the 2080s with narrower probability range in inland compared with larger range on the coast. In the UKCP09 projections, probabilities increase over time due to the current imperfect knowledge and natural variability of the climate system, caused mainly by uncertainties in climate feedback.

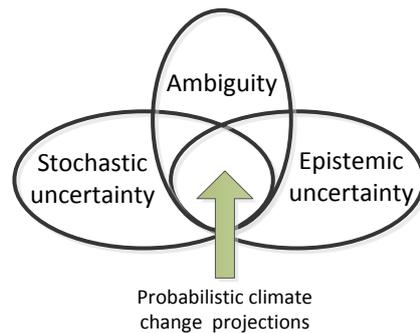


**Figure 1-4 The spatial variability of precipitation at a 90% probability level for 2080s high emissions scenario with two locations highlighting different range of uncertainty (source: (Murphy et al. 2009))**

Now the question arises, can information from climate change models help decision makers to define and deal with problems in their practice? To adapt to climate change, decision makers need to clearly define the main problem to be solved, while dealing with limited knowledge and ambiguity. In many cases a problem cannot be clearly specified, resulting in inconsistent solutions (Rittel & Webber 1973). I think that climate change adaptation is a complex or a societal problem involving many stakeholders and actors with diverse values, preferences, and judgments about a system. Climate change adaptation in forestry is an excellent example of a societal problem because forests offer multiple ecosystem services with diverse stakeholder preferences and demands. Hence, this problem is “messy” or “wicked” (Rittel & Webber 1973). A wicked problem cannot be clearly defined because of stakeholder disagreement about the problem and a limited knowledge about it (Balint et al. 2011). The solutions to wicked problems exist but instead of being true or false they can either be better or worse (Balint et al. 2011). As Allen & Gould (1986, p.22) pointed out, forest managers make new plans frequently because they lack a stopping rule, as society’s demand from forests changes and also they do not know when their plans are good. When searching for the solution to an environmental “wicked” problem, managers need to realise that no correct or best solution exists. Therefore, insufficient data and analysis are not the only reason for failing to find the best solution to a problem (Balint et al. 2011, p.209).

The novelty of this study is in bridging a gap between stochastic and epistemic uncertainty types and expanding the traditional risk assessment approach using

the probabilistic climate change projections. The advancement in climate change modelling and in probabilistic projections build upon a new understanding of stochastic uncertainty from a modeller's perspective - about the climate system's natural variability and socio-economic development. And also to build on an understanding of epistemic uncertainty and ambiguity from a decision maker's perspective - using expert judgments and imperfect knowledge. As depicted in Figure 1-5 the probabilistic projections overlay three sources of uncertainty, but not exclusively. The UKCP09 projections allow an assessment of future risks with subjective probabilities representing future hazards. In contrast, traditional risk assessment introduced by Blaikie (1994) used "frequentist" or classical probabilities based only on the past measured frequencies over a long period (Kaplan 1981). Frequentist probabilities are not applicable for future climate change as we do not have future climate measurements. Therefore, this study benefited from new subjective probabilities to calculate the future risks at different time periods and different locations across the UK while also acknowledging UKCP09 limits.



**Figure 1-5 Probabilistic climate change projections as a bridge between stochastic and epistemic uncertainty, and ambiguity**

### **1.3 Uncertainty in forestry**

In addition to climate change, uncertainty also occurs in forest planning and management, and this has been addressed in research and management for decades. Examples of uncertainties previously addressed are about when to implement silviculture measures (Johnston et al. 1967), about statistical uncertainty as errors in measurement and sampling (Holopainen et al. 2010), uncertainty about planners' attitudes toward risk (Pukkala 1998), and uncertainty about a choice (Leskinen et al. 2006; Kangas & Kangas 2004). Forest planning and management have traditionally focused on the prediction of forest properties, like timber volume and price, which have associated uncertainties such as deviations from observed values, predicted errors, and sampling errors explained by probabilistic measures (Kangas & Kangas 2004).

However, quantification of uncertainty about other ecosystem services, such as biodiversity and use of forests for recreation seemed very difficult to estimate due to their vague definitions and imprecise ability to measure them (Kangas & Kangas 2004). Variability of these services can be another reason why they are hard to estimate.

Risk, as a quantification of uncertainty, is important in decision-making because it may justify the necessity and intention to take action (Adger et al. 2009). In forestry, there are many biotic and abiotic risks affecting forest ecosystems, such as drought, fire, and wind (Gardiner & Quine 2000). However, whether or not forest planners consider these types of risks in their management plans for climate change adaptation partly depends on their individual risk perception. Previous research has concluded that risk perception is the reason for the public to take voluntary action due to climate change (O'Connor et al. 1999), and in forestry, a high risk perception has resulted in taking reduction measures (Blennow & Sallnas 2002)(cf. (Blennow et al. 2013) for a risk perception review). So although one might think that once risk has been quantified and 'certainty' has been introduced decisions will be easy, but the interpretation of risk still creates uncertainty for decision-making. For instance, if forest planners are aware of climate change uncertainty and want to actively manage it, but do not perceive the impacts of climatic hazards to be risky, then they might not adapt.

## **1.4 Research objectives and questions**

Knowledge about uncertainty and risk in the context of climate change within forest planning and management has been limited due to the previous inaccessibility of probabilistic climate data. For the first time probabilistic climate data were released in 2009 from the UKCP09 climate change projections, which allowed this study to focus on uncertainty in forest planning. Therefore, the overall objective of this study is:

*To explore climate change associated risks and uncertainties and their understanding in forest planning and management for making informed decisions about the future states of forests.*

This thesis has four objectives, which in more detail explore and investigate uncertainty. The first objective investigates forest planners understanding and management of uncertainty and their climate change risk perceptions. The second objective assesses the future drought impacts on forests in Britain. The third objective evaluates drought and climate change impacts to the key forest ecosystem services and proposes adaptation options in Scotland. The last

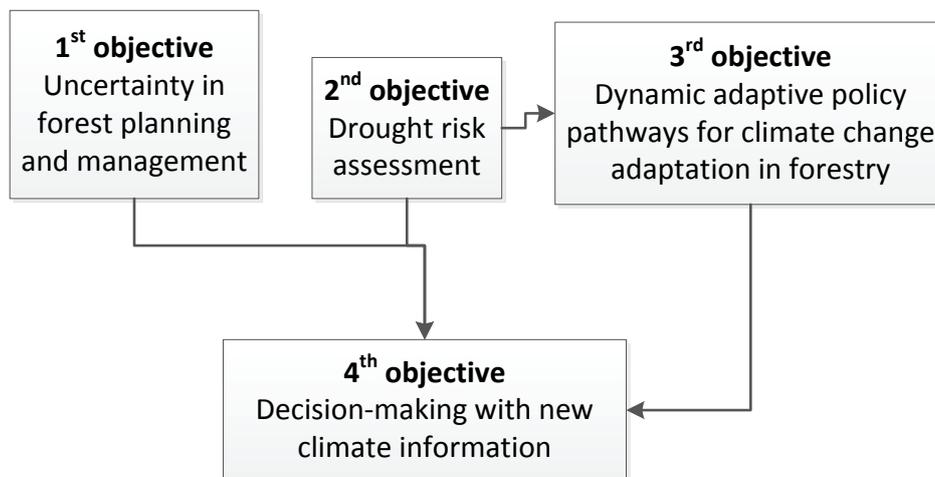
objective explores changes in forest planners' decisions with new climate change information. Each of these objectives is addressed individually with specific research questions in the text below.

The research questions categorised by the four objectives are:

- 1<sup>st</sup> objective: An Uncertainty Assessment Framework for Forest Planning Adaptation to Climate Change
  1. Which types of uncertainty do forest planners recognise in forest planning?
  2. How do forest planners prefer to manage uncertainty associated with forest models and their outcomes?
  3. How do forest planners perceive climate change risks over time?
  
- 2<sup>nd</sup> objective: A spatial and temporal drought risk assessment of three major tree species in Britain using probabilistic climate change projections
  1. How spatial and temporal climate change uncertainty affects the drought risk of three major tree species and their growth across Britain?
  
- 3<sup>rd</sup> objective: Ecosystem services application in the dynamic adaptive policy pathways to support climate change adaptation
  1. How much will drought and climate change reduce the delivery of forest ecosystem goods and services in the future under different emissions scenarios?
  2. Which forestry actions and when should forest planners choose to support climate change adaptation and sustainable forestry?
  
- 4<sup>th</sup> objective: New climate change information modifies decision makers' frames and decisions
  1. From which decade do forest planners believe climate change impacts will become serious?
  2. Will planners change their initial frames about forestry actions suitable for climate change adaptation when confronted with new climate change information?
  3. Will forest planners make different decisions about a set of forest management actions when confronted with uncertainty about emissions scenarios?

## 1.5 Research approach

An analytical framework was designed to provide a logical flow for the research and to address the research objectives and questions stated above. The framework consists of four main components, each devoted to one of the four objectives, see Figure 1-6. The following text explains in more detail how each individual objective was conducted related to one research study and a chapter.



**Figure 1-6 The analytical framework with four key objectives and their relationships**

To investigate the first objective of how forest planners understand and perceive uncertainty in forest planning within the climate change context, an uncertainty assessment framework was developed and used. This uncertainty framework consists of three sections: uncertainty recognition, uncertainty management, and climate change risks' perceptions. To explore how planners think about uncertainty described in the framework, online survey was conducted among 33 forest planners between October and November 2011. These planners were employed by the Forestry Commission<sup>1</sup> in all three devolved countries (England, Wales, and Scotland).

To assess the second objective of the potential climate change impacts on forests in Britain over the next 80 years, this study developed new drought risk assessment. Drought represents one of the hazards affecting forests in Britain.

<sup>1</sup> The Forestry Commission (FC) is the government department responsible for management of the public forest estate in the Great Britain. From April 2013 the FC is responsible for England and Scotland.

Drought is defined as a situation when evaporation is higher than precipitation. To provide information about the potential drought impacts, probabilistic climate data from the UKCP09 Weather generator (Jones et al. 2009) were used. These data were available for the climatic reference baseline (1961-1990) and for the seven future 30-year overlapping time periods from the 2020s until 2080s, and for three SRES emissions scenarios - B1, A1B, and A1FI (Nakicenovic et al. 2000). Drought risk assessment was carried out for the tree major species – Sitka spruce, Scots pine, and pedunculate oak. The assessment combined drought probabilities and tree species vulnerabilities represented by their growth potential (yield class). The forested data were obtained from the freely available national forest estate database<sup>2</sup>.

To answer the third objective which aims to provide options for climate change adaptation in forestry, we used the new approach of dynamic adaptive policy pathways modified for forestry application. This method consists of assessing critical limits as expiry dates for actions, in our case forestry management actions related to forest planning. The action's expiry dates describe a situation when an action does not meet its objective. Forest ecosystem services were used for defining expiry dates when a particular forestry action stops delivering a required amount of services. The expiry dates were represented by a relative change in forest ecosystem services between no climate change impacts and climate change impacts. The assessed services were: forest production, stand yield class, sequestered carbon, and tourism potential. The same UKCP09 climate data as in second objective were used to assess each of these forest services.

To answer the last objective of decision-making under uncertainty in the forest planning context, we explored how forest planners make decisions with information including climate change impacts on forest ecosystem services. Data were collected from workshops in three districts with 10 forest planners to explore their decision-making processes and understanding of climate change information. These districts cover different climates and have different tree species composition. One district is in the east with dry conditions and a high proportion of pine forests, the second district is in the south-west with wetter conditions and a high proportion of spruce forests, and the last district is in the south-east of Scotland with dry and wet conditions - moisture gradient – and a high proportion of spruce forests.

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<sup>2</sup> Available at: <http://www.forestry.gov.uk/datadownload>

## **1.6 Study area**

This study focuses on the public forest estate and forest planning in Britain. Forest planning and management is where decisions are made about future forests. It is guided by a set of policy objectives and forestry standards. The objectives are used to evaluate planning decisions at a tactical and an operational management level. Management plans at the operational level in Britain are Forest Design Plans (Forestry Commission 2007). Such plans address economic, environmental, and social issues relevant to forest management objectives. The relatively new environmental phenomenon of climate change has become important to forest planning practice. Therefore, forest planners should now consider the expected impacts of climate change in their decisions, but currently they lack information about climate change impacts on the main forest ecosystem services.

The core forest policy objectives are very similar in England, Wales, and Scotland. However, there are some small differences. For example, forest policies stress the social benefits of forests in England and Wales (Defra 2007; Forestry Commission Wales 2009), whereas policies in Scotland emphasise timber production (Forestry Commission Scotland 2006). Such differences might also affect a forest planner's decision-making with different objectives and their priorities. Forest planning is initiated at, and flows from, national, to tactical and to operational level (Forestry Commission 2007). A detailed planning of forest management activities is done at tactical and operational levels by forest district and design planners. These planners differentiate through different responsibilities and the management decisions they make. A district planner is responsible for decisions at district level whereas a design planner is responsible for forest design plans at operational level.

The climate across the United Kingdom (UK) varies considerably, there is a particular difference between the west and east, as is clearly visible in Figure 1-7a. In the last 100 years climate has dramatically changed. The climate trends for the UK summarised by Jenkins et al. (2008) show, for example, an increase in temperature by 0.8°C in Scotland since 1980, the recorded warmest year on record was 2006, and summers becoming drier. Another observed change is reduced precipitation during summer months up to -20% as a difference between 1961-1990 and 1971-2000. In the baseline (1961 – 1990) the drought represented by the moisture deficit shows drier south-east part of Britain, and wetter west and especially north-west part of Britain, see Figure 1-7a.

In this thesis two types of case studies were used to investigate climate change and drought impacts on forests, and to explore the responses and decision-

making processes of forests planners. The first case study encompasses the public forest estate in England, Wales, and Scotland, whereas the second study focuses on a detailed investigation of forestry only in Scotland.

### 1.6.1 British forestry

The area of forest in Britain has increased since the beginning of the 20<sup>th</sup> century from 4.7% of land cover in 1905 to 12.8% in 2012, covering almost 3.1 mil hectares (Forestry Commission 2012b). The Forestry Commission manages the public forest estate, which represents about 27% of all woodlands in Britain, see the spatial extent in Figure 1-7b. The three main conifer tree species by area in Britain are Sitka spruce (*Picea sitchensis*) (692,000 ha), Scots pine (*Pinus sylvestris*) (227,000 ha), and Lodgepole pine (*Pinus contorta*) (135,000 ha). On the other hand, broadleaves cover a smaller area with the dominant species being sessile and pedunculate oak (223,000 ha) (Forestry Commission 2012b). A disparity exists between area proportions of species among countries. The majority of conifers accounting for 68% are growing in Scotland and majority of broadleaves accounting for 66% are growing in England.

Forests provide many benefits to society from a wide range of ecosystem services, such as timber production, carbon stocks, and forest recreation. The societal, economic, and environmental values of these services depend, for example, on how accurate they can be estimated. For instance, carbon currently stored in UK woodlands was estimated to equal to 150 MtC, with England and Scotland contributing with 63 and 62 MtC, respectively (Read et al. 2009). Additionally, the value of non-market forest benefits like forest recreation was estimated to an annual contribution of £392.65 mil (Willis et al. 2003).

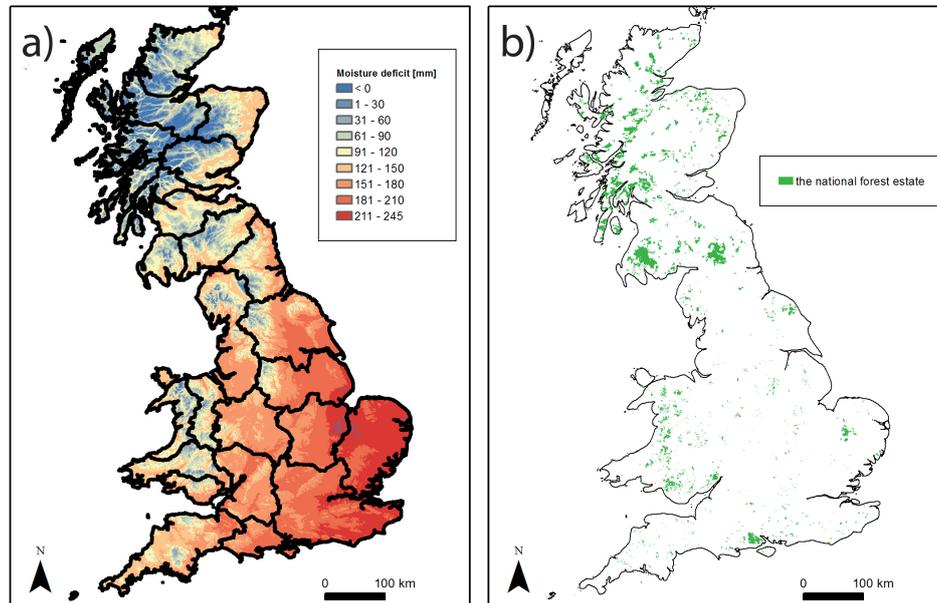


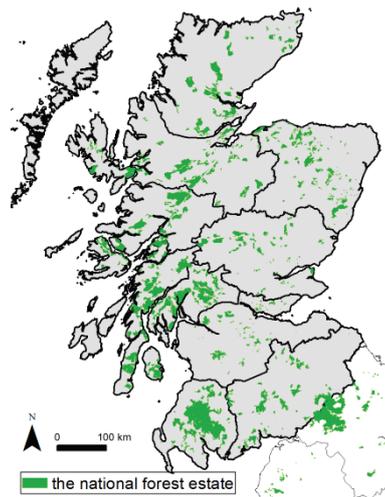
Figure 1-7 Description of a) extent of forest districts and drought conditions represented by moisture deficit in the baseline (1961-1990) and b) the spatial extent of the public forest estate managed by Forestry Commission in England and Scotland and by Natural Resources in Wales.

### 1.6.2 Scottish forestry

Detailed study of climate change impacts on forests, and a study of forest planning processes was done in Scotland. Forest covers 17.9% of the land area in Scotland (1,392,000 ha), from which the public forest estate covers 481,000 ha (Forestry Commission 2012b). The dominant conifers covering the largest area are Sitka spruce (528,000 ha) and Scots pine (140,000 ha), and the main broadleaves is Birch (78,000 ha) (*Betula*). Public forests managed by Forestry Commission Scotland is mainly in the west part of Scotland, see Figure 1-8. Forests offer many ecosystem services, such as biodiversity as a supporting service and places for well-being as cultural service, but the main traditional provisioning service in Scotland is timber production.

From the forest policy perspective, Scottish Government specifies a broad policy vision such as an increase of woodland area from 17% to 25%, an increase of carbon sequestration, and a contribution to public health benefits (Forestry Commission Scotland 2006). Other recent targets include new woodland creation of 10,000ha per year by 2020 (Scottish Government 2011). The new strategic direction for the national forest estate in Scotland defines new targets such as providing smooth timber production of at least three

millions of softwood timber annually over the next 50 years and adapting to climate change (Forestry Commission Scotland 2013). This strategic document highlights the need to tackle climate change while ensuring the future adaptation of the national estate.

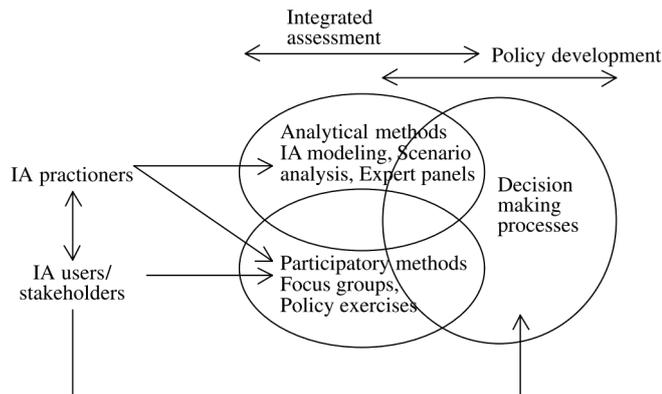


**Figure 1-8 The spatial extent of the national forest estate managed by Forestry Commission Scotland and the boundaries of ten forest districts**

## ***1.7 Science-policy interface: Integrated Assessment***

Given that this thesis covers research on risk perceptions, modelling of drought impacts, and on decision-making with climate change information, I position this work within the integrated assessment domain. The integrated assessment (IA) is an interdisciplinary approach combining knowledge from different scientific disciplines to provide additional value to the assessment of issues, such as climate change, and also supply useful information to decision makers (Rotmans 1998; Sluijs 2002). Besides that, the IA is an iterative process where scientists communicate their knowledge to decision makers, which reversely input their feedback to scientists for the scientific assessment (Rotmans 1998). The strength of the IA is a combination of qualitative and quantitative methods to answer complex problems of the human-environment system, as highlighted in the Figure 1-9. Another strength of the IA as Sluijs (2002) describes is about summarising, evaluating, interpreting, and communicating to inexperienced but intelligent decision maker. In addition, as Rotmans (1998) described, we can distinguish between two types of researchers: analytical and social scientists. The analytical scientists use analytical methods, mainly models and scenarios to assess socio-economic and environmental impacts on our environment. On the other hand, social scientists mainly use participatory approaches for policy

making. Since this study explores the interaction between science and policy – described in chapters two and five – and assesses the climate change impacts with models – in chapters three and four, it provides further indications of the integrated assessment analysis and nature of this research.



**Figure 1-9 The description of the Integrated Assessment and interactions among different domains (source: (Sluijs 2002))**

The IA covers also other disciplines, mainly technology assessment, risk analysis, and policy analysis (Rotmans 1998), still the overarching issue in these domains is how they deal with uncertainty. Furthermore, sources and types of uncertainty have to be identified and clarified when addressing a complex problem in addition to the risks that might occur, as stressed by (Rotmans 1998). In this thesis I classify uncertainty from two diverse perspectives, from a decision-makers and modeller's point of view (Walker et al. 2003; van Asselt 2000). Research on environmental management has tended to study uncertainty from a modeller's rather than a decision maker's point of view (Brown 2004; Lindner et al. 2002; Mowrer 2000; Refsgaard et al. 2007; Reckhow 1994; Walker et al. 2003; Warmink et al. 2010). However, only a small number of studies have investigated a decision maker's view on uncertainty, such as (Bijlsma et al. 2011; Gabbert et al. 2010; Gregory et al. 2006). Likewise, studies on forest planning and management have mainly addressed uncertainty from the modeller's perspective (Lindner et al. 2002; Holopainen et al. 2010) but have not addressed planners' uncertainties about for example management goals. Ignoring uncertainty about climate change in forest planning and management, i.e. beyond modelling uncertainty, can lead to a failure in forest adaptive management or inertia to climate change adaptation, and to misunderstanding of reasons for such failures.

## **1.8 Outline of the thesis**

The thesis addresses the broader topics of uncertainty, risk, climate change, and decision-making within the forest planning and management context and is organized into six chapters. From two uncertainty perspectives, Chapters 2 and 5 explore uncertainty from a decision maker's perspective whereas Chapters 3 and 4 investigate uncertainty from a modeller's perspective. The Chapter 2 explores uncertainty recognition, uncertainty management and climate change risk perceptions in the British forest planning within a 30-year time frame. The following Chapter 3 reports on the outputs from the drought risk assessment across Britain for the three major species and provides a better understanding of quantified climate change uncertainty. Chapter 4 highlights changes of the main forest ecosystem goods and services under climate change impacts over the next 80 years, and suggests how they can be incorporated within the dynamic adaptive policy pathways approach modified for forestry application. Additionally, uncertainty about climate change impacts as well as emissions scenarios is discussed in this chapter. The next Chapter 5 reports on changes in forest planners' decisions about expiry dates for forestry management actions due to new climate change information and discuss the barriers for uptake of this information in the forest planning. It also discusses the reasons of possible barriers for climate change adaptation. The final Chapter 6 reflects on the key findings, relate them to the practical climate change adaptation, and discuss their use for new climate change policies. Furthermore, it highlights new understanding of uncertainty in this study that contributes to the climate change research domain and a better forest planning and management.

## Chapter 2

### **An Uncertainty Assessment Framework for Forest Planning Adaptation to Climate Change**

Making decisions without a complete understanding or with confronting views on a problem is common in environmental management. This also implies to forest planning, where planners decide about future forests under uncertainty. This chapter investigates with an empirical study the understanding of uncertainty by forest planners. Hence, in this chapter we treat uncertainty from a decision maker's perspective rather than a modeller's perspective as introduced in Chapter 1. With this perspective we focus on forest planners' interpretation and perception of uncertainty in the context of forest planning and climate change. Additionally, this chapter addresses all three sources of uncertainty as previously introduced (see Figure 1-3).

This chapter is based on:

Petr, M., Boerboom, L., Ray, D., van der Veen, A., 2014. An uncertainty assessment framework for forest planning adaptation to climate change. *Forest Policy and Economics*, 41, pp.1–11.

## **Abstract**

Uncertainty in forest planning is a prevailing problem affecting decision-making processes, especially those relating to climate change adaptation. Limited knowledge about uncertainty has prompted this empirical investigation of forest planners' understanding of uncertainty related to its recognition, its management and risk perception. We used a comprehensive uncertainty framework to address and test these uncertainties, with data from an online survey, to identify the views of 33 forest planners through Britain. Responses were analysed using non-parametric tests. The results showed that planners have significantly different views on uncertainty among economic, social and climatic categories. Uncertainty in the climatic category was more acutely perceived than in the economic and social categories. Planners preferred to practice active uncertainty management, as the results suggest they feel more able to manage uncertainty in forest models and their outcomes. Forest planners also indicated diverse perceptions of salient risks of change over the next 30 years. The results show they may take action only to pests, drought and wind risks posing a threat to forests even though they perceived these risks potentially to be highly regulated and controlled by forestry policies. The findings provide a better understanding of uncertainty as a source of inertia to climate change adaptation in forestry, identify new research objectives and support the development of forestry policies for climate change adaptation.

## **2.1 Introduction**

In forest planning and management, uncertainty is one of the main challenges for climate change adaptation (Lindner et al. 2008; Ogden & Innes 2007; Spittlehouse & Stewart 2003; Spittlehouse 2005). This issue of uncertainty has been known across scientific disciplines but with different frames and definitions. Hence, we acknowledge a rich literature identifying and defining uncertainty in a general context (Newig et al. 2005; van Asselt & Rotmans 2002; van Asselt 2000; Walker et al. 2003; Brugnach et al. 2008) and in forest management (Holopainen et al. 2010; Kangas & Kangas 2004; Hoogstra & Schanz 2009; Pukkala 1998; Leskinen et al. 2006). In this study we adopt the following uncertainty definition “the situation in which there is not a unique and complete understanding of the system to be managed”(Brugnach et al. 2008).

Despite the many uncertainties ever present in forest management, forest plan development cycles have progressed. However, climate change brings additional uncertainty to forest planning. We believe that this uncertainty can be a reason for inertia to climate change adaptation in forestry. Climate change uncertainty is recognized both in research (Bolte et al. 2009; Ogden & Innes 2007; Spittlehouse & Stewart 2003) and in forestry policies (Defra 2007; Forestry Commission Scotland 2006; Forestry Commission Wales 2009) therefore forest planners and managers need to accept that climate change is uncertain and that they have to make decisions despite the uncertainty. However, as Ogden and Innes (2007) highlighted “uncertainties associated with climate change have discouraged forest managers from incorporating climate change into management plans”.

This is an important observation, because unless climate change adaptation is implemented in forest management plans, actual change will not take place. And for researchers, such an observation raises the question whether climate change uncertainty should be different from any other type of uncertainty in forest planning. Clearly we need to focus on a decision maker’s perspective of uncertainty (Gregory et al. 2006; Gabbert et al. 2010; Bijlsma et al. 2011), not on a modeller’s perspective (Walker et al. 2003; Warmink et al. 2010; Refsgaard et al. 2007) as introduced in Chapter 1, because forest planning and management is about decision-making. Studies on forest planning and management have mainly addressed uncertainty from the modeller’s perspective (Lindner et al. 2002; Holopainen et al. 2010) but have not addressed planners’ uncertainties about for example management goals. Ignoring uncertainty about climate change in forest planning and management, i.e. beyond modelling uncertainty, can lead to a failure in adaptive forest

management or inertia to climate change adaptation, and to a misunderstanding of the reasons for such failures.

As yet there is no literature that investigates the different types of uncertainty related to forest planning within a comprehensive uncertainty framework, although in other disciplines this has been achieved, for example, in 'technological innovations' (Meijer et al. 2006) and 'environmental modelling' (Warmink et al. 2010). As an example, (van Asselt 2000; Meijer et al. 2006) used a typology based on action, yield, political, model and monitoring, and goal uncertainty among others. Based on uncertainty understanding introduced in Chapter 1, we propose a new uncertainty analytical framework which addresses salient uncertainties from a decision-maker's perspective in forest planning and consists of uncertainty recognition, management and climate change risk perceptions.

Knowledge exists about these three components in different disciplines but this is limited in forest planning. First, uncertainty recognition studies have provided knowledge about a few types of uncertainty that appear in forest planning and management (Kangas & Kangas 2004; Holopainen et al. 2010). However, little attention has been paid, and little empirical evidence exists of the types of uncertainty that forest planners recognize in their practice. Second, the management of uncertainty has been investigated in several studies, e.g. describing uncertainty management as active or passive in policy development (Bijlsma et al. 2011), offering strategies for dealing with diverse uncertainty types in water management (Brugnach et al. 2008) or as part of adaptive forest management approaches (Bolte et al. 2009). Although several methods for uncertainty management are available, the uncertainty of climate change relating to forest planning has not been evaluated before. Finally, many studies have investigated risk perceptions in diverse disciplines such as water and environment management (O'Connor et al. 1999; McDaniels et al. 1997), mitigation of wild fire (Martin et al. 2009), or assessment of ecological risks (McDaniels & Axelrod 1995). Risk is important in decision-making because it may justify the necessity and intention to take action (Adger et al. 2009). However, whether or not forest planners consider risk in their management plans for climate change adaptation should depend on their individual risk perception. Yet there is a knowledge gap about what level of climate change risk perception forest planners have.

Our main objective is to investigate uncertainty in forest planning within a structured analytical framework. We address and answer the following three research questions: a) identify which types of uncertainty forest planners recognize in forest planning b) determine how forest planners prefer to manage

uncertainty associated with forest models and their outcomes, and c) analyse how forest planners perceive climate change risks over time. Using a survey method, the study explores views and perceptions about uncertainty and risk in forest planning in Britain. The objects of analysis are the forest planners who decide about the future states of forests. We next describe the method for data collection, the uncertainty analytical framework and the data analysis. The subsequent section presents achieved results, and finally the last section summarizes and discusses the key findings.

## **2.2 Materials and methods**

### **2.2.1 Data collection**

The target population consisted of forest planners working for the Forestry Commission (FC), responsible for the management of the 812,000 ha of the national forest estate, representing 27% of the forest area in Britain with 7% in England, 4% in Wales, and 16% in Scotland (Forestry Commission 2012b). We surveyed two groups of planners, district planners who are responsible for strategic decisions at a district level and design planners who are responsible for operational decisions at a local forest block level. In addition since forestry is a devolved function in Britain, we expected forest planners to have a diverse uncertainty understanding due to different forestry policies in the three countries of Britain, i.e. England, Scotland, and Wales, which are affected by different climatic and edaphic conditions with diverse risks. Based on the research questions we selected purposive sampling (see (Babbie 2010) p. 193) as a suitable sampling method. The sample included all 25 forest district planners with one design planner for each district, making a total sample size of 50. In each district, a district planner randomly chose one design planner. We received in total 38 responses. After filtering out incomplete responses the response rate was 72% for forest district (n=18) and 52% for forest design planners (n=12), with two forest districts without design planners and three responses from planners having both roles. For the countries, the number of planners were for England (n=12), for Wales (n=5), and for Scotland (n=16).

To collect views about uncertainty among planners we used an online survey, which has shown to be a suitable method in similar studies (Stedman et al. 2004; Bellamy & Hulme 2011). We conducted the survey using SurveyMonkey (SurveyMonkey 2011). The online survey method was a more practical solution for data analysis, it was easily accessible by the planners and it had the ability to effectively reach the survey group simultaneously. We pre-tested the survey with a pretesting protocol (Fowler 1995) using four experts from Forest Research, UK and one forest planner working at a National FC Planning Office.

The survey consisted of four sections: 1) statements about the recognition of uncertainty, 2) statements about the management of uncertainty, 3) statements about climate change risk perceptions, and 4) general questions about respondents. All statements were on a 7-point Likert scale. For uncertainty recognition and management the scaling ranged from strongly disagree to strongly agree, but specific scaling was used for risk perceptions (see details in section 2.2.2.3). Statements included a “Don’t know” option. To measure different types of uncertainty, we scrutinized statements in terms of their face and content validity. Additionally, statements were in a random order within each section to avoid leading information from the previous statements. The general section of the survey included information about job title, forest district name, length of time the respondent had worked in the current role, age category, and the highest achieved qualification. Data were collected between October and November 2011 for a period of 5 weeks, giving respondents sufficient time to fill out the survey which required about 20 minutes to complete. After the initial two weeks we sent an email reminder, which increased the response rate.

## ***2.2.2 Uncertainty analytical framework***

Our framework consisted of three key components. The first component was the recognition of different types of uncertainty with respect to social, economic and climatic (environmental) categories, the three pillars of sustainable forest management (Forestry Commission 2007). If climate change uncertainty was not recognized or it was recognized differently to other types of uncertainty in forest planning and management, we would have a first indication for the inertia about climate change adaptation. The second component was about uncertainty management. If forest planners were to take a passive rather than an active attitude towards uncertainty management, we would have a second indication for the inertia about climate change adaptation. The third component was risk perception, i.e. a quantitative representation of uncertainty (van Asselt 2005) as perceived by forest planners. In forest planning risks are valued, interpreted, avoided, or accepted. We accept the conventional definition of risk as a combination of the hazard and the impact (Blaikie 1994) but also expand our risk understanding to the non-technical risk definition of “intuitive judgments” (Slovic 1987). In the following three sections we describe these components.

### ***2.2.2.1 Recognition of uncertainty***

A generic method for uncertainty recognition was applied (Table 2-1) based on the knowledge from previous studies in other domains (van Asselt 2000; Meijer et al. 2006; Brugnach et al. 2008; Walker et al. 2003; van Asselt & Rotmans 2002). Table 2-1 presents the assessed uncertainty types along with their definitions. A set of statements addressing uncertainty in economic, social and

climatic categories is in the appendix (Table 7-1). These categories represent the main problems that forest planners deal with in practice. The economic category measures the uncertainty of monetised goods and services in forestry, e.g. timber production; the social category measures the cultural service benefits of forests to society, e.g. recreation use; and the climatic category measures the impacts of climate on the forest ecosystem, e.g. the effect of wind on forests. To provide further information to researchers and policy-makers from a decision maker's perspective, we classified types of uncertainty to three main sources and also to one dimension of uncertainty (see Chapter 1) (van Asselt & Rotmans 2002; Walker et al. 2003; Brugnach et al. 2008). In this perspective we addressed these uncertainty sources: epistemic uncertainty, stochastic uncertainty, ambiguity, and a level of uncertainty as a dimension of uncertainty (see Table 2-1). Epistemic uncertainty is due to the imperfect knowledge, stochastic uncertainty is due to natural variability, ambiguity is due to multiple views on a problem by a decision maker, and the level of uncertainty represents the degree of limited knowledge.

**Table 2-1 The definitions of the main uncertainty types present in decision-making processes**

Sources and a dimension of uncertainty	Uncertainty type	Definitions	References
Epistemic or limited knowledge	<b>Action (3)<sup>a,b,c</sup></b>	"Uncertainty with respect to the composition of the set of alternative options"	(van Asselt 2000)
	<b>Model and monitoring(2)<sup>a,c</sup></b>	"Decision makers' doubt on the validity of the model and data sets they employ"	
	<b>Yield(3)<sup>a,b,c</sup></b>	Uncertainty in a respect to associated costs and benefits of each alternative option	
Stochastic or variability of a system	<b>Goal(3)<sup>a,b,c</sup></b>	"Uncertainty or ambiguity about the preferences or goals the decision-maker aims to satisfy"	(van Asselt 2000)
	<b>Randomness of nature(3)<sup>c</sup></b>	"the chaotic and unpredictable nature of natural processes"	(Walker et al. 2003; van Asselt



(Bijlsma et al. 2011). When forest planners share or explore uncertainty in their planning practice they apply active methods, whereas when they ignore uncertainty they apply passive methods. To investigate this uncertainty we chose methods from (Bijlsma et al. 2011) relevant to forest planning and developed specific statements. Using the statements in Table 2-2 we explored how forest planners manage uncertainty about forest model characteristics and their outputs. Before providing statements to planners, a list of the five main forest models, such as Ecological Site Classification (Pyatt et al. 2001) and ForestGales (Gardiner et al. 2006) widely available to planners across Britain were given as examples in order to be clear about a forest model definition.

**Table 2-2 The management methods for dealing with model and monitoring uncertainty (methods from (Bijlsma et al. 2011))**

Methods	The sub-sequent methods	Statements
<b>Active</b>	Transparency	In my forest planning practice I talk about sources of inaccuracies in forest models with colleagues or stakeholders involved in forest planning.
<b>Active</b>	Safeguards	In my forest planning practice I work with ranges of predictions from forest models.
<b>Active</b>	Knowledge acquisition	In my forest planning practice I gather additional information to reduce inaccuracies from forest models.
<b>Active</b>	Establishing best available knowledge	In my forest planning practice I discuss contested knowledge about assumptions within forest models with colleagues or stakeholders involved in forest planning.
<b>Passive</b>	Recognized ignorance	I am aware of inaccuracies in forest models but I do not incorporate these inaccuracies into my forest planning practice.
<b>Passive</b>	Avoidance	In my forest planning practice I change objectives of forest design plans when forest models are inaccurate.

### **2.2.2.3 Climate change risk perception**

For the assessment of forest planners' risk perceptions to climate change, previously developed judgment scales, representing characteristics of risk, were utilized (McDaniels & Axelrod 1995; McDaniels et al. 1997). From the original list of 31 scales we chose 6 judgment scales. The rationale for selection was based on their relevancy to: i) forest ecosystems and forest planning practice, ii) the climate related hazards studied, iii) the measurability of change to hazards studied, and iv) providing large variability across judgment scales. Practical reasons dictated the small number of scales tested, enabling planners to fill out the survey in a short time in contrast to 2-3 hours in the original study (McDaniels & Axelrod 1995). In addition, this study included one new scale of "concern" to measure the degree of worry or fear about individual hazards,

since it was considered an important factor for taking action (Raaijmakers et al. 2008). The original statements of (McDaniels & Axelrod 1995) were re-worded to better relate to forestry planning practice, the assessment of climate change risk perception, and to address change over time while considering the impacts of each hazard. Planners were asked to assess risk over a time frame of 30 years because this time period relates to the medium-term climate change impacts and is similar to the mid-rotation length of managed forest stands in Britain. In order to assess risk perception based on our risk definition, all statements included the words of “the impacts” and the hazards. Table 2-3 summarizes judgment scales and shows statements with the corresponding Likert scaling. The hazards under investigation were drought, fire, frost, pests, water-logging and wind because they represent the major hazards already affecting forests in Britain (Read et al. 2009).

**Table 2-3 The judgment scales with statements used in the survey for measuring climate change risk perceptions**

Judgment scale	Statements <sup>b</sup>	Scaling <sup>c</sup> (7 point Likert scale)
<b>Ability of nature to adapt<sup>d</sup></b>	...how will the forests natural adaptive capacity to the impacts of these hazards change?	1 - strongly decrease to 7 - strongly increase
<b>Concern</b>	...how will your concern about the impacts of these hazards change?	1 - strongly decrease to 7 - strongly increase
<b>Ability to regulate</b>	...how much more or less will Forestry Commission policies which regulate the impacts on forests for these hazards change?	1 – much more to 7 – much less
<b>Controllability<sup>d</sup></b>	...how will forest design planning ability to control the impacts on forests for these hazards change?	1 - strongly decrease to 7 - strongly increase
<b>Frequency<sup>a</sup></b>	...how will the frequency of impacts on forests from these hazards change?	1 - strongly decrease to 7 - strongly increase
<b>Scope</b>	...how will the extent of the forested area affected by these hazards change?	1 - strongly decrease to 7 - strongly increase
<b>Predictability<sup>d</sup></b>	...how well can the impacts of these hazards be predicted?	1 – not at all to 7 – very well

<sup>a</sup> – originally this scale was called “Duration” in (McDaniels & Axelrod 1995) but for forestry and studied hazards “Frequency” is more appropriate.

<sup>b</sup> – In the survey all statements started with “*In the next 30 years in your forest district*”

<sup>c</sup> – “Don’t know” was the 8<sup>th</sup> option in the survey.

<sup>d</sup> – Judgment scales with reversed scaling.

### 2.2.3 Data analysis

In the analytical framework we assessed uncertainty through the different constructs (e.g. active uncertainty management) related to specific statements. We ensured that each construct was unidimensional and reliable. The measure of a construct was highly unreliable if based only on one statement because the level of random error the statement explains was unknown (Zeller & Carmines 1980). However, a composite measure consisting of statements provided a more reliable representation of a construct, which we assessed with Cronbach's alpha. First, to ensure that each composite measure was unidimensional, i.e. representing only one construct, we used a principal component analysis (PCA) with an unrotated matrix. The PCA shows the highest explanatory variance of the 1<sup>st</sup> factor - representing the composite measure (Hunter & Rinner 2004; Zeller & Carmines 1980). For composite measures we used only representative statements with high factor loadings (ideally > 0.7 but also > 0.6 were considered for further analysis), because of the small sample size (Field 2009). In addition, the statements needed to meet the constraint of inter-item-correlation between 0.3 and 0.9, to avoid problems of collinearity (Field 2009). Second, for the reliability and consistency of composite measures consisting of several statements, Cronbach's alpha was used (Field 2009; Zeller & Carmines 1980). The acceptable Cronbach's alpha value for measures should be above 0.6 (O'Connor et al. 1999) or 0.7 (Field 2009) and values  $\geq 0.7$  were used in our analysis. For the statistical analysis all responses from planners were summed for statements representing a single composite measure e.g. uncertainty in the economic category. For example, the economic category consists of three statements thus the range of values was from 3 to 21, with low values representing certainty whereas high values indicating uncertainty about economic issues, and values around 14 representing a neutral perspective.

Using non-parametric tests we tested the differences in the views on uncertainty for the whole sample of planners then between the two types of planners - district and design, and finally we tested for differences among all planners in each of the three devolved countries of Britain (England, Wales, and Scotland). We used these tests because of the small sample size and data in some cases did not meet the assumption of normality (Field 2009). For the assessment of differences between two independent groups of district and design planners, the Mann-Whitney test was used which ranks the summed response data. For the assessment of differences among all planners and three independent groups of planners within three countries, the Kruskal-Wallis test was used (Gibbons 1993; Field 2009). For all composite measures we stated the null hypothesis ( $H_0$ ): 'there is no difference in uncertainty perspectives between planners or among countries'. And the alternative hypothesis ( $H_1$ ) tested: 'there is a

difference in perspectives on uncertainty, first between types of planners and secondly among all planners within three countries'. Finally, we used the Shapiro-Wilks test for normality testing of the composite measures (Field 2009), which for some measures confirmed a non-normal distribution. Responses from four planners were excluded from the statistical analysis of the risk perception due to the inconsistency of their answers, which included a majority of 'Don't know' responses. We used the R 2.13.1 statistical program (R Development Core Team 2011) with the statistical package "psych"(Revelle 2011) for the data analysis, and the "ggplot2" package (Wickham 2009) for the visualization.

## 2.3 Results

### 2.3.1 Recognition of uncertainty

The composite measures used for the recognition of uncertainty which met the criteria of unidimensionality and acceptable internal consistency are shown in Table 2-4. Only a small number of statements from the total number met these criteria, except for the randomness of nature measure which includes all of them. The Cronbach's alpha values  $\geq 0.7$  indicate acceptable internal consistency of used statements.

**Table 2-4 Measures representing different types of uncertainty, with number of used statements and Cronbach's alpha representing internal consistency**

<b>Measures</b>	<b>Number of selected statements<sup>a</sup></b>	<b>Cronbach's alpha</b>
<b>Uncertainty types:</b> Randomness of nature	3 (3)	0.75
<b>Category:</b> Economic	3 (8)	0.74
<b>Category:</b> Social	5 (7)	0.78
<b>Category:</b> Climatic	4 (10)	0.73
<b>Sources of uncertainty:</b> Epistemic	5 (8)	0.70
<b>Sources of uncertainty:</b> Stochastic	4 (10)	0.73

<sup>a</sup>() – number of all statements

Classification of statements into measures is in appendix (Table 7-2)

Table 2-5 shows results that indicate a very significant difference in uncertainty recognition among economic, social, and climatic categories for all planners  $H(2)=22.2$ ,  $p < .001$ , with their median values 4, 2, 5, respectively. This suggests that planners understood uncertainty for each category differently, with the climatic category being more uncertain and the social category being less uncertain.

**Table 2-5 Comparison of responses for uncertainty recognition among economic, social, and climatic categories for all forest planners**

<b>Measures for categories</b>	<b>All forest planners [median value]<sup>a,b</sup></b>
Economic	4 (3,6)***
Social	2 (2,4) ***
Climatic	5 (3,6) ***

<sup>a</sup> Seven-point scale: 1 = strongly recognize certainty, 7 = strongly recognize uncertainty

<sup>b</sup> - ( ): values represent 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses

Level of significance: \*  $p < 0.5$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

Uncertainty recognition by forest design and district planners was mostly the same (Table 2-6). The only significant difference between their uncertainty recognition was within the social category. For this category we rejected the  $H_0$  and accepted  $H_1$  saying that there is a significant difference between design and district planners in their uncertainty recognition for social issues related to forest recreation,  $U=47$ ,  $p < 0.01$ . In addition, the median values for design (2) and district (3) planners indicated a lower recognition of uncertainty for the social category. The 25<sup>th</sup> and 75<sup>th</sup> percentiles for design (2, 2) and for district planners (2, 5) for the social category suggested a higher level of uncertainty agreement for design, but a lower level for district planners. For other measures the null hypotheses were not rejected suggesting no difference between planners' uncertainty recognition. Higher uncertainty recognition occurred only for the randomness of nature and climatic category.

**Table 2-6 Differences in recognition of uncertainty between design and district planners**

	<b>Uncertainty type<sup>a, b</sup></b>	<b>Categories for uncertainty<sup>a, b</sup></b>			<b>Sources of uncertainty<sup>a, b</sup></b>	
	<b>Randomness of nature</b>	<b>Economic</b>	<b>Social</b>	<b>Climatic</b>	<b>Epistemic</b>	<b>Stochastic</b>
<b>Design planners</b>	5 (3,6)	4 (3,5.75)	2** (2,2)	5 (4,6)	3 (2,5)	3 (2,5)
<b>District planners</b>	5 (3,6)	4 (3,6)	3** (2,5)	5 (4,6)	3 (2,5)	3 (2,6)

<sup>a</sup> Seven-point scale: 1 = strongly recognize certainty, 7 = strongly recognize uncertainty

<sup>b</sup> - ( ): values represent 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses

Level of significance: \*  $p < 0.5$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

The results did not reveal significant differences among countries in the planners' recognition of uncertainty (Table 2-7), thus we could not reject the  $H_0$ . The results indicate a higher recognition of uncertainty for randomness of nature and climatic category and greater certainty about the social category, as well as epistemic and stochastic uncertainty.

**Table 2-7 Differences in recognition of uncertainty for forest planners among England, Wales, and Scotland**

	Uncertainty type <sup>a, b</sup>	Categories for uncertainty <sup>a, b</sup>			Sources of uncertainty <sup>a, b</sup>	
		Randomness of nature	Economic	Social	Climatic	Epistemic
<b>England</b>	4 (2,5)	5 (4,6)	3 (2,5)	4.5 (2,6)	4 (3,6)	5 (3,6)
<b>Wales</b>	5 (4,6)	3 (3,4.5)	2 (2,3)	5 (4.75,6)	3 (2,5)	3 (1,6)
<b>Scotland</b>	5 (4,6)	4 (3,6)	2 (2,4)	5 (4,6)	3 (2,5)	3 (2,5)

<sup>a</sup> Seven-point scale: 1 = strongly recognize certainty, 7 = strongly recognize uncertainty

<sup>b</sup> - ( ): values represent 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses

Level of significance: \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

From a statistical perspective, it was unreliable to combine the majority of statements into composite measures of uncertainty due to the high variability of uncertainty among categories and the low consistency of measures indicated by Cronbach's alpha. Therefore, the responses for the five highest and the five lowest median values representing uncertainty recognition for specific uncertainty types are shown in

Table 2-8. The highest uncertainty recognition occurred for the economic (<sup>a</sup>) and climatic categories (<sup>c</sup>), contrary to less uncertainty or greater certainty related to social issues (<sup>b</sup>).

**Table 2-8 The responses from all planners showing the statements with the five highest and the five lowest median values**

Rank	Statements	Median response values <sup>d,e</sup>	Type of uncertainty
1 <sup>st</sup>	The measured standing timber volume and harvested volume is not the same.	6 (5,7)	statistical <sup>a</sup>
2 <sup>nd</sup>	Soil moisture variability strongly affects my forest design planning.	6 (5,6)	Randomness of nature <sup>c</sup>
3 <sup>rd</sup>	In my planning practice I consider different future timber demands.	6 (5,6)	scenario <sup>a</sup>
4 <sup>th</sup>	I know the full cost for a coupe rotation in advance. <sup>r</sup>	6 (4,6)	yield <sup>a</sup>
5 <sup>th</sup>	Wind variability strongly affects my forest design planning.	6 (4,6)	Randomness of nature <sup>c</sup>
23 <sup>rd</sup>	Among stakeholders involved in forest planning in my district, there is no consensus about how forests are used for recreation.	2 (2,4)	Multiple knowledge frames <sup>b</sup>
24 <sup>th</sup>	I know what the benefits are of forest adaptation measures to extreme weather events. <sup>r</sup>	2 (2,3)	yield <sup>c</sup>
25 <sup>th</sup>	It is difficult to choose forest management options suitable for recreation use.	2 (2,3)	action <sup>b</sup>
26 <sup>th</sup>	I am aware of different objectives that local key stakeholders have for the forests. <sup>r</sup>	2 (2,2)	goal <sup>b</sup>
27 <sup>th</sup>	I know the effects of forest management practices on recreational use. <sup>r</sup>	2 (1,2)	yield <sup>b</sup>

Category: <sup>a</sup> – economic, <sup>b</sup> – social, <sup>c</sup> – climatic

<sup>d</sup> Seven-point scale: 1 = strongly recognize certainty, 7 = strongly recognize uncertainty

<sup>e</sup> - ( ): values represent 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses

<sup>r</sup> - a statement with a reversed scale

### 2.3.2 Management of uncertainty

The statements for active uncertainty management provided a reliable measure for model and monitoring uncertainty, but passive statements did not. The measure of active management based on four statements (see Table 2-1) had a very high internal consistency (Cronbach's alpha = 0.89). The results in Table 2-9 show no significant difference in active management among forest planners

or across the three countries, hence we could not reject the null hypotheses. All planners indicated a higher active management of uncertainty with median values from 5 to 6 meaning that they “slightly agree” or “agree” with active methods. The variability of responses, represented by 25<sup>th</sup> and 75<sup>th</sup> percentiles, was small with values close to the medians except for planners in England, where results show a wider range of planners’ opinions from disagreement to agreement about active uncertainty management (Table 2-9).

For the passive uncertainty management, results for the two individual statements suggest that forest planners were either not passive or not sure about the passive management (Table 2-9). Planners mostly disagreed with a recognized ignorance statement suggesting an active management method. Only in England did planners indicate slight agreement for recognized ignorance. The results for an avoidance management method showed overall neutrality and also a diversity in opinions among planners and among countries. Design planners appeared to be slightly more passive, and district planners were slightly less passive about uncertainty management. Results among countries showed that planners in Wales favoured slightly more passive management, with more neutral management in Scotland, and more active management in England. In summary, the results suggest that planners are inclined to pursue active uncertainty management of forest models and their outputs and they have no strong tendency to passive management.

**Table 2-9 Differences in active and passive management of model and monitoring uncertainty by planners and by countries, with composite measure for active management.**

<b>Active/passive management methods</b>	<b>Design planners<sup>a,b</sup></b>	<b>District planners<sup>a,b</sup></b>	<b>England<sup>a,b</sup></b>	<b>Wales<sup>a,b</sup></b>	<b>Scotland<sup>a,b</sup></b>
<b>Active:</b> composite measure	5.5 (4,6)	5.5 (5,6)	5 (2,6)	6 (5,7)	5 (4,6)
<b>Passive:</b> Recognized ignorance (statement)	4 (2,4)	3 (3,4)	4 (4,5)	2 (1,3)	3 (2.5,4)
<b>Passive:</b> Avoidance (statement)	4 (4,5.5)	4 (2,5)	4 (2,4)	4 (4,6)	4 (3,5)

<sup>a</sup> Seven-point scale: 1 = strongly disagree, 7 = strongly agree

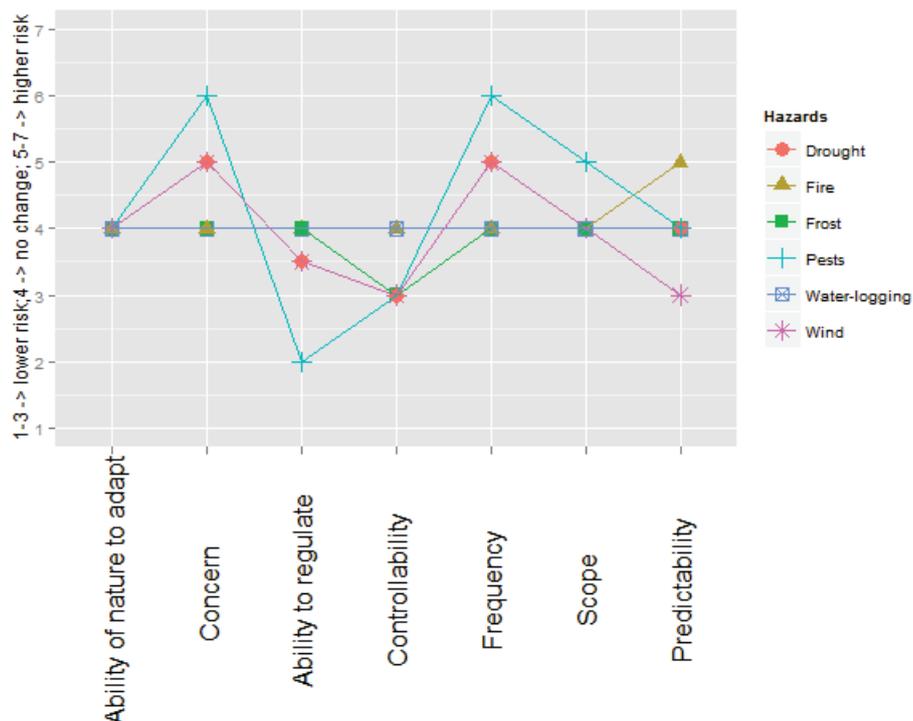
<sup>b</sup> - (): values represent 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses

Level of significance: \*  $p < 0.5$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

### 2.3.3 Climate change risk perception

Forest planners’ climate change risk perceptions measured as a change from the current situation over the next 30 years differ depending on the judgment

scale used (see Table 2-3) and the risks assessed. Our results in Figure 2-1 show this variability, with partial overlay of symbols representing individual risks. Higher risk perceptions were for “concern” and “frequency” judgment scales, very high values for pests (6, 6), and high values for drought (5, 5) and wind (5, 5) hazards. On the other hand, lower risk perceptions were for the same hazards but on the “ability to regulate” and “controllability” judgment scales. This is a surprising finding - that planners perceive the same hazards on the one hand with high concern and thus higher risk but, on the other hand, with a high level of regulation through forestry policies and thus lower risk. Hence, we decided to investigate this further and show results only for drought, pests and wind which planners perceived of higher risk.



**Figure 2-1 Hazards profile based on median values showing changes in risk perceptions over the next 30 years for the judgment scales, responses from 33 forest planners**

No significant differences in climate change risk perceptions were seen between design and district planners (Table 2-10). This means that the planners’ decision-making at different management levels does not affect their risk perception. The results also show a high consistency in the planners’ risk perceptions, mostly with a small deviation from the median, measured by 25<sup>th</sup> and 75<sup>th</sup> percentiles. Only for pests and the “ability of nature to adapt” scale did

risk perceptions range from lower to higher risk, suggesting planners were not sure how forest management can adapt to pest impacts.

**Table 2-10 Changes in climate change risk perception from the current situation over the next 30 years for design and district forest planners**

Hazards	Judgment scales <sup>a</sup>							
	Ability of nature to adapt	Concern	Ability to regulate	Controllability	Frequency	Scope	Predictability	
<b>Drought</b>	Design planners	5 (4,5)	5 (4,6)	3 (2,4)	4 (3,5)	5 (4,6)	4 (3,5)	3.5 (3,4,75)
	District planners	4 (3,5)	5 (4,5)	3.5 (3,4)	3 (3,4)	5 (4,5)	4 (4,5)	4 (3,5)
<b>Pests</b>	Design planners	3 (2,6)	6 (5,6)	3 (2,4,5)	3 (2,4)	6 (5,5,6)	5 (4,6)	3.5 (3,4)
	District planners	6 (3,6)	7 (5,5,7)	2 (1,3)	3 (2,4)	6 (5,7)	5 (3,75,6,25)	5 (3,6)
<b>Wind</b>	Design planners	3 (3,5)	5 (4,5)	3.5 (3,4)	3 (3,3)	5 (4,5,5,5)	4 (4,5)	3 (3,4)
	District planners	4 (4,5)	5 (4,75,6)	3 (3,4)	3 (2,75,3,25)	5 (5,6)	4 (4,5)	3 (3,5)

<sup>a</sup> *Seven-point scale: 1 to 3 = lower risk, 4 = no change, 5 - 7 = higher risk*  
*- ( ): indication of 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses to a particular judgment scale*

A significant difference in the forest planners' risk perception occurred among England, Wales, and Scotland on the "concern" scale for drought (Table 2-11). The  $H_0$  was rejected and  $H_1$  accepted suggesting significant differences in the planners' drought risk perception across the three countries,  $H(2)$ ,  $p < .05$ , with the median values for England (5 – higher risk), Wales (5 – higher risk) and Scotland (4 – no change). For this scale results showed a higher consistency of drought risk perception for England and Wales (5 to 6) and a lower consistency for Scotland (3 to 5), measured with the 25<sup>th</sup> and 75<sup>th</sup> percentiles. It suggests that for climatic conditions related to drought, with England being warmer and drier, this might influence the planners' perceptions about the future drought risk. The consistency of risk perception, for most scales, is high with small deviations from the median values. However, higher deviations greater or equal to 3 points, suggesting a low degree of agreement among planners, occurred for pests in Scotland and Wales on the "ability of nature to adapt", "controllability", "scope" and "predictability" scales.

**Table 2-11 Changes in climate change risk perception from the current situation over the next 30 years for forest planners across England, Wales, and Scotland**

Hazards	Judgment scales <sup>a</sup>							
	Ability of nature to adapt	Concern	Ability to regulate	Control-ability	Frequency	Scope	Predictability	
Drought	England	3.5 (3.75,5.25)	5* (5,6)	3 (2,4.25)	3 (3,4)	5 (5,6.25)	4 (4,5)	4.5 (3,6)
	Wales	4.5 (3.75,5)	5* (5,5)	4 (3,4)	3 (3,4)	5 (4.75,5)	4 (4,5)	3 (3,4)
	Scotland	4 (4,5)	4* (3,5)	3 (3,4)	3.5 (3,4)	4 (3.25,5)	4 (3,5)	4 (3,4)
Pests	England	3 (3,5)	5.5 (5,6.25)	2.5 (2,3)	2.5 (2,3)	5.5 (5,6.25)	4.5 (3.75,6)	5 (4,25,6)
	Wales	4.5 (3,6.25)	7 (5,7)	2 (1.5,3.5)	3 (2,3)	5.5 (5,6.25)	4 (4,5)	3 (3,6)
	Scotland	6 (3,6)	6.5 (6,7)	2 (2,3.25)	3.5 (2,5)	6 (6,7)	6 (4,7)	4 (3,5)
Wind	England	4 (3.75,5)	4 (4,5)	4 (3.25, 4)	3 (3,4)	5 (4.5, 5.5)	4 (4,5)	3 (3,6)
	Wales	4 (4,4.25)	5 (4,5)	3 (2.5,4)	3 (2,3)	5 (4.75, 5.25)	4 (4,4)	3 (3,3.5)
	Scotland	3.5 (3,5)	5 (5,6)	3 (3,4)	3 (3,3)	5 (5,6)	5 (3,5)	3 (3,4)

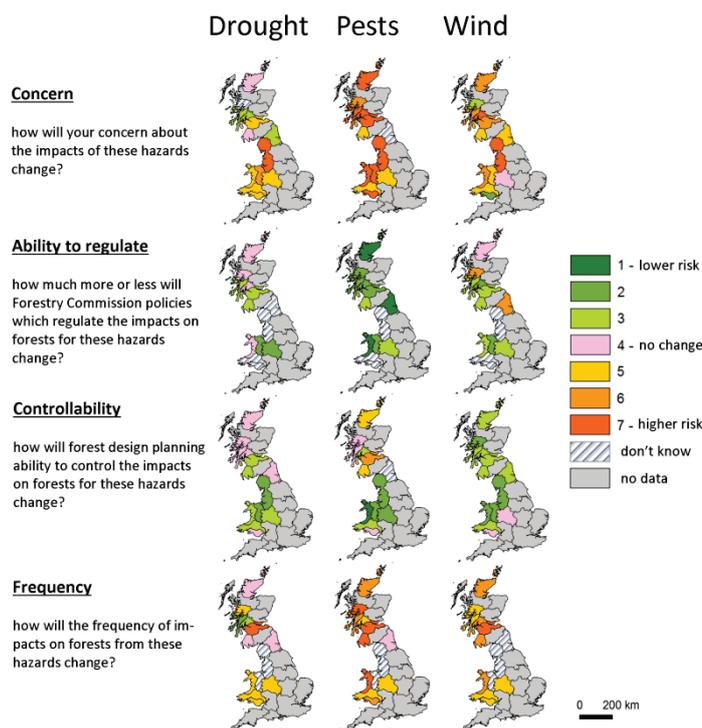
<sup>a</sup> Seven-point scale: 1 to 3 = lower risk, 4 = no change, 5 - 7 = higher risk

\* p<0.5; \*\* p<0.01; \*\*\* p<0.001

- ( ): indication of 25<sup>th</sup> and 75<sup>th</sup> percentiles for responses to a particular judgment scale

For the selected judgment scales we show spatially the district planners' risk perceptions of drought, pests and wind (Figure 2-2). In the visualization we

excluded responses from planners who did not want to be identified. The maps show a high perception of risks on the “concern” scale for all hazards, very high for pests, in the western part of Britain. Higher risk perceptions for all hazards on the “frequency” scale are in Scotland and Wales, with a rather low response rate in England. Only in two districts in south-west Scotland did planners indicate a lower drought risk on both the “concern” and “frequency” scales. On the “ability to regulate” and the “controllability” scales planners have a lower risk perception (Figure 2-2). On the “ability to regulate” scale planners perceived pest risk as very high, especially in Scotland, and no clear indication of lower or higher drought or wind risk in England and Wales. This means that planners think that regulation through forestry policies will help to reduce the impact of pests in the next 30 years in Scotland. On the “controllability” scale, planners perceived lower wind risk across Britain and for drought and pests lower risk in England and Wales but with no change or slightly higher risk for pest control in Scotland. These findings suggest that in each forest district, planners might manage risks differently.



**Figure 2-2 Spatial differences in district planners' risk perception over the next 30 years for drought, pests and wind and four judgment scales (with the original statements).**

## **2.4 Discussion and conclusions**

This study has investigated the forest planners' degree of uncertainty recognition across Britain, the uncertainty management strategy preferred, and which climate change related risks perceived important. No previous studies have investigated uncertainty within forest planning in such detail. We discuss each of these three topics before drawing conclusions about uncertainty in forest planning.

### **2.4.1 Recognition of uncertainty**

From the set of 27 statements classified into economic, social and climatic categories and the 10 uncertainty types, we have derived 6 composite measures of uncertainty. From the responses of 33 forest planners our statistical analysis of these measures revealed a significant difference between forest planners' recognition of uncertainty in economic, social and climatic categories, with planners being less uncertain in economic and social categories than in the climatic category. This observation is surprising as the scientific literature claims that the climate system is more predictable and less uncertain than economic or social systems (Adger et al. 2009). From all measures planners recognized only high uncertainty about the climatic category and the randomness of nature, which are possibly a cause of inertia to climate change adaptation in forest planning. Consequently, planners may opt for less uncertain forest management options (Pukkala 1998) which consider more certain economic and social development opportunities but do not consider uncertain climate change futures. We could not find significant differences in uncertainty recognition of different measures between district and design planners with the exception of the social category, and no difference among planners across England, Wales, and Scotland. Therefore, the level of management, either operational or tactical (Forestry Commission 2007), does not influence a planner's uncertainty recognition, and despite different forestry policies and different climate conditions in the three countries, planners had a similar recognition of uncertainty.

Our findings also show a high variability in the planners' recognition of different types of uncertainty represented by individual statements and within each of the categories. Furthermore, in most cases each uncertainty type had a distinct meaning within a category thus their combination into composite measures does not provide a reliable measure of uncertainty. The consequences and benefits of knowing about which uncertainty types, measures or even statements are more uncertain than others can affect the planners' selection of suitable adaptive forest measures. For example planners were very certain in their recognition of the social category statement relating to management

practices on recreational use, but they were very uncertain in the climatic category assessment of soil moisture variability. This means that they know a lot about how people use forests but very little about how soil moisture variability affects forests. Knowing about which type of uncertainty forest planners consider or know about within economic, social and climatic categories should help forest policy-makers to prioritize, avoid, accept or better communicate specific uncertainties in policy documents, especially for climate change adaptation.

### *2.4.2 Management of uncertainty*

From the active and passive management methods of model and monitoring uncertainty related to forest models and their outputs, forest planners were inclined to active management and did not indicate clear support for, or against, passive management. We found no significant differences in active uncertainty management between district and design planners or among planners across all three countries. This active management attitude is promising for the development and implementation of new forest models that include climate change uncertainty, for example using new probabilistic climate change projections (UKCP09) (Murphy et al. 2009). We would then expect active uncertainty management in forest planning by means of forest models and Decision Support Systems to support climate change adaptation. However, we only investigated the management of model and monitoring uncertainty. Planners might manage other types, such as goal and action uncertainty, differently. To conclude, our findings indicate that the planners' attitudes towards uncertainty management should not be considered as a source of inertia for climate change adaptation.

### *2.4.3 Climate change risk perception*

The perception relating to changes in climate risks over the next 30 years varied greatly among planners both on seven individual judgment scales and six climate related hazards, indicating planners have a broad risk understanding. Forest planners do not expect changes for fire, frost and waterlogging risks but major changes for drought, pests and wind risks. Less concern was implicit for changes in fire, frost and waterlogging, and might be explained by the low visibility of their impacts in British forests (Read et al. 2009). Whereas the evidence and high visibility of drought, pests and wind impacts (Read et al. 2009; Ray 2008; Ray et al. 2010) possibly explain planners' higher concern for these hazards.

Only for drought did we find significant differences in the planners' perception of changing risk among countries on the "concern" judgment scale. Hence, a

higher perception of drought risk change in England and Wales is more likely a reason for taking action in these countries compared to Scotland, where the change of drought risk was perceived to be lower. The highest perception of changing risk on the “concern” scale is for pests followed by drought and wind, giving some urgency to address these risks in forest planning and providing an incentive for further research on the topic. On the “frequency” scale planners indicated a higher perception of changing risk of drought, pests and wind due to their increased frequency, which may affect their decisions about tree species choice and forest management systems. Studies of risk perception have concluded that due to a higher risk perception of weather events managers were keener to use the future climate forecasts in their decision-making (O’Connor et al. 2005) or to take voluntary action due to a higher perception of global warming (O’Connor et al. 1999). Hence, when planners are highly concerned about pests, drought and wind they might take action to reduce or manage these risks. In contrast, on the “ability to regulate” and “controllability” judgment scales planners perceived a lower change of risk for drought, pests and wind. A similar observation of environmental risk perceptions for different hazards (McDaniels et al. 1997) showed a higher controllability of hazards which coincided with an increased need to regulate the risks. On the one hand the planners perceived changes in risks to be controllable, regulated by forestry policies and by forest planning practice leading to an overall lower risk. On the other hand planners recognized changes in risks to be of high concern and high frequency, indicating that they may still consider drought, pests and wind to be a serious threat to British forests. It seems that the perceived need for adaptation action also depends on the location of the district managed, as our findings showed that the district planners have more diverse perceptions of changes relating to drought, pests and wind risks, probably based on the prominent issues of the districts which vary across Britain. To conclude, the ability to control and regulate the risks which planners perceived of high concern on the “concern” and “frequency” scales can be a cause for planners not to take action and is probably a key reason for inertia to climate change adaptation in forestry, since risk perception has been recognized as a reason for society to adapt (Adger et al. 2009).

#### **2.4.4 Conclusions**

The analytical framework has allowed us to assess the forest planners’ understanding of the salient uncertainties relating to forest planning. The framework proposes a new approach to scrutinize uncertainty in forest planning that can be repeated over time or used in other disciplines if statements are substituted. The main advantages of the framework are the ability to apply, from different angles, a detailed and structured empirical analysis of uncertainty as

perceived by a planner, i.e. recognition of uncertainty, management of uncertainty and changes in climate change risk perceptions. This will be useful for forestry policy development, management, and the prioritisation of research. The weak points of the study link to the low response survey rate in England, the length of the survey which possibly affected the response rate, and the potential assessment of incomplete uncertainty types present in forest planning. Our findings reveal that forest planners have a high recognition of uncertainty in the climatic category of statements, but a low recognition of uncertainty in economic and social categories. Planners prefer to promote an active management of uncertainty relating to forest models. They perceive changes in climate risks relating to pests, drought and wind to be of high concern but also highly controllable and regulative by forestry policies and forest planning. Given that uncertainty is present in forest planning, we conclude that inertia to climate change adaptation from the uncertainty perspective is mostly driven by the planners' recognition of uncertainty in the climatic category, randomness of nature, and low risk perceptions of pests, drought and wind on the "ability to regulate" and the "controllability" scales.



## Chapter 3

### **A spatial and temporal drought risk assessment of three major tree species in Britain using probabilistic climate change projections**

Climate change impacts will affect the tree growth but the severity and the extent of these impacts is still questionable. The reason for this unpredictability is uncertainty about climate change and its impacts due to our limited knowledge and a natural variability of a climate system. This chapter explores the use of quantified climate change uncertainty as subjective probabilities in the drought risk assessment. Hence, in this chapter we treat uncertainty from a modeller's perspective rather than a decision maker's perspective as introduced in Chapter 1. With this perspective we focus on quantification of uncertainty from models. Additionally, this chapter addresses three sources of uncertainty: epistemic, stochastic, and ambiguity (see Figure 1-5).

This chapter is based on:

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## **Abstract**

Probabilistic climate data have become available for the first time through the UK Climate Projections 2009, so that the risk of change in tree growth can be quantified. We assessed the drought risk spatially and temporally using drought probabilities calculated from the weather generator data and tree species vulnerabilities using Ecological Site Classification model across Britain. We evaluated the drought impact on the potential yield class of three major tree species (*Picea sitchensis*, *Pinus sylvestris*, and *Quercus robur*), which cover around 59% (400,700 ha) of state-managed forests, across the lowlands and uplands. We show that drought impacts result mostly in reduced tree growth over the next 80 years when using B1, A1B, and A1FI IPCC emissions scenarios, but varied spatially. We found a maximum reduction of 94% but also a maximum increase of 56% in potential stand yield class in the 2080s from the baseline climate (1961-1990). Furthermore, potential production over the state-managed forests for all three species in the 2080s is estimated to decrease due to drought by 42% in the lowlands and by 32% in the uplands in comparison to the baseline climate. Our results reveal that potential tree growth and forest production on the state-managed forests in Britain is likely to reduce, and indicate where and when adaptation measures are required. Moreover, this paper demonstrates the value of probabilistic climate projections for an important economic and environmental sector.

### 3.1 Introduction

Drought has resulted in high forest mortality (Allen et al. 2010; van Mantgem et al. 2009) and has reduced tree productivity in Europe (Ciais et al. 2005). With a projected shift in the seasonal distribution of rainfall, and warmer and drier summers in Britain due to climate change (Murphy et al. 2009) we expect an increase in drought impacts reducing tree growth for many species (Read et al. 2009). However, the inherent uncertainty about climate change and its impacts have been a limiting factor for impact studies (Naylor et al. 2007; Lindner et al. 2010). The need for quantification of climate change uncertainty expressed as probabilities of impacts have been recognized for policy advice and risk management (Kunreuther et al. 2013). Since 2009, subjective probabilities representing climate change uncertainty have become available from the fifth generation UK Climate Projections (UKCP09) (Murphy et al. 2009). In a risk assessment these probabilities for climate variables can represent the likelihood of occurrence of natural hazards like drought. The second part of the risk assessment deals with the vulnerability of a system to the hazard (Turner et al. 2003) such as the response of tree growth to drought.

Few studies have investigated climate change impacts on tree growth in Britain (Proe et al. 1996; Broadmeadow et al. 2005). Impacts on tree growth have been estimated with an empirical non-linear model for Sitka spruce in Scotland (Proe et al. 1996), and with a knowledge-based model for oak, beech, and ash across Britain (Broadmeadow et al. 2005). These models demonstrated inter alia growth rates increase for Sitka spruce between 2.4 and 2.8  $\text{m}^3\text{ha}^{-1}\text{year}^{-1}$  for each  $1^\circ\text{C}$  warming, but also variable tree growth depending on the location and the drought index. However, these studies used deterministic climate data – i.e. used a single climate projection, and therefore omitted uncertainty in climate modelling, and offered limited information about climate change impacts over time.

Uncertainty is a salient component of a risk assessment: a process of identification and evaluation of risks (Willows & Connell 2003). Uncertainty, defined as an incomplete understanding of a system to be managed (Brugnach et al. 2008) limits our knowledge about potential drought impacts and its probability of occurrence. Quantified uncertainty handles risk as a combination of the “true” probability of a natural hazard and its impacts (Blaikie 1994). Future risk has been difficult to assess in forestry due to the lack of information about the probability of natural hazards (Gadow 2000). In risk assessments however, analysts deal with two types of uncertainty: epistemic – associated with limited knowledge - and stochastic – associated with variability (Walker et al. 2003; Suter et al. 1987). Although it is possible to reduce epistemic uncertainty with

new knowledge and a better understanding of the system acquired from new research, additional research cannot reduce stochastic uncertainty (Walker et al. 2003). Fortunately, the UKCP09 climate change projections quantify uncertainty into probabilities allowing development of a new type of risk assessment. Simulation of a large number of ensembles with the Met Office HadCM3 model and twelve international climate models used in the IPCC 4<sup>th</sup> Assessment Report allowed UKCP09 to quantify subjective probabilities representing uncertainty in modelling and natural climate variability (Murphy et al. 2009). We extend these probabilities to define spatial and temporal uncertainty as a variation in climate over space and over time, respectively. Additionally, we place the probabilistic climate change projections within the three main sources of uncertainty within our uncertainty typology introduced in Chapter 1, and as depicted in Figure 1-5. Quantification of epistemic and stochastic uncertainty into probabilities within the UKP09 projections then has enabled us to assess the future drought risk to forests.

Our main question is how spatial and temporal climate change uncertainty affects the drought risk of three major tree species and their growth, represented by the potential stand yield class, across Britain. The consequent research objective is to assess drought risk of the conifer species Sitka spruce (*Picea sitchensis*) and Scots pine (*Pinus sylvestris*), and the broadleaf species pedunculate oak (*Quercus robur*). Sitka spruce and Scots pine account for 49% (692 000 ha) and 16% (227 000 ha) of the conifer area, and oak (pedunculate and sessile) account for 23% (223 000 ha) of the broadleaf area of all forests in Britain (Forestry Commission 2012b), of which the public forest estate - managed by the Forestry Commission and Natural Resources Wales - represents approximately one quarter. We analysed spruce, pine, and oak stands covering approximately 59% (400,700 ha) of the public forest estate. For the risk assessment we used climate data from the baseline (1961-1990) and simulated projections for the seven future 30 year time periods representing the 2020s to the 2080s using precipitation and potential-evapotranspiration data from the UKCP09 Weather Generator. Drought conditions correspond to moisture deficit, when potential-evapotranspiration is higher than precipitation. To define the baseline and future drought we used probabilistic climate data – characterizing probabilities of the future climate variables, and to define the vulnerability of trees to drought represented by predicted stand yield classes (YC) we used the Ecological Site Classification (ESC) knowledge-based model (Broadmeadow et al. 2005). Yield class represents the maximum achievable average rate of volume increment. The total potential stand yield class change is our drought risk measure calculated as accumulated multiplications of different degrees of drought with associated vulnerabilities, following a risk calculation method by Smith (1992). In the risk assessment only drought was

evaluated, without considering for example edaphic factors of soil wetness and fertility important for tree growth, because of limited knowledge about the climate change effect on soil factors. We stratified the public forests into lowland and upland sites because of different rates of tree growth in different climate zones, from which we spatially and randomly sampled climate data.

### 3.1.1 Risk assessment

For our drought risk assessment we followed a “top-down” approach introduced by Dessai and Hulme (2004), which proposed first to estimate the future climate with climate models and then to assess the physical vulnerability, in our case for trees, to known baseline climate conditions with impact models. Our innovation in the risk assessment is the combination of different future drought subjective probabilities from UKCP09 and tree vulnerability derived from the Ecological Site Classification model.

The first part of our risk assessment is hazard, which has a certain probability. The complexity of estimating the probability of the future climatic conditions has been recognized in many studies (Dessai & Hulme 2004; Mastrandrea & Schneider 2004; Schneider 2001). Although we cannot have true probabilities, i.e. measured frequencies, as these studies suggested we can calculate subjective or conditional probabilities with a Bayesian probability framework (Dessai & Hulme 2004; Schneider 2001). This Bayesian approach led to the probabilistic UKCP09 climate change projections, which offer subjective probabilities of climate variables within the current knowledge bounds of the climate system (Murphy et al. 2009). Additionally, the expert judgment about model parameters and their distributions was incorporated into these probabilities. Data from the UKCP09 projections have allowed us to create drought probability curves as empirical cumulative distribution functions (ECDF) using only moisture deficit values. The ECDF curves represent drought probabilities for the future time periods, for a range of emissions scenarios, and for different locations across Britain. To assess and compare drought risk across different plausible futures we used the available SRES emissions scenarios of B1, A1B, and A1FI (Nakicenovic et al. 2000).

The second part of our risk assessment is physical vulnerability, which defined how trees respond to external factors such as drought. One approach for defining vulnerability is to choose a critical threshold as a deterministic value (Jones 2001) which has been used for example in a risk assessment of rice production (Naylor et al. 2007). The limitation of this approach is in evaluating and precisely defining the critical value while omitting responses of the system to other degrees of exposure. By contrast, the second approach uses the range

of possible impacts known as loss functions or ratios (Kerns & Ager 2007) or vulnerability curves (Papathoma-Köhle et al. 2012). These curves define the response of the system to degrees of impact, in our case tree growth across the range of drought levels. We developed vulnerability curves of the growth response of three tree species to different levels of drought using observed drought conditions across Britain in the baseline climate (1961-1990). These curves describe the relationship between drought – represented by moisture deficit index - and predicted stand yield class, where yield predictions were used from the Ecological Site Classification model (Broadmeadow et al. 2005). We assumed the same relationship between the moisture deficit index and the stand yield class in the baseline will persist into the future, as Williams et al. (2010) have shown in the US.

## **3.2 Material and methods**

### **3.2.1 Data collection**

Baseline climate (1961-1990) data were available from the Ecological Site Classification (ESC) model and the UKCP09. From the ESC model we used averages of annual accumulated temperature (AT - sum of day degrees > 5°C representing warmth index for growing season) and moisture deficit (MD - drought index) previously downscaled to 250m across Britain (Broadmeadow et al. 2005). ESC originally used MD values calculated from the Met Office MORECS dataset (Thompson et al. 1981) and AT values from the Climatic Research Unit. The UKCP09 climate projections (Murphy et al. 2009) with the Weather Generator (WG) simulated climate data at 5km spatial resolution (Jones et al. 2009). For the calculation of moisture deficit index we used these climate variables in WG: precipitation [mm] and potential evapotranspiration [mm/day] for grass (PET); with PET calculated by the Penman-Monteith method (see (Jones et al. 2009)) which provides more accurate drought estimates than some temperature based PET methods (Sheffield et al. 2012). The climate projections were available for three greenhouse gas emissions scenarios equivalent to the IPCC SRES scenarios: low (B1), medium (A1B), and high (A1FI); and seven overlapping 30-year time periods starting from the 2020s (2010 – 2039) until the 2080s (2070-2099), in addition to the baseline (1961-1990) period. We randomly sampled 100 runs from the 10,000 available model variant runs for each emissions scenario and time period to obtain probabilistic data. The structure of each climate data output was 100 runs across 30 years of daily values.

We designed a stratified random sampling experiment to spatially sample locations across Britain with different climatic conditions. We randomly sampled

one Weather Generator site which included at least one patch of the public forest estate within two strata: (i) 100km regular square grid cells from the British National Grid, and (ii) the lowlands and the uplands. This sampling allowed an accurate depiction of the spatial changes in the stand yield class for spruce, pine, and oak. There was a logistic constraint in gathering large volumes of climate data from the weather generator, hence we limited our selection to up to two weather generator sites per one 100km grid cell. We believe that weather generator sites at 5x5km spatial resolution are representative of both lowland and upland forested areas within 100km grid cells. Therefore, we present outputs at a resolution of the 100km grid. We used twenty-nine 100km grid cells each containing at least 25% of landmass area, i.e. less than 75% of water area. The lowlands and the uplands were delineated by climate zones using AT and MD (Clark et al. 2010). The lowlands consist of Warm Dry and Warm Moist climate zones and the uplands consist of Warm Wet, Cool Wet, and Cool Moist climate zones defined by the Ecological Site Classification model (see section Figure 7-1). Using this definition, our northern upland areas are at the lower elevation than our southern upland areas in Great Britain. However, the spatial extent of the uplands and the lowlands in Britain was similar to Clark et al. (2010). Our final sample consisted of 28 WG sites in the lowlands and 23 WG sites in the uplands (Figure 7-3 and Table 7-4).

### 3.2.2 Data analysis

#### 3.2.2.1 Hazard assessment

For the hazard assessment, we first calculated a single annual climatic moisture deficit index (Zimmermann & Kienast 1999) as accumulation of positive monthly MD values, by subtracting monthly precipitation values from monthly PET values. We developed a Python script to automate calculation of MD values. Due to the differences between MD values used in the ESC model and those calculated from the weather generator in the baseline period, we developed a moisture index adjustment linear regression model using median MD values (see section 7.2 in appendix). This linear regression model was parameterised using 100 runs and 30 years of WG data and 400 MD values from the ESC model (at 250m resolution) covering all 51 WG sites. We adjusted WG MD values within the regression model limits when values were below 205mm. Next, we computed MD values for all WG sites 3000 times - consisting of 100 runs for each 30 years of MD values - for the baseline and seven time periods (from the 2020s till the 2080s), and for three emissions scenarios (B1,A1B, and A1FI), similar to the approach by Oven et al., (2012). Finally, we constructed an empirical cumulative distribution function (ECDF) from 3000 MD values to estimate MD subjective probabilities.

### **3.2.2.2 Vulnerability assessment**

For the vulnerability assessment, we created vulnerability curves for spruce, pine, and oak by combining the calculated potential stand yield class and the ESC moisture deficit in the baseline climate, which described the growth response of a tree to drought conditions (Figure 7-4). Using MD and accumulated temperature values we calculated the stand yield class as a multiplication of maximum potential achievable yield class in Britain (spruce = 28, pine = 16, and oak = 8 ( $\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$ )) and adjustment factors for AT and MD based on the response function of each tree species using the ESC model at 250m spatial resolution. In this calculation, for the baseline climate, we used warmth and moisture deficit to get a realistic estimation of the stand yield class in British conditions. Next, we plotted the 3.545 million points – each at 250m spatial resolution - for the estimated stand yield classes and MD values, and calculated average and standard deviation for each stand yield class across 10mm MD discrete intervals, and with error bars showing standard deviations representing the variability caused by AT values (see Figure 7-4). In the final step we fitted a cubic function between average stand yield classes and moisture deficit values across the 10mm MD discrete intervals for spruce, pine, and oak to obtain vulnerability equations for each tree in the baseline climate.

### **3.2.2.3 Risk assessment**

The risk assessment combines hazard and vulnerability, for which we calculated drought risk as a multiplication of drought level probabilities and tree species vulnerabilities. We extracted moisture deficit probabilities from the 100 equally distributed bins – discrete class intervals - across the empirical cumulative distribution function curves, for the baseline and each emissions scenario in the future time periods. The probability of each discrete class was defined by subtracting the lower from the higher partial probability from the two class boundaries. For a reference point in the baseline we calculated the potential stand yield class for the median MD value of each of the 51 WG sites using the stand yield class estimation equation. To calculate vulnerability, we computed the stand yield class using the stand yield class estimation equation and assigned it to each MD class centroid. The estimated future stand yield class was subtracted from the baseline stand yield class - reference point - which gave us the stand yield class change for each MD class. We calculated partial risk values for each of the 100 MD classes, by multiplying the probability of the MD class with the corresponding stand yield class change value represented by its centroid. The final total potential stand yield class change, either positive or negative, from the baseline into the future was calculated as a sum of the 100 partial risk values (more details in section 7.2 in appendix). In addition, we calculated the future stand yield class as a relative change from the baseline stand yield class.

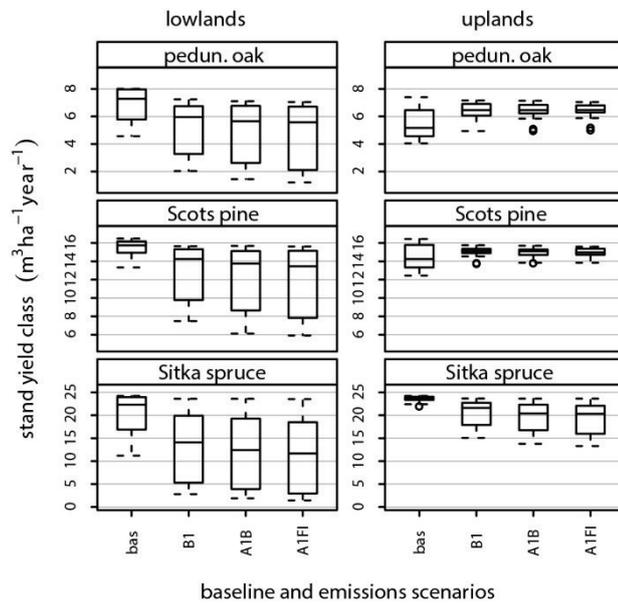
#### **3.2.2.4 Forest production estimation**

To assess the impact of drought risk, we calculated the total potential forest production of the public forest estate, now and in to the future, for each 100km grid cell, and separately for the lowlands and uplands. We used the public forest estate dataset (<http://www.forestry.gov.uk/datadownload>) including information about tree species, stand area, and yield class, to calculate the baseline forest production ( $\text{m}^3 \text{ year}^{-1}$ ) as a multiplication of the stand yield class by the stand area, for spruce, pine, and oak, within each of the twenty-nine 100km grid cells. For the future, we calculated the potential stand yield class as a multiplication of the baseline stand yield class with the relative stand yield class change value for lowland or upland sites attributed to each 100km grid cell. The future forest production was then calculated as the product of the adjusted future stand yield class value by the current stand area. It was not possible to validate the stand yield class for each species across Britain due to the lack of observed data, therefore our approach is conservative for the calculation of future forest production by using relative stand yield class change values.

We performed all analyses in R statistical software (R Development Core Team 2012) and used the lattice package for visualization (Sarkar 2008).

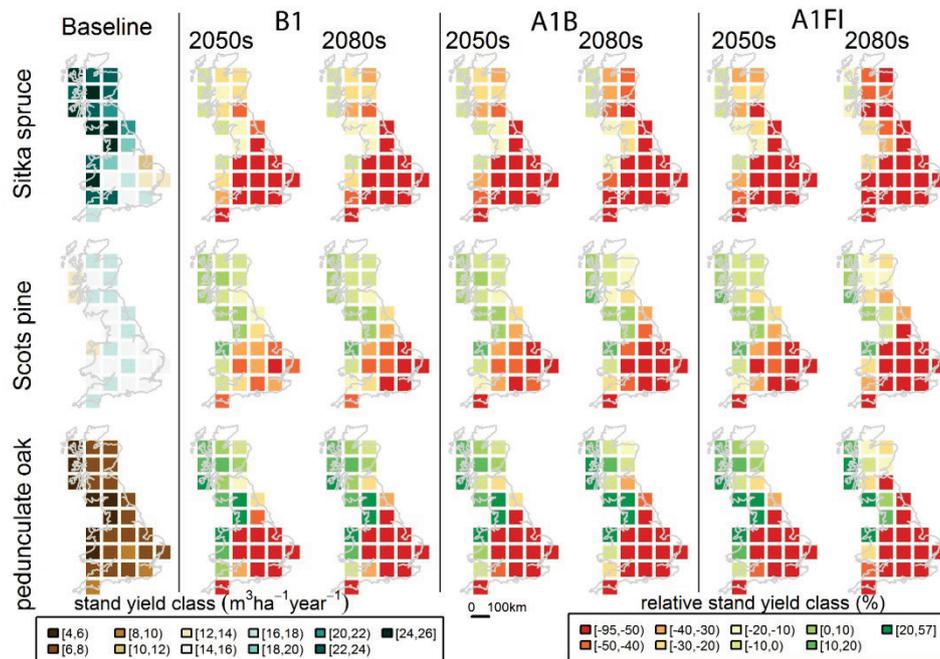
### **3.3 Results**

Drought risk of the future potential stand yield class for all 28 lowland and 23 upland sites using the Weather Generator squares is summarized in Figure 3-1. As the stand rotation length for spruce is around 50 years in Britain, we selected the 2050s from the seven time periods in Figure 3-1. For instance, in the lowlands and for the medium A1B emissions scenario we see a greater reduction of the median stand yield class for spruce from 22.3 to 12.4  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  and a smaller reduction for pine and oak from 15.7 to 13.7  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  and 7.3 to 5.7  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , respectively. On the other hand, in the uplands and for the same emissions scenario we see a smaller reduction in the median stand yield class for spruce from 23.7 to 20.4  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  and an increase for pine and oak from 14.3 to 15.1  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$  and 5.2 to 6.5  $\text{m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ , respectively. In the future, drought conditions may cause a larger reduction in the stand yield class in the lowlands and a smaller reduction or even an increase in in the uplands, making the uplands more suitable for the future forest production under all emissions scenarios.



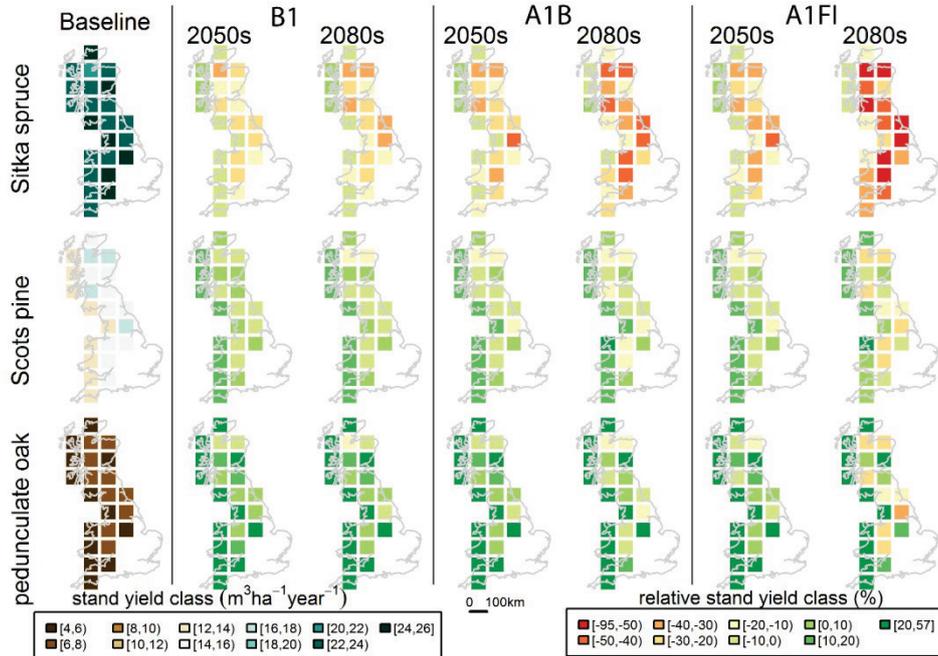
**Figure 3-1 Potential stand yield classes for Sitka spruce, Scots pine, and pedunculate oak in the 2050s for emissions scenarios (B1, A1B, A1FI) and the baseline “bas” (1961-1990), and for lowland (n=28) and upland (n=23) sites.**

From the summary statistics of the predicted potential stand yield classes we turn to the spatial and temporal drought risk assessment within 100km grid cells. Each grid cell represents results for one weather generator square for forests either in the lowlands or uplands. The drought risk across Britain will lead to a reduction of the stand yield class depending on the species, emissions scenario, and the location. In the lowlands, drought impacts reduced the stand yield class by up to 94% in south-east Britain, whereas the drought conditions had a positive impact on yield class with an increase up to 42% in west and north-west Britain across three emissions scenarios in the 2050s and 2080s (Figure 3-2). In north-east Britain, on higher spruce yield class sites in the baseline, a smaller predicted stand yield class reduction was predicted until the 2080s, resulting in more resilient spruce stands to drought than in other parts of Britain, except for the west. Conversely, on higher pine and oak yield class sites in the baseline period in east and south-east Britain, predicted higher stand yield class reduction making such stands less resilient to drought than in other locations.



**Figure 3-2** Changes in the lowlands of relative stand yield classes [%] from the baseline to the future (2050s and 2080s) due to drought conditions for Sitka spruce, Scots pine, and pedunculate oak for emissions scenarios (B1, A1B, A1FI). Red indicates a reduction and green indicates an increase in the predicted stand yield class.

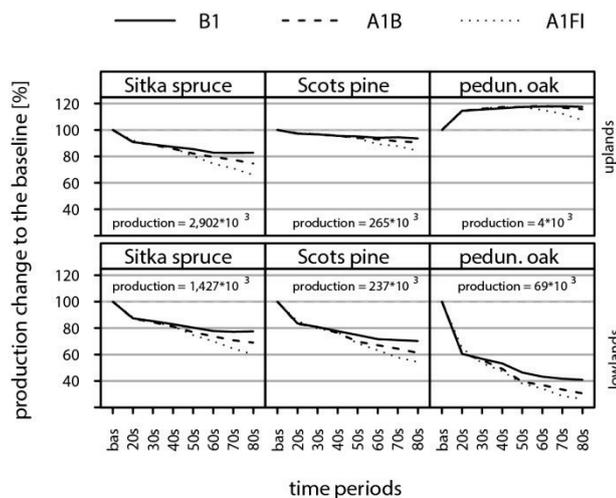
In the uplands, the drought impacts reduced the potential stand yield class by up to 64% in the east of Britain. Drought conditions may be less extreme in the west of Britain, and our results show an increase in the stand yield class by up to 56% across the three emissions scenarios in both the 2050s and 2080s (Figure 3-3). The higher future decline in spruce yield class will be on sites with current estimated high yield, making stands less resilient to drought in the future. By contrast, increased pine and oak stand yield class, especially on sites with current low yield, suggests these stands will be more resilient to drought in the future. Due to the lower pine and oak yield class values in the baseline, the predicted small relative increase in yield class will be small in absolute growth terms. The predicted relative yield class changes for all species, for the seven time periods from the 2020s to the 2080s, and for both the lowlands and uplands are shown in Figure 7-6 to Figure 7-8 in appendix.



**Figure 3-3** Changes in the uplands of relative stand yield classes [%] from the baseline to the future (2050s and 2080s) due to drought conditions for Sitka spruce, Scots pine and pedunculate oak for emissions scenarios (B1, A1B, A1FI). Red indicates a reduction and green indicates an increase in the predicted stand yield class.

We extrapolated the projected drought effects to predict the potential future forest production for the public forest estate in Britain. The total potential production for spruce, pine, and oak stands is predicted to decrease over the next 80 years. The biggest negative drought effect on forest production was for the A1FI emissions scenario in the 2080s, which is not surprising as A1FI represents the IPCC scenario with the greatest temperature increase, resulting in drier climatic conditions. In the lowlands, the biggest reduction of 74% in relative forest production from the baseline was for oak (Figure 3-4). In absolute terms, the largest reduction in forest production of  $570 \times 10^3 \text{ m}^3 \text{ year}^{-1}$  (equivalent to 39% reduction) was for spruce. In the uplands, on the other hand, the largest reduction in forest production in absolute terms was  $987 \times 10^3 \text{ m}^3 \text{ year}^{-1}$  (equivalent to 35% reduction) for spruce, but there was also an 18% increase for oak in the A1B emissions scenario in the 2060s. Due to higher forest production in the uplands, the largest absolute reduction of  $987 \times 10^3 \text{ m}^3 \text{ year}^{-1}$  was for spruce, almost twice the production than in the lowlands. The combined total loss in forest production for stands of spruce, pine, and oak across the public forest estate was predicted to be larger in the uplands ( $515$  to  $1,028 \times 10^3 \text{ m}^3 \text{ year}^{-1}$ ) than in the lowlands ( $432$  to  $729 \times 10^3 \text{ m}^3 \text{ year}^{-1}$ ) for the B1

and A1FI emissions scenarios in the 2080s. The reason for greater future forest production losses in the uplands is mainly due to higher forest productivity over a larger forest area, despite being less affected by drought and having better climatic conditions for growth than in the lowlands. For more details on baseline forest production within 100km grid cells for spruce, pine, and oak see maps in Figure 7-5 in appendix.



**Figure 3-4** Relative changes [%] in the total potential forest production for spruce, pine, and oak forests of the British public forest estate in the lowlands (143 500 ha) and the uplands (257 000 ha) from the baseline “bas” until the 2080s for three emissions scenarios (B1, A1B, A1FI).

### 3.4 Discussion and conclusions

Our drought risk assessment reveals a high likelihood mainly of future potential reduction in tree growth for the three major species in Britain. The assessment does not consider among others soil water content and soil available water capacity at each site, which may reduce the impacts of drought on tree growth, and so we describe our findings as a potential reduction in tree growth. For example, increased drought conditions and consequent drier soils have caused higher tree mortality on *Pinus edulis* in south-western US (Breshears et al. 2005) on drier sites following a very severe drought in 2002-2003.

Depending on location, time period, and the future emissions scenario, increased drought conditions will exert different impacts on the total potential stand yield class for spruce, pine, and oak. With respect to location, we predict growth reduction of up to 94% for total stand yield class in the lowlands and as much as a 64% reduction in the uplands mostly across south-east and east Britain in the 2080s (Figure 3-2 and Figure 3-3). In addition, our results

demonstrate the impact of the more drought sensitive spruce stands compared with pine and oak, with a median stand yield class reduction of 44% from the baseline in the lowlands in the 2050s (Figure 3-1). For oak, our results show a 13% reduction of the median stand yield class in the 2050s (Figure 3-1) similar to a study (Broadmeadow et al. 2005) which incorporated additional limiting factors to tree growth and used previous UK climate change projections (UKCIP2002), but without probabilistic climate change data. A study of drought impacts in the US showed a 25% reduction in yield from pine plantations by 2100 (Battles et al. 2007). With respect to time periods, we found a large yield class reduction of up to 89% in the 2050s and even higher reductions up to 94% by the 2080s. The detailed drought analysis for the next 80 years (Figure 7-6 to Figure 7-8 in appendix) provides more information about when, in seven decadal time periods, and where in Britain, forest adaptation should be targeted and prioritised. In contrast, previous studies mostly evaluated impacts only for one time period e.g. 2050-2099 (Williams et al. 2010) or over three time periods (Battles et al. 2007). With respect to the emissions scenarios, our results emphasise increased changes in the drought risk particularly after the 2050s in accordance with higher emissions scenario uncertainty (Murphy et al. 2009; Meehl et al. 2007). We conclude that our new spatial and temporal assessment of drought risk across Britain will provide valuable forest management information for medium to long-term climate change adaptation.

We predicted potential forest production losses due to drought conditions on the public forest estate in Britain, considering forest location, tree area of forest, tree species composition of forest stands, and changes in potential tree growth. However, the predicted production volumes omitted the effects of the changing species age distribution. Spruce, the species with the largest forest area and being more sensitive to drought, contributed to combined forest production losses by 78% and 96%, respectively, resulting in overall forest production loss of 42% in the lowlands and 32% in the uplands from the baseline to the 2080s for the A1FI emissions scenario. This finding is similar to the evidence from the US (Williams et al. 2010), which reported mean tree growth reductions of 34% in ponderosa pine due to a projected warmer and drier climate for the A1B emissions scenario between 2050-2099, as well as to the estimated 30% reduction in forest productivity in Europe in 2003 (Ciais et al. 2005) due to the observed extreme heat wave and drought. Besides losses in forest production, drought can also trigger higher tree mortality (van Mantgem et al. 2009; Allen et al. 2010) and reduce trees productivity under elevated CO<sub>2</sub> levels (Warren et al. 2011), not investigated in this study. Moreover, predicted drought impacts will result in more vulnerable forests in the lowlands and uplands, and this concurs with the reduction of species range (Hanewinkel et al. 2012), especially for spruce by 2100.

In our drought risk assessment the use of probabilistic climate data with the Ecological Site Classification model allowed the investigation of spatial and temporal climate change uncertainty, and epistemic uncertainty or a limited knowledge relating to tree vulnerability and climate projections. We are aware that the probabilistic climate change projections can give an impression of “false” drought certainty. In fact, complete certainty is not achievable for an open system such as climate change (Pielke 2001) since uncertainty in the form of recognized or total ignorance remains (Walker et al. 2003). However, the probabilistic climate data captures some of the recognized uncertainty from climate models within the current knowledge bounds of the climate system. The degree of climate change uncertainty varies spatially and increases through each decade up to the 2080s due to the different agreements about climate parameters within climate models, as study by (Mbogga et al. 2010) has also shown for aspen habitat distribution. This uncertainty also affects drought risk, which in most cases reduces the total stand yield class (Figure 3-2 and Figure 3-3) and forest production (Figure 3-4) across Britain. Different futures driven by plausible emissions scenarios represent another level of uncertainty (Walker et al. 2003). At a site level, we found diverging drought risk estimates across emissions scenarios after the 2050s (Figure 7-6 to Figure 7-8 in appendix) as well as at the national level (Figure 3-4) which is supported by UKCP09 projections (Murphy et al. 2009) and global warming projections (Meehl et al. 2007). Epistemic uncertainty as a limited knowledge about tree species response to drought was a challenge in this assessment. We have a better understanding of tree species vulnerability to average drought in current and recent British conditions than about tree vulnerability to extreme droughts. A recent study (Zimmermann et al. 2009) highlighted the need for information about climate extremes that can improve our understanding of species limits and support robust future estimations of species distributions. Extreme droughts are more damaging, affect forest productivity (Ciais et al. 2005), and are projected to become more frequent in the future (Meehl & Tebaldi 2004). Uncertainty still remains a constraint for risk assessments but its quantification as a subjective probability provides a better understanding of drought risk.

The findings of this research can help forest managers at local and national levels to identify and reduce drought risk to sustain timber production over the next 80 years. At a local level, forest managers can incorporate information about trends from drought risk outputs at 5km spatial resolution into medium to long-term forest plans supporting climate change adaptation measures such as species choice while considering uncertainty. These measures are mostly applied at a local level, where a great need for risk and vulnerability assessments exists (Williams et al. 2010). At the national level, our results enable forest managers to spatially and temporally identify drought risk

hotspots, using modelled losses and gains of the potential stand yield class. Such a strategic application of the analysis will help forest managers decide which species, when, and where - in the lowlands or in the uplands - they may adapt forest management or expand woodlands with appropriate species. This information will offer more confidence for long-term adaptation strategies. Furthermore, with respect to emissions scenarios, forest managers can respond similarly to the drought risk over the next 40 years before making decisions to adapt based on a particular emissions scenario, since drought risk diverges among scenarios after the 2050s. Forest managers can mitigate and manage the drought risk to acceptable thresholds specified by policymakers (Hall et al. 2012). Additionally, an aspiration exists to expand the woodland area in each of the devolved countries of Britain, for example, in Scotland from 17% to 25% by the second half of 21<sup>st</sup> century (Forestry Commission Scotland 2006), and where currently there is a woodland creation target of 10,000ha per year over the next 10 years (Scottish Government 2011). Forest managers may establish new forests preferably on upland sites which tend to be less drought sensitive compared with lowlands sites, as our findings suggest. However, they must still consider factors such as forest site conditions. The continued future sustainable provision of ecosystem services is a key policy requirement and a target of long-term forestry strategies in Britain (Defra 2007; Forestry Commission Wales 2009; Forestry Commission Scotland 2006). However, the challenge remains about where and when to adapt to climate change, and our drought risk assessment addresses part of this problem.

The combination of a tree's vulnerability to drought and the drought probability with probabilistic climate data offer a new and robust way to assess drought risk across Britain. Probabilistic data reduce the epistemic uncertainty associated with drought risk, in contrast to traditional single based climate models, but uncertainty still remains a challenge for the future risk assessments. Future research should focus on a better understanding of tree species response to extreme drought conditions; and on a drought risk assessment for other tree species that may provide new alternatives for future sustainable forestry. Overall, our findings show that the west and north-west part of the Britain is much less sensitive to drought, and hence forests can deliver more ecosystem goods and services and forest expansion should be targeted in these areas.

## Chapter 4

### **Ecosystem services application in the dynamic adaptive policy pathways to support climate change adaptation**

Natural ecosystems provide valuable goods and services to the society. The amount of these services will change in the future due to socio-economic and environmental impacts. Knowledge about impacts from climate change on a range of forest ecosystem services is still limited due to uncertainty. This chapter investigates uncertainty within climate change and impact models to estimate climate impacts on four ecosystem services, which are incorporated into adaptation pathways. Hence, in this chapter we treat uncertainty from a modeller's perspective rather than a decision maker's perspective as introduced in Chapter 1. With this perspective we focus on quantification of uncertainty from different models and for emissions scenarios. Additionally, this chapter addresses two main sources of uncertainty: epistemic and stochastic (see Figure 1-3) and scenario uncertainty (see Figure 1-2).

This chapter is based on:

Petr, M., Boerboom, L., Ray, D., van der Veen, A., 2014. Ecosystem services application in the dynamic adaptive policy pathways to support climate change adaptation – the Scottish forestry study, *to be submitted*

## **Abstract**

Climate change impacts and its inherent uncertainty is one of the main challenges for adaptation in environmental management. The lack of knowledge about these impacts on ecosystem services at high spatial and temporal resolution limits when and what adaptation measures can be taken. We addressed these limits, first with four assessed ecosystem services, these being forest production, yield class, sequestered carbon, and tourism potential due to drought or climate change impacts. Then we adapted dynamic adaptive policy pathways for forestry incorporating evaluated services to set expiry dates for forestry actions and to propose possible adaptation pathways. Assessment has been done for the next 80 years using probabilistic climate change data from the weather generator for the case study of the national forest estate in Scotland and the major tree species – Sitka spruce, Scots pine, and pedunculate oak. Findings show that drought has an overall long-term negative impact on provision of assessed services with a decrease up to 41%, whereas climate change has a positive impact on tourism potential with an up to five times increase in good conditions (Tourism Climatic Index  $\geq 60$ ) during summer months. Furthermore, the results for the adaptation pathways highlighted forestry actions, mainly in the lowlands, reaching their defined environmental limits during the next 80 years. Assessed ecosystem services and adaptation pathways reduce knowledge uncertainty and highlight when and where adaptation can take place.

## 4.1 Introduction

Climate change will undoubtedly affect natural ecosystems in the future (Ciscar et al. 2011; Fischlin et al. 2007) but adaptation can help to minimise its negative impacts (Hall et al. 2012; Jones et al. 2012). The essential components of climate change adaptation are how, where, and when to adapt (Smit et al. 1999), and also to what climate stimuli. Many studies have investigated adaptation to potential climate change impacts on a wide range of ecosystems (Lindner et al. 2010; Schroter et al. 2005) and proposed many adaptation measures. However, these studies lack the level of spatial and temporal detail necessary for medium to long-term management, such as decadal information. To overcome this issue, improvements in climate change modelling have allowed climatologists to offer climate data at higher spatial and temporal resolutions, as is the case for the UKCP09 climate projections (Murphy et al. 2009).

In forestry, climate change adaptation is a long-term process as trees grow for many decades. Different adaptation approaches to climate change exist based on modelling of the natural environment, such as “silviculture adaptation measures” (Mason et al. 2012) or integrative adaptive forest management (Bolte et al. 2009); or sociological approaches, such as “risk perceptions” (Williamson et al. 2005). Still, these studies lack detailed information, such as when and where forest managers should start to adapt. A novel approach of dynamic adaptive policy pathways developed in the literature for water management (Haasnoot et al. 2013) seems as a promising method, which can support informed and spatially oriented adaptation to climate change impacts in forestry. This can provide possible adaptation pathways for forest planning that evaluate relevant forest ecosystem services.

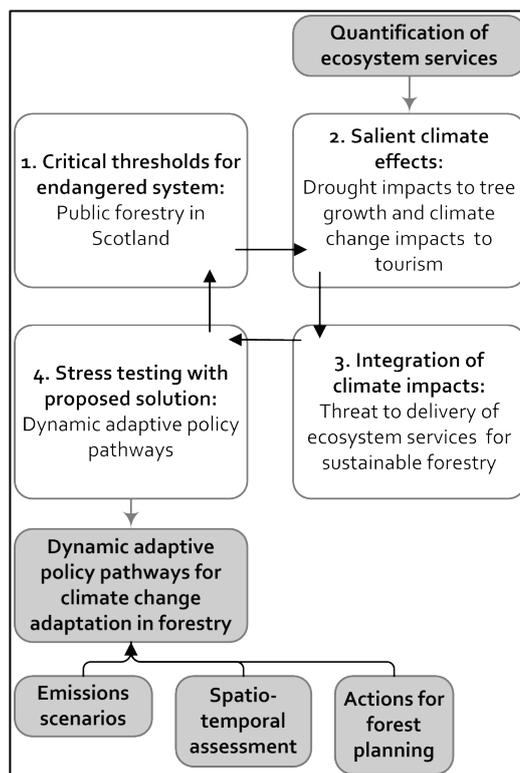
The approach of dynamic adaptive policy pathways introduced by Haasnoot et al. (2013) emerged as a combination of “adaptive policymaking” and “adaptive pathways” that deal with deep uncertainties as a result of social, political, technological, economic, and climatic changes. The essential component of these pathways is to define an expiry date for each action – e.g. rise of dykes - described by the authors as a “sell-by date” at which the plan’s objectives are not met anymore. Furthermore, an expiry date defines boundaries for a set of adaptation pathways from which under different perspectives new adaptation pathways emerge. Haasnoot et al. (2013) used for different perspectives cultural theory and its worldviews (Thompson et al. 1990). Limits of this pathways approach are: missing detailed quantification of actions and ecosystem services beyond experts’ knowledge, having a degree of change – e.g. relative reduction, and application in the actual decision-making process.

Ecosystem services assessments emerged in the last decade at a global scale (Millennium Ecosystem Assessment 2005) and at a national scale (UK National Ecosystem Assessment 2011). Traditionally, in forestry the main services have been forest production and contribution to the local economy, but recently new services emerged, such as carbon sequestration and recreation (Quine et al. 2011). Therefore, information is needed about the degree of climate change impacts on the traditional as well as new forest services. New classification of forest ecosystem services emerged with four groups: provisioning, regulating, cultural, and supporting services introduced in (Quine et al. 2011). To cover a wide range of services, we addressed two provisioning services: tree growth potential and forest production; one regulating service being carbon sequestration; and one cultural service being tourism potential. Tree growth potential indicates changes in the stand yield class – site productivity, which is a key parameter in assessing tree species choice in forest management (Read et al. 2009). Forest production indicates the amount of available timber which can be harvested - timber industry requires this information. Carbon sequestration describes the long-term amount of carbon captured by trees (Morison et al. 2012) and is a common indicator used in climate change mitigation studies (Read et al. 2009) and policy documents (Scottish Government 2011). The last service is tourism potential defined by the human comfort conditions for light tourism (Mieczkowski 1985). Even though sophisticated models exist to assess traditional services, such as wood production (Metzger et al. 2008), only a limited number of models are available to assess newer services, such as recreation, especially when incorporating climate change impacts (Bateman et al. 2013). To support climate change adaptation in forestry, multiple ecosystem services should be evaluated for environmental management as suggested by Bateman et al. (2013).

The main objective of this chapter is to assess four forest ecosystem services and incorporate them into the dynamic adaptive policy pathways that can support climate change adaptation in Scottish forestry. The two research questions are: a) how much will drought and climate change reduce the delivery of forest ecosystem goods and services in the future under different emissions scenarios, and b) which forestry actions and when should forest planners choose to support climate change adaptation and sustainable forestry. The unit of analysis is the National Forest Estate in Scotland for which changes in ecosystem services were evaluated in the lowlands and uplands using probabilistic climate change projections (UKCP09) (Murphy et al. 2009). To evaluate climate change adaptation and its intrinsic uncertainty in forestry, information about ecosystem services was incorporated into dynamic adaptive policy pathways.

The chapter is organized into three sections. Materials and methods describes the quantification of ecosystem goods and services now and into the future, which were used to assess forestry actions in modified dynamic adaptive policy pathways. The climate and forestry data which were used are also described here. The following section presents the results for changes in provision of ecosystem services in the lowlands and uplands, at decadal intervals, and until the 2080s, and then present possible adaptive pathways. Finally, the discussion section relates our results to a broader climate change adaptation and forest management context, and then discusses how the results can inform actual climate change adaptation in Scottish forestry. This study demonstrates that changes in the key forest ecosystem services allow identification of future adaptation pathways even under deep uncertainty.

## 4.2 Materials and methods



**Figure 4-1** The use of a climate stress testing framework to guide the assessment of ecosystem services and dynamic adaptive policy pathways to forestry - in grey boxes (modified from (Swart et al. 2013))

We used a climate stress testing framework, see Figure 4-1, as a guidance to investigate how resilient is the provision of forest ecosystem services on the

National Forest Estate in Scotland. This framework guided our assessment of ecosystem services and the development of dynamic adaptive policy pathways for forestry. First, we assessed four ecosystem services relevant to forest planning: forest production, mean yield class, sequestered carbon, and tourism potential. Second, we expanded the original dynamic adaptive policy pathways with uncertainty represented by three emissions scenarios, spatiotemporal assessment of ecosystem services, and relevant forestry actions. Furthermore, we applied adaptive pathways to a real case of forest planning and management in Scotland. The following three sub-sections first describe: data used, the methods for evaluating ecosystem services, and modification of dynamic adaptive policy pathways for forestry.

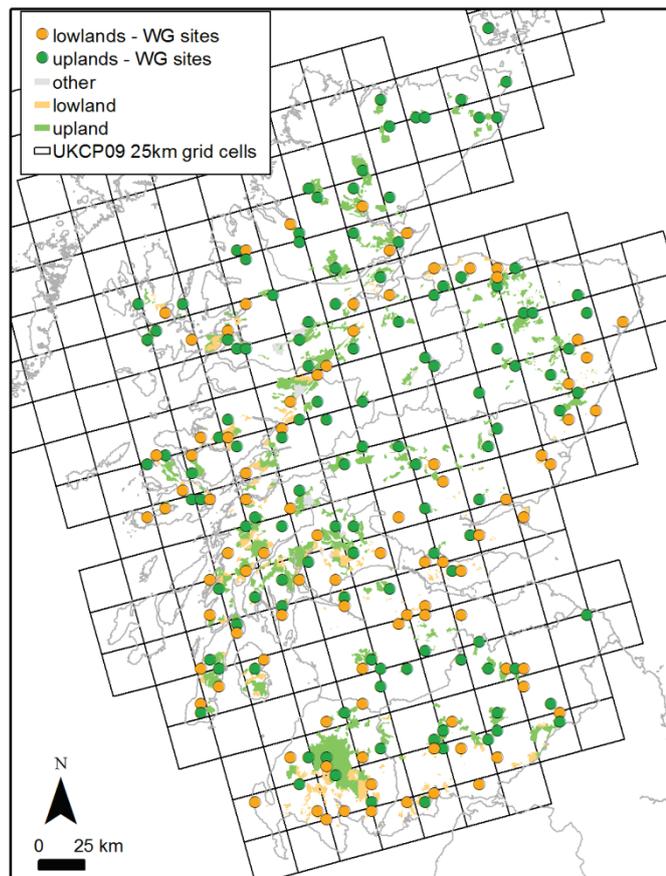
#### *4.2.1 Data collection*

The same analysis methods and the same type of climate data as in Chapter 3 were used to calculate drought impacts on tree growth. Simulated climate data were obtained from the weather generator (WG) available from the UKCP09 climate projections (Murphy et al. 2009; Jones et al. 2009). The weather generator data have a 5km spatial resolution. To calculate moisture deficit (MD) – a proxy for drought - key climate variables available in the WG were used: precipitation [mm] and potential evapotranspiration for grass (PET) [mm/day]. Other climate variables required from the WG to calculate tourism climatic index were: maximum daily temperature [°C], mean daily temperature [°C], mean daily relative humidity [%], precipitation [mm], and sunshine [hours/day]. Wind speed data were missing in the WG dataset, hence we used the MetOffice gridded observation dataset with monthly averages for a climatic period 1971 – 2000 at 10 m height (Jenkins et al. 2008). Weather generator climate data were available for the baseline period (1961-1990), for seven 30-year overlapping time periods from the 2020s (2010-2039) until the 2080s (2070-2099), and for three emissions scenarios: low (B1), medium (A1B), and high (A1FI) similar to SRES (Nakicenovic et al. 2000).

We modified the sampling experiment introduced in Chapter 3 to increase the sampling density of weather generator sites and to expand the coverage of spruce, pine, and oak forests on the national forest estate in Scotland. Sampling was random with one WG site within two strata: a) UKCP09 25 km grid cell overlaying the national forest estate, and b) within the lowlands or uplands. We chose 25 km grid cells to have a regular block design and also because weather generator sites at this scale have the same set of Change Factors for climate data (Jones et al. 2009). The lowlands were characterised by drier and warmer climate zones and the uplands by colder and wetter climate zones (see Chapter 3 for details). The forestry data were obtained from the Forestry

Commission database, with details available in Chapter 3. Our final climate data consisted of 215 WG sites with 92 in the lowlands and 123 in the uplands, see Figure 4-2 for the spatial distribution of WG sites.

We performed all analyses in R 2.14.2 statistical software (R Development Core Team 2012) using plyr (Wickham 2011) package and lattice package for visualisation (Sarkar 2008).



**Figure 4-2** The spatial distribution of the weather generator (WG) sites in the lowlands (92 WG sites) and in the uplands (123 WG sites), and the spatial extent of the National Forest Estate in Scotland.

#### 4.2.2 Methods for ecosystem services

We first estimated drought impacts on tree growth, forest production, and carbon sequestration, and then climate change impacts on tourism. We defined drought using an index of climatic moisture deficit (see Chapter 3) and climate change as impacts of multiple climate variables, e.g. temperature, precipitation, and humidity. For each forest ecosystem service we used a relevant indicator

calculated either with a model developed for British conditions – drought risk assessment or carbon - or developed for international conditions - tourism (see Table 4-1 for details).

**Table 4-1 Indicators for ecosystem services in forestry**

Type of service from UK NEA classification <sup>a</sup>	Ecosystem services	Indicators [units]	Models
Provisioning – trees for timber	Tree growth	Weighted mean stand yield class [m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> ]	Drought risk assessment (see Chapter 3)
Provisioning – trees for timber	Forest production	Volume of available timber [m <sup>3</sup> year <sup>-1</sup> ]	Drought risk assessment (see Chapter 3)
Regulating – climate	Carbon sequestration	Carbon sequestration [tCO <sub>2</sub> equivalent year <sup>-1</sup> ]	Woodland carbon code and CSORT model (Morison et al. 2012)
Cultural – environmental settings	Tourism potential	Tourism Climatic Index [no. of “good” days month <sup>-1</sup> ]	Tourism Climatic Index (Mieczkowski 1985)

Note: <sup>a</sup> (Quine et al. 2011)

The main input for assessing drought impacts was tree growth represented by the stand yield class for Sitka spruce (*Picea sitchensis*), Scots pine (*Pinus silvestris*), and pedunculate oak (*Quercus robur*). We used a drought risk measure combining information about tree growth vulnerability to drought and its probability (see Chapter 3 for details). With this measure we adjusted the baseline yield class (1961-1990) for each tree species by the same relative yield class change factor for the future time periods within each 25km grid cell, and the lowland and upland sites. The outputs were absolute stand yield classes for each tree species within a forest stand, for seven future time periods, and for three emissions scenarios.

These yield classes were applied to calculate the potential weighted mean stand yield classes for spruce, pine, and oak. The yield classes were weighted by the species area within a stand available from the national forest estate database. Then, we computed the potential forest production for the future with the adjusted stand yield classes, assuming the same future forest extent. Forest production was then calculated as the forest stand area multiplied by the stand yield class.

Next, we estimated cumulative sequestered carbon stocks for spruce, pine, and oak stands in Scotland using the freely available Woodland Carbon Code calculator (WCC) (<http://www.forestry.gov.uk/carboncode>), which is based on the CSORT model (Morison et al. 2012). For each species we calculated the sequestered carbon depending on: tree age, adjusted stand yield class to

drought conditions, tree spacing, and without any forest management regime such as thinning. Calculated carbon in the WCC is based on five year periods reducing yearly growth variability. The cumulative carbon values represent sequestered carbon in biomass and debris over the tree age.

Finally, we calculated tourism potential for forests into the future with Tourism Climatic Index (TCI) representing human comfort (Mieczkowski 1985; Perch-Nielsen et al. 2010). Daily climate data from the weather generator were used to calculate five monthly sub-indices required for TCI: daytime comfort index (CID), daily comfort index (CIA), precipitation (R), sunshine (S), and wind (W). The formula for TCI with weighted sub-indices is then:  $TCI = 2(4 \cdot CID + CIA + 2R + 2S + W)$ . The only missing climate variable was minimum daily relative humidity, which we replaced with the mean daily relative humidity as described in (Perch-Nielsen et al. 2010). All climate variables were available for the baseline period (1961 – 1990) except for wind data, which were only available for 1971-2000 but still provide a good proxy for the baseline. To calculate changes in tourism potential between the baseline and the future, we used the number of “good days” with  $TCI \geq 60$  indicating suitable conditions for light tourism; a similar proxy was used by Perch-Nielsen et al. (2010). The highest visitor numbers in Scottish forests are in summer, hence we analysed changes in average number of good days in summer months (June, July, and August). The detailed calculation steps for ecosystem services are in the appendix in section 7.3.

#### ***4.2.3 Method for dynamic adaptation policy pathways in forestry***

Building upon the dynamic adaptive policy pathways method developed for water management (Haasnoot et al. 2013), we expanded this method with spatial and temporal evaluations of forestry actions. Following the first five analysis steps by Haasnoot et al. (2013), we first describe the study area, then specify the problem in Scottish forestry, provide a list of relevant forestry actions, assess these actions, and finally propose an action expiration map for with two sets of threshold values.

##### ***4.2.3.1 Step 1: Study area - Scottish public forestry***

We analysed three major tree species in Scotland on the national forest estate which covers 481,000 hectares. In contrast, the private sector covers 912,000 hectares (Forestry Commission 2012b). In the lowlands and uplands, Sitka spruce, as the major production species, covers more than 50% of forests; Scots pine covers around 10% of forests; and pedunculate/sessile oak covers up to 1% of forests. The climatic conditions in Scotland have changed with an increase in mean annual temperature of 0.8°C over the last three decades and the current mean annual temperature is close to 8.0°C; and the changes in

precipitation in summer range between -5% to 4.6% in contrast to winter with an increase between 35.9% to 65.8% from 1961 to 2006 (Jenkins et al. 2008).

From the forest policy perspective, Scottish Government specifies broad policy targets such as an increase of woodland area from 17% to 25%, an increase of carbon sequestration, and contribution of forests to public health benefits (Forestry Commission Scotland 2006). Other targets are short term, such as woodland creation of 10,000 ha per year by 2020 (Scottish Government 2011) or more specific targets such as providing smooth timber production of at least three millions of softwood timber annually over the next 50 years (Forestry Commission Scotland 2013).

#### **4.2.3.2 Step 2: Problem in Scottish forestry**

Climate change and its potential impacts is one of the main threats to the delivery of key forest ecosystem services in Scotland (Forestry Commission Scotland 2006). The problem for forest managers is to know when and where they should adapt and by what means. The opportunities exist either in woodlands expansion on suitable sites or choosing more resilient tree species to the expected climate change. Vulnerabilities exist for major tree species, such as growth rate reduction due to drought (Allen et al. 2010).

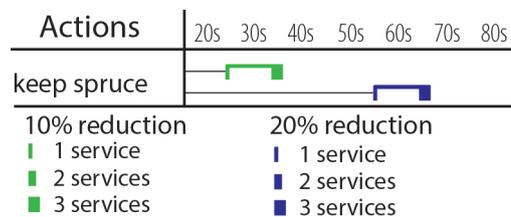
#### **4.2.3.3 Step 3: Forestry actions relevant to forest planning and management**

We chose forestry actions relevant to forest management for which we can quantify forest ecosystem services into the future. The forestry actions are: keep the current tree species, adjustment of forest recreation facilities, and expand tree species to new areas. We grouped all actions into three groups: investment in forest management to growing the current tree species, investment in tourism potential, and investment in forest area expansion. In each group we split the actions for the lowlands and uplands; and we related each action to the three species, except for tourism which is not species sensitive.

#### **4.2.3.4 Step 4: Evaluation of forestry actions**

Each action was evaluated by how much ecosystem service it can deliver with and without climate change, similar to the scorecards by (Haasnoot et al. 2013). We used previously quantified ecosystem services (forest production, stand yield class, carbon sequestration, and tourism) explained in a section 4.2.2 to define expiry dates after which actions will stop delivering the required amount of service. To be able to compare differences among ecosystem services we used relative values. Moreover, we specified two sets of threshold values: a 10% and a 20% reduction indicating decline in the amount of services compared with no climate change impacts. Once an action reaches 10% or

20% threshold value, we define it as an expiry date or a “stop” point. On the contrary, for tourism we defined different threshold values with a 100% and a 200% increase in the number of “good days” as climate change should have a positive impact. These ecosystem services start to drop at first for one and later in the course of time for the remaining two services. The example in Figure 4-3 shows this with various widths of vertical bars or boxes for the number of services (from one to three). The distance between the first and the last expiry date – vertical bars - depicts a “window of necessity”, and is shown as a connecting horizontal bar. This window indicates how much time forest managers have left before remaining services reach their expiry date. The horizontal line in Figure 4-3 indicates that that all services did not reach an expiry date. We evaluated all actions for the lowlands and uplands and for three emissions scenarios.



**Figure 4-3** Illustration of a forestry action and accompanying 10% and 20% threshold values with expiry dates for one, two, and three ecosystem services (forest production, stand yield class, and carbon sequestration). The seven decades range from the 2020s (20s) until 2080s (80s).

#### 4.2.3.5 Step 5: Action expiration map

Having a set of forestry actions with expiry dates defined by ecosystem services at two threshold values, we can draw windows of necessity and adaptation pathways under three emissions scenarios. Expiry dates define limits to each pathway but also specify which action a forest planner can still follow. Consequently, these expiry dates are part of the uncertainty that planners have to face now and will have to face in the future. They do not know how society will value ecosystem services, hence influencing objectives for forest planning and management. Stated otherwise, planners have to deal with ambiguity (Brugnach et al. 2008), as one of the main three sources of uncertainty (introduced in Chapter 1). That is the reason, we offer two threshold values for consideration, for which expiry dates are defined. A second type of uncertainty relates to future socio-economic developments represented by three emissions scenarios before making any decision about forests. In the last step we created an action expiration map for forestry. This map can help to draw adaptation pathways and outline where – in the lowlands or uplands, when – for seven time periods, and under which future – emissions scenarios - adaptation should start.

Furthermore, action expiration maps allow evaluation of whether forest area expansions or orientations to forest tourism are reasonable adaptation options.

### **4.3 Results**

We first present the absolute changes in ecosystem services due to drought or climate change impacts in Scotland. Then, we show the application of the dynamic adaptive policy pathways for Scottish forestry.

#### **4.3.1 Spatiotemporal climate change driven assessment of ecosystem services**

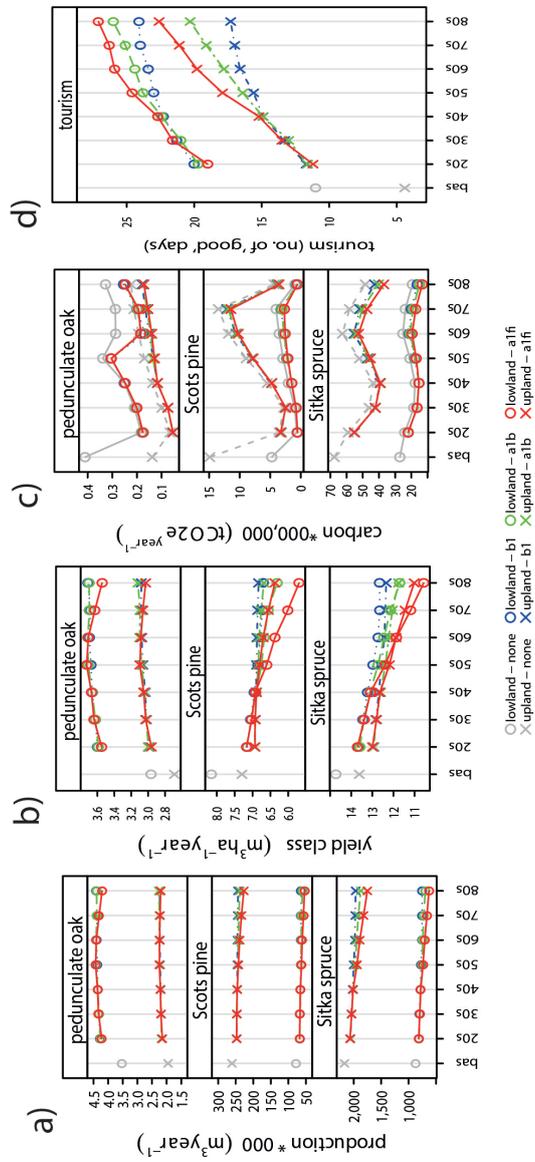
Total future forest production combined for spruce, pine, and oak in the lowlands and uplands reduces compared with the baseline. Spruce contributed the most to this decrease of 664,000 m<sup>3</sup>year<sup>-1</sup>, followed by pine with almost 12 times smaller contribution of 57,000 m<sup>3</sup>year<sup>-1</sup>, and oak contributed with a marginal increase of 900 m<sup>3</sup>year<sup>-1</sup> assessed for the A1FI emissions scenario in the 2080s (Figure 4-4). The absolute forest production for spruce reduces 1.6 times more in the uplands than in lowlands in the 2080s for the A1FI scenario. Furthermore, the difference in spruce forest production between the B1 and A1FI scenarios in the 2080s is 1.7 times higher in the uplands than in lowlands.

Calculated weighted mean stand yield class may decrease or increase for assessed species (see Figure 4-4). Spruce has a higher growth potential in the lowlands rather than in the uplands, but yield class still decrease into the future. However, in the 2080s in the A1B scenario and from the 2060s in the A1FI scenario spruce's yield class in the uplands overtakes yield class in the lowlands. Spruce yield class decreases, for example, from 14.7 to 10.6 m<sup>3</sup>ha<sup>-1</sup>year<sup>-1</sup> in the lowlands for the A1FI scenario in the 2080s. Pine has a yield class almost two-fold smaller than spruce in the baseline, but has a smaller absolute reduction in yield class, from 8.1 to 5.7 m<sup>3</sup>ha<sup>-1</sup>year<sup>-1</sup> in the lowlands in the 2080s. We found a switch for pine to a higher yield class from the lowlands to uplands in the 2050s. In contrast to spruce and pine, oak yield class increases from the baseline over the next 80 years. Apparently, drier conditions help oak to increase its yield class from 2.9 to 3.5 and from 2.6 to 3 m<sup>3</sup>ha<sup>-1</sup>year<sup>-1</sup> in the lowlands and uplands, respectively, by the 2080s.

In Scotland, spruce dominates with the total amount of sequestered carbon in biomass, which is almost five times higher than pine and 173 times higher than oak as Figure 4-4 shows. We estimated the reduction in sequestered carbon combined for the lowlands and uplands forests by species, and compared it with no drought impacts. For spruce, drought impacts can be noticed already from the 2020s, with the highest reduction of 17,502,000 [tCO<sub>2</sub>e year<sup>-1</sup>] in the 2080s

for the A1FI scenario. The highest reduction in sequestered carbon for pine is by 3,400,000 [tCO<sub>2</sub>e year<sup>-1</sup>] in the 2070s for the same scenario. Surprisingly, the highest reduction in sequestered carbon for oak is by 160,000 [tCO<sub>2</sub>e year<sup>-1</sup>] in the 2060s for the B1 scenario. Age distribution and species rotation lengths explain the “s” shape curve of sequestered carbon for all species (more information in appendix, section 7.3).

The climate conditions should become more favourable for light tourism in the lowlands and uplands in Scotland. The mean number of “good days” (Tourism Climatic Index  $\geq 60$ ) during summer months increases almost three times in the lowlands and five times in the uplands over the next 80 years in contrast to the baseline (1961 - 1990) as Figure 4-4 shows. We found a steeper increase in the number of good days in the uplands than in lowlands. Also, the absolute difference between the lowlands and uplands reduces from about 8 good days in the 2020s to 5 good days in the 2080s. The baseline representing standard climate period 1961 – 1990 clarifies the sharp increase in the number of good days to the 2020s.

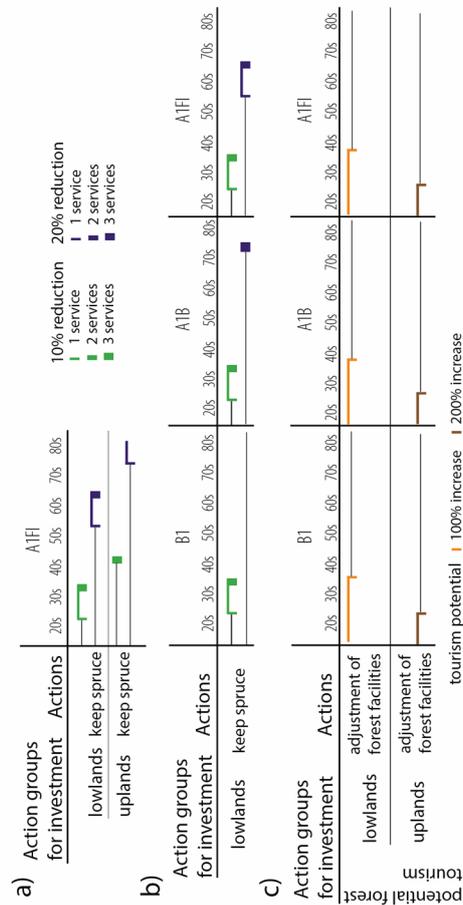


**Figure 4-4** Estimated a) potential forest production; b) potential weighted mean stand yield class; c) potential sequestered carbon; and d) tourism potential for the number of “good days” (Tourism Climatic Index > 60) due to drought and climate change impacts in Scotland for the lowlands and uplands; for the B1, A1B, and A1FI emissions scenarios where “none” represents no climate change; and for the baseline (1961 – 1990) and seven time periods (2020s until 2080s)

### 4.3.2 *Dynamic adaptive policy pathways for forestry – action expiration maps*

We evaluated quantifiable forestry actions for the National Forest Estate for two sets of threshold values a 10% and a 20% reduction in ecosystem services, which defined future expiry dates. We compared changes in provision of ecosystem services relative to no climate change. These changes were computed for two spatial units – the lowlands and uplands – and for three emissions scenarios - B1, A1B, and A1FI. We present results for combined services: forest production, mean yield class, and carbon sequestered.

First, as an example, we present findings on for spruce forestry action and the A1FI emissions scenario, see Figure 4-5. A faster decrease in delivery of these services for a 10% reduction value is in the lowlands with one service already reaching its expiry date after the 2020s and all three services after the 2030s. This results in one decade for window of necessity, whereas in the uplands all three services reach their expiry dates during the 2040s without a window of necessity. For a 20% reduction value, in the lowlands one service reaches its expiry date after the 2050s and all three services after the 2060s with one decade window of necessity, whereas in the uplands only one service reaches its limits in the 2070s. Moreover, as a second example, we extend our results by introducing expiry dates for forest services for three emissions scenarios as shown in Figure 4-5. Only at 20% reduction value, expiry dates for forest services differ, with no expiry dates for the B1 scenario, but all three services reach expiry dates for the A1B scenario after the 2070s and for the A1FI scenario after the 2060s. In a final example we present expiry dates for summer months for tourism potential, with positive expiry dates of a 100% in the lowlands and a 200% in the uplands. We found that in the lowlands and uplands and across three emissions scenarios the climate will become more favourable reaching positive expiry dates after the 2020s or 2030s making forests more valuable for recreation, see Figure 4-5.



**Figure 4-5 Expiry dates of a 10% and a 20% values for forest production, mean yield class, and carbon sequestered for spruce forestry action a) in the lowlands and uplands; b) for the B1, A1B, and A1FI emissions scenarios. Expiry dates c) for a 100% and a 200% increase for tourism potential for the B1, A1B, and A1FI emissions scenarios**

Building upon the set of threshold values with expiry dates for all services, for all forestry actions in the lowlands and uplands, and for all emissions scenarios, we developed action expiration maps for Scottish forestry under climate change impacts over the next 80 years. For a 10% reduction value, we found the need to adapt first in the lowlands for pine action already now and for spruce action after the 2030s. Second, in the uplands the need to adapt for spruce action is in the 2050s for the B1 or in the 2040s for the A1FI scenario, and for pine action in the 2060s for the A1FI scenario (see Figure 4-6). For a 20% reduction value, the results show a delay in the need to adapt in the lowlands with expiry dates for spruce and pine actions occurring in the 2050s or 2070s for the A1B and

A1FI scenarios, respectively. However, there are no expiry dates for actions in the uplands. Orientations to forest tourism or forest area expansion in the uplands can compensate for losses in the delivery of forest production, mean yield class, and carbon sequestration. Our findings show how a “window of necessity” changes and show urgency to take an action. But, taking an action depends on the planner’s perceptions of risk and their decisions. For example, in the lowlands pine action reduces the window of necessity from infinite to 30 years from the B1 to A1FI scenarios. Combining information about expiry dates for all forestry actions, we illustrate manually drawn adaptation pathways for a 10% threshold value with expiry dates across three scenarios (see Figure 4-6). They indicate when each forestry action reaches its expiry date and where this loss can be compensated. Overall, Scottish forestry should adapt by investing in tree species in the uplands which will have more favourable climate change conditions.

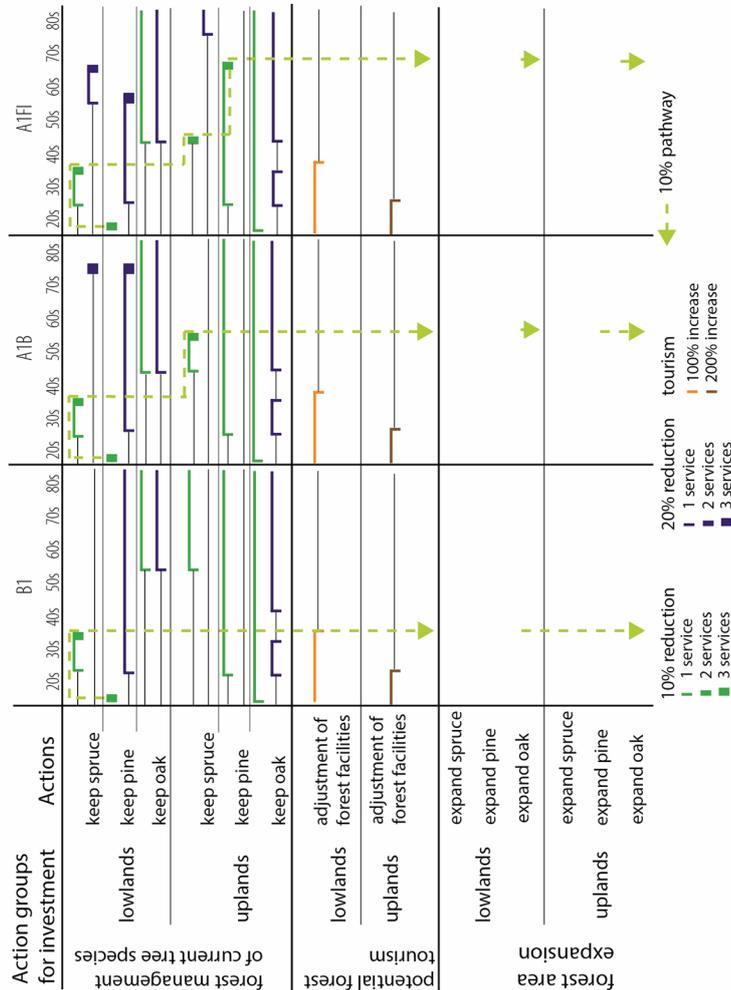


Figure 4-6 Action expiration map for the National Forest Estate in Scotland with an example of manually drawn pathways in light green dashed line for 10% reduction. Map shows expiry dates for a 10% (green) and a 20% (blue) reduction of ecosystem services; expiry dates for potential tourism for a 100% (orange) and a 200% (brown) increase; for the B1, A1B, and A1FI emissions scenarios, and over the next seven decades (the 2020s until 2080s).

## 4.4 Discussion & conclusions

### 4.4.1 Spatiotemporal assessment of ecosystem services

The findings for the major Scottish tree species show that future drought can largely reduce provision of key forest ecosystem services (forest production, mean yield class, and sequestered carbon), while climate change can increase

tourism potential. Drought impacts for all assessed tree species can result in a forest production loss up to 270,000 m<sup>3</sup> year<sup>-1</sup> in the lowlands (28.3% of total production) and a loss up to 450,000 m<sup>3</sup> year<sup>-1</sup> in the uplands (18.5%) in the 2080s (see Figure 4-4). To minimise these impacts, forest managers can apply different adaptation measures, such as a choice of drought tolerant species or apply relevant silviculture practices. The appropriate choice of forest management is important, as forest management has a higher impact on wood production than climate change (Schroter et al. 2005). At a national scale, Metzger et al. (2008) have shown a relatively small reduction in wood production until 2050-2080 across Scotland generalized for Atlantic north stratum, whereas production forecasts for softwood timber availability for Scotland showed a steep decline until 2036 by about 21.8% (Forestry Commission 2012a).

Relative changes in the stand yield classes were similar to forest production with a reduction for spruce in the lowlands up to 4.16 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> (28.2% of yield class) and in the uplands up to 2.6 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> (19.1%) in the 2080s (see Figure 4-4). Because spruce is a major timber species, these results can have a long-term impact on sustainable timber production with an average 50-year rotation period. Other studies have shown impacts of drought from a 30% reduction of gross primary productivity across Europe after the 2003 heat-wave (Ciais et al. 2005), worldwide forests' vulnerability to drought due to hydraulic failure (Choat et al. 2012), and negative modelled drought impacts on growth of Scots pine in Scotland (Xenakis et al. 2011).

Another assessed service was sequestered carbon in the standing trees. For spruce, estimated sequestered carbon in the lowlands reduced up to 6,010,000 tCO<sub>2</sub>e year<sup>-1</sup> (31% of total carbon) and in the uplands reduced up to 11,492,000 tCO<sub>2</sub>e year<sup>-1</sup> (41%) in the 2080s for the A1FI scenario (see Figure 4-4). Evidence from the previous studies suggested that drought conditions can turn forests into carbon sources as reported after the 2003 heat-wave in Europe by (Ciais et al. 2005); after extreme events, such as wind-throw with estimated 30% reduced carbon balance from the Lothar storm (LINDROTH et al. 2009); and from a combination of stem increment reduction and an increase in number of natural events (Nabuurs et al. 2013). Additionally, estimates of carbon sink in the British forests and in Scotland indicate reductions from 10.5 MtCO<sub>2</sub> year<sup>-1</sup> in 2005 to 5 MtCO<sub>2</sub> year<sup>-1</sup> by 2020, with missing information beyond 2020 (Read et al. 2009).

The last assessed service was tourism potential, indicating a positive impact of climate change with a high increase up to 16 "good days" equivalent to 250% in the lowlands and up to 19 "good days" equivalent to 520% in the uplands for the

2080s and the A1FI scenario (see Figure 4-4). Using the same index but different climate datasets, other studies reported a northward shift of “good” days to southern Scotland in the 2060s or 2080s (Hein et al. 2009; Perch-Nielsen et al. 2010), and an increase in the frequency of good days by about 5 days (Perch-Nielsen et al. 2010). Overall, we found that due to drought impacts forests in the lowlands show a smaller absolute reduction in ecosystem services than in the uplands, but the relative decrease in the provision of ecosystem services is larger in the lowlands, hence the uplands seem to be more resilient to drought.

#### ***4.4.2 Dynamic adaptive policy pathways – action expiration maps***

We found that climate change adaptation in Scottish forestry in the lowlands should start already now or in the next two decades because of expiry dates for spruce and pine forestry actions reaching a 10% reduction. For a 20% reduction value, the same actions in the lowlands reach their expiry dates from the 2050s. Furthermore, managers need to consider what amount of future services is at a stake, for example with spruce covering more than 50% of forested area in Scotland. In contrast, opportunities exist for managers, either with a shift to forest tourism or with forest area expansion preferably in the uplands. Our two threshold values – a 10% and a 20% reduction – with expiry dates provide a direction for possible pathways but these will of course also depend on planners’ risk attitudes and perceptions. This topic will be introduced and dealt with in the following Chapter 5. The planners risk perceptions will drive choices of forestry actions, as a study by O’Connor et al. (2005) has shown for water managers. Moreover, action expiration maps offer crucial information for forest management, mainly to evaluate lead time for taking actions and support climate change adaptation for forest policies. First, information about when actions can reach their expiry dates can help managers to define their lead time with knowledge about their financial, human, and technical resources. Second, action expiration maps and pathways addressing inherent climate change uncertainty can support new types of climate change policies with specific recommendations when, where, and how much current forests should change to maximise provision of forest services. This can help managers to make informed decisions while avoiding inappropriate adaptation measures that can make a system even more vulnerable (Barnett & O’Neill 2010). Furthermore, we believe policy makers should start doing “climate stress testing”, introduced by Swart et al. (2013), considering possible climate impacts to enhance forestry resilience and to evaluate adaptation policies with essential information from our action expiration maps.

The limitations of our study are the use of a single impact model – Ecological Site Classification – with limited knowledge about extreme droughts, and the use of a generic Tourism Climate Index mainly developed for southern Europe. On the other hand, strengths are the application of dynamic adaptive policy pathways as action expiration maps, the assessment of a wide range of forest ecosystem services into the future, and the assessment at high spatial and temporal resolution with probabilistic climate data. Additionally, our action expiration maps are flexible, meaning that new understanding about climate change and forest ecosystem services can refine and improve them.

#### **4.4.3 Conclusions**

This study has assessed for the first time a wide range of forest ecosystem services at a high spatial and temporal level across Scotland, which has been missing at a regional scale. Overall, drought impacts should reduce the provision of the traditional forest ecosystem services more in the lowlands than in the uplands. But, climate change impacts offer opportunities for forestry with a shift to tourism or to expansion of forest area preferably in the uplands. Additionally, assessed services enabled us to develop action expiration maps and to provide quantified expiry dates for ecosystem services while offering directions for adaptation with forestry actions. Finally, this study contributed to reducing climate change uncertainty and offer adaptation options for forestry.



## Chapter 5

### **New climate change information modifies decision makers' frames and decisions**

Information available to decision makers influences their decisions. Understanding and interpretation of this information by individuals can differ, which can result in different views on a problem under investigation as well as in a reduction or an increase of uncertainty. This chapter explores the ambiguity of forest planners about forestry actions affected by the new climate change information. Hence, in this chapter we treat uncertainty from a decision maker's perspective rather than a modeller's perspective as introduced in Chapter 1. With this perspective we focus on an influence of uncertainty on decisions in forest planning. Additionally, based on the three sources of uncertainty as presented in Chapter 1, this chapter addresses mainly ambiguity (see Figure 1-3).

This chapter is based on:

Petr, M., Boerboom, L., Ray, D., van der Veen, A., 2014 New climate change information modifies decision makers' frames and decisions – an exploratory study in forest planning, *to be submitted*

## **Abstract**

Information helps decision makers to address and to decide about environmental problems. In the context of climate change adaptation, knowledge is missing how the available information from impact models affects decision-making process. The main aim of this study was to explore the influence of new climate change information on forest planners' decisions and the presence of ambiguity. We investigated planners' decisions about forestry actions representing species choice and forest tourism, and their expiry dates representing environmental constraints to provision of ecosystem services. Forest planners evaluated expiry dates with use of four forest ecosystem services: forest production, stand yield class, sequestered carbon, and potential tourism previously assessed under drought and climate change impacts. Data were collected during workshops with ten forest planners from three Forest Districts in Scotland. Presented climate change information modified planners' understandings and frames about forestry actions assessed with their expiry dates. Changes in the planners' frames result mainly in sooner but sometimes also in later expiry dates. When confronted with emissions scenarios uncertainty, planners in a group inclined to cautious decisions about forestry actions leading to a smaller urgency to act. Planners' ambiguity was found to be dependent on planners' diverse frames and difficulty to evaluate multiple ecosystem services. These findings imply that due to ambiguity forest planners might find it hard to choose climate change adaptation measures.

## 5.1 Introduction

Climate change will have an impact on both socio-economic and environmental systems but whether or not and how society should adapt is still a discussion of many public forums and research debates (IPCC 2007; Adger et al. 2009). The knowledge about climate change impacts on different types of ecosystems is available in many studies at global or regional scales (Fischlin et al. 2007; Schroter et al. 2005; Bateman et al. 2013). However, uncertainty remains about climate change impacts due to the natural variability of a climate system and due to our lack of knowledge about its natural processes. Climate change uncertainty also influences the decision makers' perceptions of climate change risks, as was the case for forest planners (see chapter 2). Decision makers managing natural ecosystems, such as forests, will have to decide which suitable climate change adaptation measures they want to apply (Lindner et al. 2010). The factors that influence their decisions in applying adaptation measures are, for example, climate change risk perceptions (Etkin & Ho 2007)(see chapter 2), beliefs about climate change (Blennow & Persson 2009), and the framing of climate change as a problem (Dewulf 2013; Morton et al. 2011). But, knowledge is still missing about how decision makers change their understandings or frames about climate change with new information.

Information about future climate change impacts presented to decision makers should support their decision-making and help them to adapt to the potential adverse impacts. Climate change adaptation aims to reduce potential future impacts (Jones et al. 2012). But, in applying adaptation measures decision makers should try to avoid maladaptation – a situation when applied adaptation measures make the system more vulnerable (Barnett & O'Neill 2010). Crucial aspects of adaptation are the views decision makers have on climate change as represented by their “frames” and how they frame problems related to climate change. By frames we mean an interpretation of a reality or a problem (Brugnach et al. 2008). In addition, in a situation when decision makers have multiple frames about a reality then ambiguity, as uncertainty, occurs (Dewulf et al. 2005). The analysis of people's frames and framing has many benefits, for example, it helps to better understand how people make decisions (Tversky & Kahneman 1981), to find differences of a problem's understanding by decision makers (Brugnach et al. 2008), and to understand the information that is used to address a problem and whether a problem exists (Dewulf 2013). Additionally, a problem, such as use of land in a national park, can be framed in multiple ways and consequently will result in diverse perspectives with different solutions (Dewulf et al. 2005). We can illustrate the concept of framing, for example, through a case of when pests damage a tree, with one frame highlighting the

high vulnerability of the tree to pest attack and the other frame stressing the high capability of pests to damage the tree.

All aspects of framing also apply to the climate change adaptation discourse. A study by Dewulf (2013) concluded that understanding of a problem, and of frames about gathered and used information are important for climate change adaptation. Types of information presented to a decision maker will influence his/her frame resulting in different understandings of a problem and possibly in taking different actions. Nevertheless, knowledge is lacking whether frames can direct or delay adaptation actions (Dewulf 2013). Previous studies mainly investigated what frames decision makers have about a decision problem (Dewulf et al. 2005) and about climate change (Morton et al. 2011), but empirical knowledge is still missing on whether new information will change the frames decision makers hold for a particular climate change problem.

Hence, the main objective of this study is to explore whether new climate change information about drought and climate change will modify the frames of forest planners, for the case of National Forest Estate management in Scotland. We investigated changes in planners' frames on forestry actions, which represent those forest management activities planners do as part of the planning process. Consequently, the three research questions examined in this study are: i) from which decade do forest planners believe climate change impacts will become serious, ii) will planners change their initial frames about forestry actions suitable for climate change adaptation when confronted with new climate change information, and iii) will forest planners make different decisions about a set of forest management actions when confronted with uncertainty about emissions scenarios. To answer these questions we first used information from the assessment of drought and climate change impacts on four ecosystem services to show two possible threshold values with expiry dates for forestry management actions. These threshold values were specific for each of the three investigated forest districts. Second, threshold values with expiry dates for eight forestry management actions were incorporated into action expiration maps based on the method of dynamic adaptive policy pathways (Haasnoot et al. 2013)(see chapter 4). Finally, using information from the action expiration maps in three workshops we explored how forest planners decide about forestry actions with and without climate change information.

We structured this chapter as follows. First we describe the structure of the workshops used to explore forest planning without and with new climate change information, and with an outline description of how we analysed the data. Next section presents the results, showing changes in the frames of forest planners due to different expiry dates of forestry actions. The final section discusses the

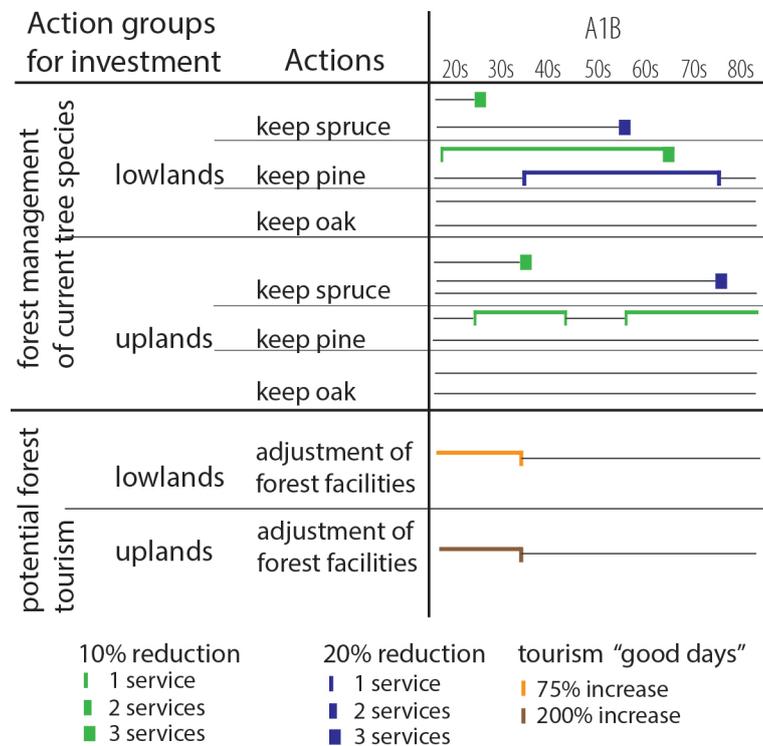
findings in a wider climate change adaptation context in forest planning and management and concludes with a summary of the stud.

## **5.2 Materials and Methods**

### **5.2.1 Input data**

Information for the workshops consisted of eight pre-defined forestry actions evaluated with four ecosystem services and incorporated into an action expiration map for each of the three districts. These districts were: Moray & Aberdeenshire (Moray), Dumfries & Borders (Dumfries), and Galloway. These actions (see Figure 5-1) relate to two groups: a) investment in keeping the current species while applying the same forest management and b) investment in potential forest tourism to improve forest facilities. Additionally, we split the actions into the lowlands and uplands as described in Chapter 3 because of different tree growth rates. The forestry actions were assessed for four forest ecosystem services: the traditional provisioning services of forest production and mean stand yield class, and the regulating service of sequestered carbon; and a new cultural service: tourism potential. These services were assessed for drought and climate change impacts, as described in Chapter 4.

To simplify the information to the planners, we defined two specific threshold values and expiry dates for forestry actions for each district because of different climate change impacts on traditional ecosystem services. For example, when a 10% threshold value drops below 10%, this is when an expiry date occurs. Therefore, these threshold values were set for traditional services accordingly: in Dumfries at 10% and 20% reduction, in Galloway at 5% and 15% reduction, and in Moray at 20% and 30% reduction. The two threshold values per district indicated a degree of change relative to no climate change impacts on a time scale from the 2020s until 2080s. The final action expiration maps presented to the planners consisted of action groups, forestry actions in the lowlands and uplands, and assessed ecosystem services illustrated as coloured boxes on a time scale from the 2020s until 2080s, see Figure 5-1. The green and blue boxes represent three traditional ecosystem services — forest production, stand yield class, and sequestered carbon, and the orange and brown boxes represent potential tourism as number of “good days”.



**Figure 5-1 Example of an action expiration map for medium (A1B) emissions scenario with two threshold values at 10% and 20% for ecosystem services and at 75% and 200% for tourism "good days". Horizontal lines represent no expiration for forestry actions.**

### 5.2.2 Frames in forest planning

Forest planners have their own views and interpretations of forests, which provide multiple benefits for people, such as a source of a timber and a place for recreation. Of course, the planners are aware of multiple ecosystem services forests deliver, which have also been introduced in recent forestry policies (Forestry Commission Scotland 2013). The evidence from the previous research in Britain suggests that forest planners actively manage uncertainty associated with forest models and they also believe in high degree of controllability of drought impacts with forest management (see Chapter 2). This observation confirms that the planners already have their own frames of drought and acknowledge the limits of forest models. Therefore, they should be keen to actively look for information and adaptation options to climate change. However, planners' frames about a problem under investigation can change due to new information, which can be provided from the research community. For example, a study of natural resource management in Ecuador by Dewulf et al (2005) showed a that diverse understanding of problems among stakeholders

stimulated with different information led to changes in stakeholder frames. Similarly, forest planners in their plans have to consider multiple services that forests provide as well as diverse demand from the public. But, the conflict of interests among stakeholders and the public, about the best use of forests, can be a reason of ambiguity for the planners. Ambiguity is then a source of uncertainty as explained in the Chapter 1 and is a part of our uncertainty space (see Figure 1-3). In the case of forest planning, we then have to understand forest planners' frames of forestry actions and associated ecosystem service, climate change, and the urgency for their decisions. Analysis of these frames then allows us to better understand the reasons for the planning decisions and to explain the planners' willingness to adapt to climate change.

### **5.2.3 Data collection**

#### **5.2.3.1 Workshop design and assessment**

To explore how forest planners decide about forestry actions without and with new climate change information in their own district, we used a workshop setting. This workshop setup was selected as it proved to be suitable a method in similar studies, for example, in exploring stakeholders' preferences about coastal management (Tompkins et al. 2008) and investigating expert judgments of alternatives for forest management (McDaniels et al. 2012). The strength of our design was, first, without any prior information about climate change, to explore how planners define expiry dates to forestry actions and then, with presented climate change information, how they define expiry dates to the same actions. We could thus investigate whether new climate change information would stimulate change in the planners' frames, and how their decisions changed under uncertainty conditions. Additionally, the workshops helped us to collect data, to interact with planners, and to investigate how planners make decisions in a small group. The limitations of our workshops were that their preparation was time consuming and we ran them with a small number of forest planners.

We structured the workshop into five steps listed in Table 5-1. The first two steps investigate the planners own forestry management actions associated with drought and then explore how they define expiry dates to pre-defined forestry actions. The concept of expiry dates as limits is not new to forest planners because they already set their own constraints to different forestry actions in their day-to-day decisions, such as limits for tree growth. In the third step we presented and explained to the planners drought and climate change impacts on forests, and described step-by-step the development of action expiration maps. The fourth step involved investigating decisions about pre-defined forestry actions but this time with new information about drought and

climate change impacts shown in action expiration maps. In the final step planners evaluated the practicality of the presented information for forest planning. Each step consisted of one or two simple tasks, which took about 15 minutes each, and a group discussion that lasted between 45 to 60 minutes. We pre-tested the workshop within our research group before running the workshops with the planners.

**Table 5-1 Workshop structure with the main steps and a description of tasks presented to the planners**

<b>Main steps in a workshop</b>	<b>Description of tasks</b>
1 <sup>st</sup> : Investigating forestry actions related to drought impacts without presenting any information	- A blank sheet for forestry actions. Planners define expiry dates for forestry actions and provide reasons for their decisions; planners also describe drought in their own words.
2 <sup>nd</sup> : Exploring expiry dates to a pre-defined list of forestry actions related to drought impacts without presenting any information	- A sheet with a pre-defined list of actions for which planners have to define an expiry date for each action; and provide reasons for their decisions.
3 <sup>rd</sup> : Explaining to planners drought and drought risk assessment for forestry; explaining forest related ecosystem services; and describing step-by-step modified dynamic adaptive policy pathways for forestry on an action expiration map	- no task
4 <sup>th</sup> : Exploring use of climate change information in action expiration maps by forest planners to define expiry dates to forestry actions for one or three emissions scenarios	- A sheet with information in an action expiration map for pre-defined list of actions for a district:  - first, individual planners define expiry dates for actions with information for one randomly chosen emissions scenario and provide a rationale for their choice. - second, a group of planners define expiry dates for actions with information for three emissions scenarios and provide a rationale for their choice.
5 <sup>th</sup> : Evaluating the forestry actions and a usefulness of information in action expiration maps for forest planning	- A sheet with four statements asking how difficult it was for planners to make decisions about forestry actions with presented information

In total, the planners undertook five tasks as outlined in Table 5-1. In the first task the planners free listed forestry actions related to their own understanding of drought impacts in their district. Then, for each action they specified expiry date in the future. In the second task planners defined for a pre-defined list of forestry actions when these might or might not reach their expiry date. For the expiry dates we used seven future decades from the 2020s until 2080s to keep it consistent with time periods in climate change data. For the third task we first provided to each planner an action expiration map for their district with two assessed threshold values - district specific – and for one randomly chosen emissions scenario. The planners then specified an expiry date for each forestry action. After individual assessments of forestry actions, the planners collectively decided in a group on expiry dates for forestry actions while considering all three emissions scenarios. In the last task the planners reflected on how useful they found presented information in the action expiration maps for their forest planning. Specifically, we investigated how easy it was for them to define expiry dates for actions and to decide about actions with two different threshold values. We collected all responses from planners in task sheets and audio-recorded the discussions during workshops.

#### **5.2.3.2 Study area**

We approached planning teams in three Forest Districts in Scotland, with different estimated drought impacts on key forest ecosystem services. This allowed us to gain an understanding of diverse opinions about drought and climate change impacts across Scotland. We chose Forest Districts of the National Forest Estate, managed by Forestry Commission Scotland, as a study area because drought is expected to have a large impact on forests and on the provision of ecosystem goods and services.

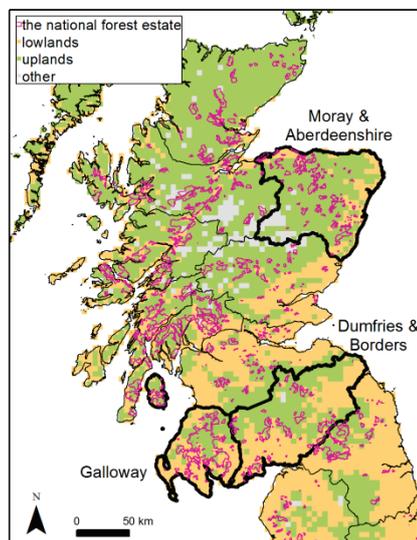
Table 5-2 presents information about species composition in each district and Figure 5-2 shows extent of the forested area in each district. For each district we ran either a full-day or a half-day workshop with the planning team in January 2014. About a third of all planners employed by Forestry Commission Scotland took part in the workshops with five planners in Moray & Aberdeenshire, three planners in Dumfries & Borders, and three planners in Galloway. All workshops were held in the district offices, which provided a natural environment for planners.

**Table 5-2 Summary statistics for the main tree species within the three Forest Districts in Scotland**

Forest district	Sitka spruce (% from a district)	Scots pine (% from a district)	Broadleaves (including pedunculate oak) (% from a district)
Dumfries & Borders	35,920 ha (80%)	6,286 ha (14%) <sup>a</sup>	2,694 ha (6%)
Galloway	58,592 ha (79%)	6,984 ha (9%) <sup>b</sup>	3,070 ha (4%)
Moray & Aberdeenshire	18,608 ha (38%)	12,732 ha (26%)	2,448 ha (5%)

Notes: <sup>a</sup> - for pines and larches; <sup>b</sup> - for pines

Source: Forest districts strategic plans: <http://www.forestry.gov.uk/fesplans>



**Figure 5-2 Three assessed Forest Districts in bold with the extent of the National Forest Estate and classified land to the lowlands and uplands**

#### 5.2.4 Data analysis

We conducted data and text analysis of the planners' responses to show how the planners decide about expiry dates for forestry actions both without and the with climate change information. We organised and coded all planners' written responses by tasks and by forest district into a spreadsheet. Recordings from group discussions were transcribed, where the planners discussed and defined expiry dates to forestry actions for three SRES scenarios. Then, we coded (Babbie 2010) all forestry actions from the free listing task into the following groups: require information, other actions, silviculture practice, site preparation, and species choice. Next, we decoded unclear responses for expiry dates of

forestry actions to specific decades, such as “the rest of the century” was decoded to 2100. Also, when the responses were unavailable or unclear we used text in a rationale, specified by the planners, to define expiry dates for actions. Having coded forestry actions, we calculated absolute frequencies for actions by expiry dates into decades. These frequencies were compared with planners’ responses before and after we presented to them the climate information in the action expiration maps. We then analysed transcribed discussions among planners about setting expiry dates for forestry actions. Finally, we evaluated how helpful the information from the adaptive pathways approach in action expiration maps was for planning practice and how easy it was for the planners to define expiry dates for forestry actions on a 7-point Likert scale (from 1 very helpful to 7 very unhelpful, and DN for don’t know). We performed all the analyses in R 2.14.2 statistical software (R Development Core Team 2012) with plyr 1.8 package (Wickham 2011), and used the lattice 0.20-10 package for visualization (Sarkar 2008).

### **5.3 Results**

Results are presented in five sections structured by tasks in the same sequence as presented during the workshops and with one additional section for comparing results. First, we provide a summary of the free listing of forestry management actions relevant to forest planning. Next, we summarise responses indicating expiry dates of forestry actions first without any climate change information and then with the provided climate change information. Additionally, we present observations from a group discussion among planners about forestry actions. Then, we highlight observed differences in planners’ understanding of forestry actions and their expiry dates due to new climate change information. Finally, we evaluate the usability of the new climate change information for forest planning.

#### **5.3.1 Free listing of forestry management actions**

Without any information about climate change and drought the forest planners had to free list any forestry actions they considered drought sensitive and relevant to their district. Additionally, they had to define expiry dates for these actions and provide a rationale for their choice. In the Moray district – with a relatively dry climate and with the highest potential drought impacts – the planners indicated that 13 actions (46% of total number of all actions) would reach their expiry dates in the 2050s, see Figure 5-3. The planners identified the site preparation and silviculture practice actions as the dominant ones in the 2050s. Still, the planners were unable to define expiry dates for seven actions (25% of total number of all actions). On the other hand, in the Galloway district – with a relatively wet climate - planners believed that no expiry dates in the

future would exist for four forestry actions related to drought, with species choice representing the main forestry action. In the Dumfries district – with a relatively wet climate in the west and a dryer climate in the east – the planners indicated that eight forestry actions (60% of total number of all actions) would reach their expiry dates by the 2030s. The planners in Dumfries identified expiry dates for species choice action in most of the time periods. From all forestry actions the planners recognised the species choice action in all forest districts to be sensitive to drought impacts and hence important for the future forest planning.

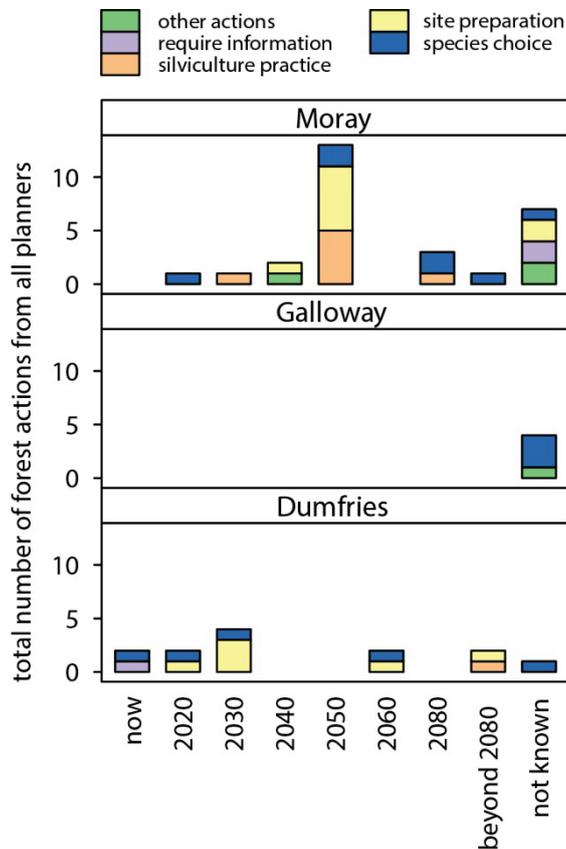


Figure 5-3 Frequency of free listed forestry actions and their expiry dates in the future in three Forest Districts in Scotland (planners: Moray n=5, Galloway n = 3, and Dumfries n = 3)

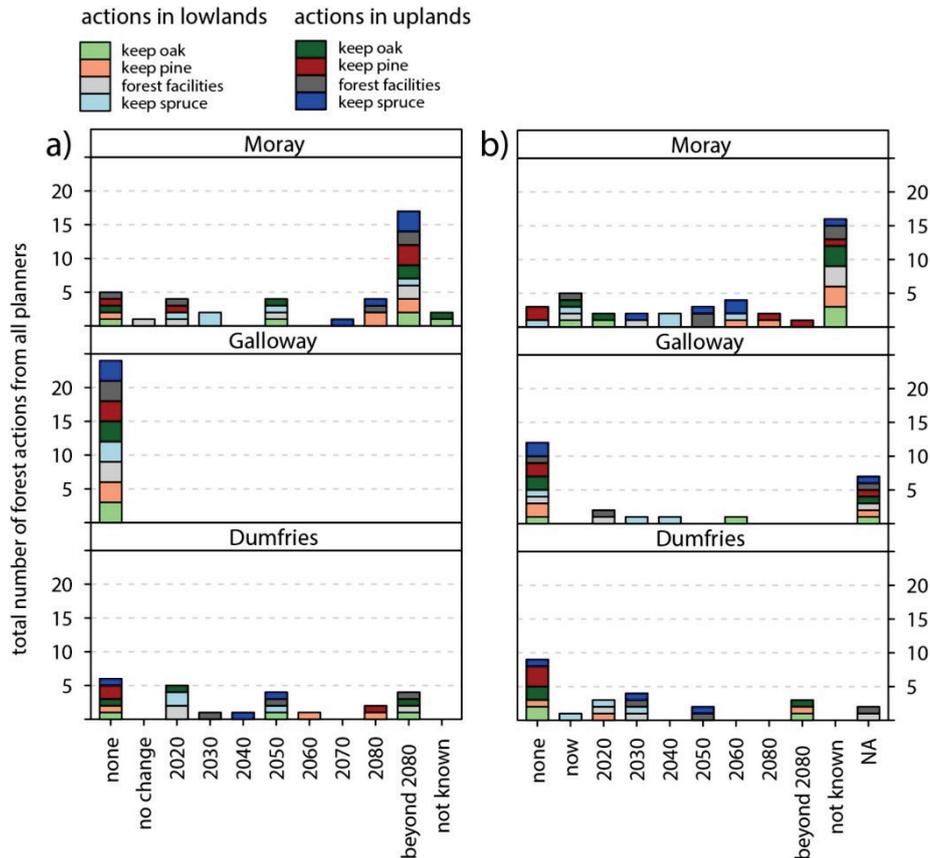
### ***5.3.2 Expiry dates for pre-defined forestry actions without climate change impacts information***

Next, the planners were asked to define expiry dates for eight pre-defined forestry actions and to provide a rationale for their choice. Having a concrete and meaningful list of actions, the planners were able to define future expiry dates for forestry actions, except for two forestry actions in the Moray district (see Figure 5-4). In Moray the planners believed that 10 forestry actions (25% of total number of all actions) would reach their expiry dates by the 2050s while five actions (12.5% of total number of all actions) have no future expiry date. In Galloway the planners indicated no expiry dates for all forestry actions, the same as the responses to their own list of actions in the previous task. In Dumfries the planners defined that 11 forestry actions (45% of total number of all actions) would reach their expiry dates by the 2050s and six forestry actions (25% of total number of all actions) would have no expiry dates in the future. The results show that in Dumfries the relative number of forestry actions until the 2050s is two times higher than in Moray. This might imply that the planners in Dumfries are more cautious or have higher drought risk perceptions.

### ***5.3.3 Expiry dates for pre-defined forestry actions with climate change impacts information***

After providing new information about drought and climate change impacts through action expiration maps, we asked the planners again to evaluate and define individually the future expiry dates for the same eight forestry actions. This time we randomly assigned drought impacts for one of three SRES emissions scenarios to each planner to reduce anchoring effects (Tversky & Kahneman 1974). In Moray the planners indicated that 14 forestry actions (35% of total number of all actions) would reach their expiry dates by the 2050s and only three actions (7.5% of total number of all actions) would have no future expiry dates (see Figure 5-4). However, the planners were unable to decide about expiry dates for 16 forestry actions (40% of total number of all actions) – representing responses for “not known” category. In Galloway the planners' responses show that four forestry actions (16% of total number of all actions) would reach their expiry dates by the 2050s, but still the largest proportion of actions equals to 12 (50% of total number of all actions) would have no expiry dates in the future. One undecided planner was the reason for the high number of “NA” responses. In Dumfries the planners believed that ten forestry actions (41% of total number of all actions) would reach their expiry dates by the 2050s but nine forestry actions (37.5% of total number of all actions) would have no expiry dates in the future. In all districts forestry actions in the lowlands – drier and warmer areas – would have their expiry dates mostly in the first half of the 21<sup>st</sup> century, whereas the majority of actions in the uplands would show either

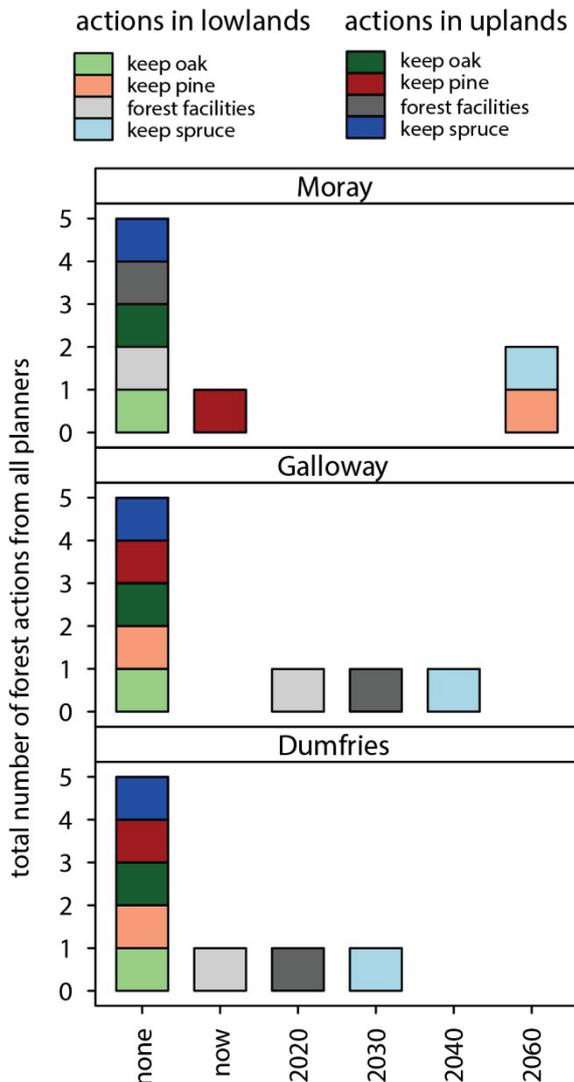
no expiry dates or unknown expiry dates. In Figure 5-4 actions in the lowlands are depicted with lighter and actions in the uplands with darker colours.



**Figure 5-4 Frequency for eight pre-defined forestry actions and their expiry dates in the future defined by individual planners a) without climate change information and b) with new climate change information available for three Forest Districts in Scotland (planners: Moray n=5, Galloway n = 3, and Dumfries n = 3)**

Next, we provided to a group of planners information about drought and climate change impacts for all three SRES emissions scenarios – B1, A1B, and A1FI (see all three maps in appendix in section 7.4.3). In the group they had to define expiry dates for the same eight forestry actions. With this group exercise we wanted to give planners a chance to exchange opinions about actions' expiry dates and even to clarify to each other what these dates might imply for their district. In all districts the planners decided that five forestry actions (62.5% of all forestry actions) would have no expiry dates in future (see Figure 5-5). In Moray the planners believed that two forestry actions in the lowlands (keeping pine and spruce) would reach their expiry dates in the second half of the

century, whereas in the uplands action for keeping pine had already reached its expiry date. In the other two districts the planners indicated that forestry actions of adjustment of forest facilities, related to forest recreation, in the lowlands and uplands would reach their expiry dates during the next 20 years. This means that more suitable conditions for recreation would come resulting possibly in a higher investment to forest facilities. The planners also suggested that for the major productive conifer species in Scotland – Sitka spruce – its expiry date would be reached in the lowlands by the 2030s and 2040s in Dumfries and in Galloway, respectively. Comparing the results from the group discussion with that of the individual planners, we found differences especially for no expiry dates (the “none” category), which in a group represented 62.5% of actions but assessed by individual planners ranged between 7.5% to 50%, see Figure 5-4 and Figure 5-5. Surprisingly, in Moray the action for pine in the uplands reaches its expiry date now even though information in the action expiration map did not show a steep decline in ecosystem services.



**Figure 5-5** Frequency for eight pre-defined forestry actions and their expiry dates in the future from a group discussion among planners with climate change information available for three Forest Districts in Scotland (planners: Moray n=5, Galloway n = 3, and Dumfries n = 3)

In a group setup, the planners discussed what are the expiry dates to forestry actions and also their relevance to the district. The Table 5-3 shows several comments from a group discussion. Even though the group discussion was the longest task it was hard for the planners to find a consensus about expiry dates for forestry actions.

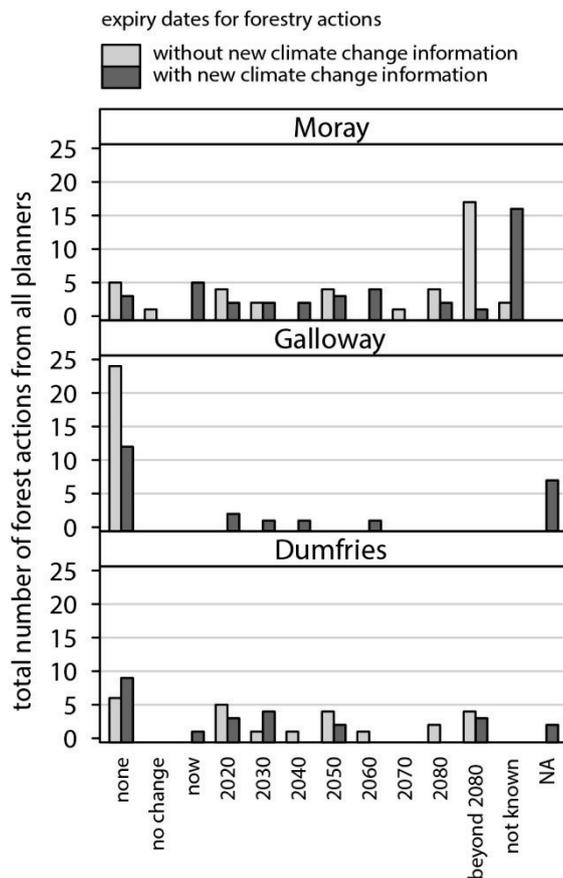
**Table 5-3 Comments from group discussion about defining expiry dates for forestry actions**

District	Comments from districts
Moray & Aberdeenshire	<ul style="list-style-type: none"> <li>- "it was hard to use relative reduction values, even though good indicators, but better to use absolute values"</li> <li>- "Pine is very important in a district and is under a stress in the future"</li> <li>- "no alternatives for actions in the lowlands hence accepted higher losses"</li> </ul>
Galloway	<ul style="list-style-type: none"> <li>- "able to choose the best species in case (they) would have yield classes as absolute values"</li> <li>- "You have to cover all three scenarios (when discussing expiry dates)"</li> <li>- "Depending on forest objectives you might expand (forests)"</li> </ul>
Dumfries & Borders	<ul style="list-style-type: none"> <li>- "It depends if you are happy with a 10% reduction. I will go for 20%. (for forest services)"</li> <li>- "I do not want to lose 20% (of services)"</li> <li>- "Happy with 10% (reduction of forest services). 20% we start to have an interest (start thinking about options)"</li> <li>- "Tree are becoming less suitable but recreation more suitable (provision of services from forests)"</li> </ul>

*Note: authors' comments in brackets*

#### **5.3.4 Comparison between expiry dates for forestry actions without and with climate change information**

We compared individual planners' responses for expiry dates of all eight forestry actions first without and then with the information about drought and climate change impacts. Climate change information was always related to a district. In Figure 5-6 we see a small shift in expiry dates for forestry actions to earlier decades across three districts after the planners have seen the new climate change information. For example, in Dumfries more forestry actions have their expiry dates now and in the 2030s. Having additional climate information, the planners reduced the amount of forestry actions with no expiry dates (the "none" category) by two actions in Moray, and by 12 actions in Galloway. On the other hand, the number of forestry actions with no expiry dates increased by three in Dumfries. If the planners would have no ambiguity about specifying expiry dates for forestry actions then we would expect the same expiry dates without and with the new climate change information. However, the results show that ambiguity, as multiple views on a problem, exists as planners changed their decisions about forestry actions.

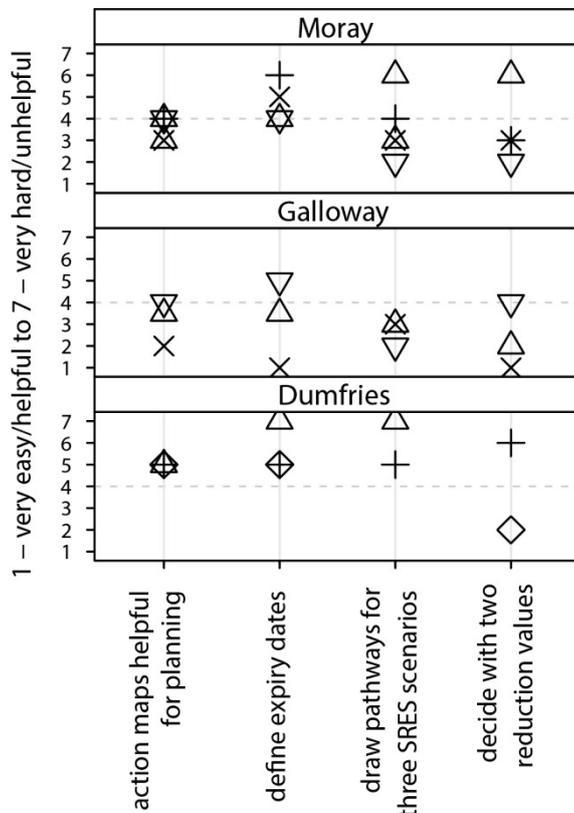


**Figure 5-6 Changes in expiry dates for forestry actions by planners before and after drought and climate change information was available for their district**

### 5.3.5 Evaluation of new climate information for forest planning

We asked forest planners in four statements to evaluate the usability and limitations of the presented information in action expiration maps for their forest planning. In their responses the planners in Moray and Galloway districts indicated small usefulness of information in action expiration maps for their forest planning but indicated in Dumfries a small uselessness (see Figure 5-7). The planners found it harder to define expiry dates for forestry actions with information from action expiration maps for their districts, with the exception in the Galloway where one planner found it easy. The planners in Moray and Galloway found it slightly easier to draw pathways but not in the Dumfries district. Last, the planners in Moray and Galloway indicated that making decisions with two threshold values for a district was slightly easier but in Dumfries planners were undecided with easy and hard decisions. Overall, the planners in Dumfries found it hard and uneasy to use and decide about expiry

dates for forestry actions compared with the planners in Galloway where it seemed easier for them to decide and easier to use presented information. Finally, in Moray district the planners were undecided and some believed that presented information in action expiration maps were useful, whereas others thought the information was useless. We received one “Don’t know” answer for a statement “draw pathways for three SRES scen.” in Dumfries, and two “Not Available” answers for a statement “decide with two reduction values” in Moray and Dumfries districts.



**Figure 5-7 Evaluation of usability of presented action expiration maps for forest planning. Symbols represent planner’s responses.**

### **5.4 Discussion and conclusions**

This explorative study focusing on forest planners’ decision-making in the context of climate change adaptation showed that new information changed planners’ decisions and frames about expiry dates for forestry actions. These changes resulted in a shift of expiry dates for forestry actions and in alternations of preferences of expiry dates for actions when discussed in a group. Furthermore, our findings suggest that planners are capable of making

decisions about forestry actions into the future. However, when they were confronted with uncertainty, represented either by too much information about climate change or by having multiple views about forestry actions, they responded with some hesitation and with different answers. In the following text, we address our three research questions and discuss their broader implications for climate change adaptation and policy development.

With respect to possible expiry dates of forestry actions, we investigated when forest planners would start to adapt to climate change, as triggered by the new information we presented about different climate change impacts. Starting with their own list, in three districts the planners indicated that between 0 and 13 forestry actions would reach their expiry dates by the 2050s. Then, with a pre-defined list of eight forestry actions - keeping spruce, pine, and oak and adjustment of forest facilities in the lowlands and uplands – but without any climate change information, the results show that between 0 to 11 forestry actions would reach their expiry dates by the 2050s. However, with climate change information available to planners they modified expiry dates for the same eight forestry actions resulting in a higher number of actions between 4 and 14 reaching their expiry dates by the 2050s. We assume that reasons for these changes are due to the frames planners hold on climate change impacts as influenced by the new presented information, as well as their different interpretations of expiry dates. Another reason can be the planners perceptions of different drought impacts on forest ecosystem services, represented by threshold values, ranging by districts with values set for Dumfries (10 and 20%), for Galloway (5 and 15%), and for Moray (20 and 30%). In case the planners would have the same frames and the same understanding of expiry dates, we would expect to see the same expiry dates without and with the climate information as it presented to the planners. During the workshops the planners mentioned that the presented information about ecosystem services was incomplete and too broad to help them to decide. However, as Dewulf et al. (2005) have mentioned, decisions always have to be made without a complete knowledge, hence we believe it is also the case for forest planners. A reason why planners defined no expiry dates for forestry actions might also be because of their disbelief in climate change with consequent avoidance of adaptation, as was the case for some Swedish forest owners (Blennow & Persson 2009). Also, our investigation of expiry dates for forestry actions can go beyond planners' perception of time, as a study of Dutch and German forest managers found that foresters think mainly within a 15 year time horizon (Hoogstra & Schanz 2009).

With respect to climate change information, we explored the influence of new information on the planners' decisions about forestry actions. Our results show that information influenced individual planners' decisions, such as a shift to

earlier expiry dates for forestry actions and caused a higher inability to specify expiry dates for actions. For example, in Moray the planners were unable to define expiry dates for 16 forestry actions compared with 2 actions where no climate information was available. In a group discussion it appeared harder for the planners to decide about expiry dates for actions than to assess them as individual planners, probably due to conflicts of understanding of available information. In a group, the planners decided that 5 forestry actions (62.5% of all actions) would have no expiry dates, whereas as individuals they could specify expiry dates to more actions with responses between 3 and 12 forestry actions (representing 7.5% and 50% of total number of all actions, respectively).

Comparing the planners' decisions without and with the climate change information we can conclude that planners have different frames about forestry actions. Ambiguity – as multiple frames of a problem – might be a reason why planners indicated different expiry dates for forestry actions. This might be as well a consequence of too much information (Dewulf et al. 2005). Additionally, a study by Eyvindson et al. (2012) has found that the amount of presented forest information changed choices of forest plans among forest science students. The consequences of ambiguity about actions and expiry dates then might influence the planners' choice of taking adaptation measures. Forest planners may have negative frames due to reduction in forest ecosystem services, which might result in risk-taking behaviour, as is known from decision-making research (Tversky & Kahneman 1981). These frames could then cause changes in expiry dates for forestry actions. On the other hand, positive frames about potential tourism may make planners keen to think about investing in forest recreation facilities. Of course new information and the planner's frames are not the only explanation for changes in expiry dates for forestry actions. Other explanations for different frames might be planners' risk perceptions of drought and climate change, as a previous study described in Chapter 2 found diverse climate change risk perceptions among British forest planners.

With respect to uncertainty, we investigated whether forest planners made different decisions with less and more uncertainty as represented by SRES emissions scenarios. The group decision-making with three emissions scenarios and high uncertainty resulted in planners specifying no expiry dates for the majority of 5 (62.5% of all actions) forestry actions. Whereas, with one scenario and low uncertainty only in Moray the planners indicated "not known" expiry dates for 16 forestry actions in contrast to none as a group (see Figure 5-4). Surprisingly, the group of planners in Moray decided that expiry dates for keeping spruce, which is the dominant tree species in all districts, occurred much later in both the lowlands and uplands than in their individual decisions. Similar results occurred for spruce in the uplands in Dumfries. Therefore, we

think that in a group discussion planners are more cautious about their decisions. Additionally, our findings benefited from reducing the anchoring effect when comparing results for forestry actions between one and three emissions scenarios. Our findings of no expiry dates for the majority of forestry actions across the three emissions scenarios relates to similar results in a climate change adaptation study by Morton et al. (2011), which found that higher uncertainty caused a reduction in the public's willingness to react when expressed with negative frames of climate change.

Findings from this study can help policy makers and scientists to better understand possible barriers but also creates new options for addressing climate change adaptation. We think that knowing about how planners comprehend, frame, and use information about climate change can support adaptation endeavour at a regional and national level. On the one hand, this empirical study revealed possible barriers to climate change adaptation when using information for decision-making because a lot of new information was hard for the planners to understand. Another barrier can be the ambiguity caused by the new climate information as compared with planners own understanding and knowledge about climate change impacts. Other studies have shown that ambiguity caused by different views on a problem remains a prevailing problem in natural resources management (Brugnach et al. 2008) and in climate change adaptation (Moser & Ekstrom 2010). One way to reduce ambiguity and to improve the uptake of new information from action expiration maps might be to hold consequent workshops allowing planners to become more familiar with this new information. On the other hand, we found that new relevant climate information has the power to shift adaptation actions over time, which could lead to a higher uptake of climate adaptation policies. Furthermore, there is a difference between individual and group decision-making. Here, our findings are in accordance with other studies, such as (Moser & Ekstrom 2010) which identified disagreement on range of options to be a common barrier in planning decisions.

Based on the planners' reflections after each workshop, we conclude that a workshop setting is a suitable method to disseminate and introduce new climate change information while offering a chance for planners to ask for clarification where required. Clearly, there are limitations to this study, particularly in presenting a large amount of climate change information, which made it hard for the planners to digest the information in one day. Moreover, our findings are subject to errors due to a small sample size of planners. With the planners, however, we also investigated the use of action expiration maps, not presented here, to define adaptation pathways as described by (Haasnoot et al. 2013). Our observation suggests that adaptation pathways were hard for the planners

to understand and to define, hence future research should expand on their empirical application.

Overall, this empirical study provided a better understanding about the application of new climate change information and its effects on decision-making, and also highlighted that ambiguity and different frames exist with respect to expiry dates of forestry actions. We believe that policy makers and scientists should be aware of these different frames, but at the same time they should promote an increase in knowledge exchange, leading to an uptake of scientific evidence in forest planning. Our findings show that frames can both delay or speed up climate change adaptation, depending on the planners' views on climate change. Finally, the evidence in our study suggests that new climate change information can change planners' frames resulting in both earlier and or later implementation of adaptation measures.

## **Chapter 6**

### **Synthesis**

This final chapter summarises and consolidates the results of this research, and it aims to contribute to a better understanding of uncertainty within forest planning and climate change. Section 6.1 draws conclusions related to the four main objectives and to the overall objective of the thesis. The following section 6.2 reflects on the results and how this study contributes to new knowledge and understanding of uncertainty within interdisciplinary research. The last section 6.3 offers space to debate and recommends how future research can build upon this study, and highlights how the findings can be used to support forest planning together with policy analysis and development focusing on climate change adaptation.

## **6.1 Conclusions**

This study explores and investigates uncertainty and risk related to forest planning and climate change adaptation processes. Uncertainty is one of the limitations influencing people's decisions, hence a better understanding can help to support decisions about forest ecosystems. Uncertainty is not only about limited knowledge, as is largely understood by forest planners or decision makers. It is also about the natural variability of a system with its unpredictable behaviour and, finally, it is about ambiguity representing differences in how decision makers understand a problem (described in chapter 1, section 1.2). Therefore this study investigates uncertainty from two diverse perspectives – those of a decision maker and those of a modeller. From a decision maker's perspective, uncertainty can be assessed through empirical exploration of uncertainty recognition and management relevant to forest planning including also climate change risk perceptions (section 6.1.1), and also through exploration of uncertainty associated with climate change information that can influence decisions about forestry management actions (section 6.1.4). From a modeller's perspective, uncertainty can be evaluated first by quantifying climate change uncertainty translated as subjective probabilities into risk and assessing future drought risk for the major tree species in Britain (section 6.1.2). Second, uncertainty can be assessed for the key forest ecosystem services under climate change uncertainty (section 6.1.3). Drought was defined as dry conditions resulting from a greater amount of evaporation than precipitation and climate change was defined as a future change of climate over a long time period.

The following four sections are structured first with a summary and the conclusions of the main findings from each chapter. Then, the research questions for each chapter are presented with answers. The final section 6.1.5 consolidates the results from the previous four chapters.

### **6.1.1 *Diverse understanding of uncertainty and climate change risk perceptions (chapter 2)***

This chapter explores whether forest planners<sup>4</sup> in Britain recognise different types of uncertainty, how they manage uncertainty relating to forest models and their outputs, and what climate change risk perceptions they hold. These three components were studied in our new uncertainty assessment framework, which allowed investigation of uncertainty from different points of view. To obtain understanding of uncertainty within forest planning, data were collected from an online survey among 33 forest planners across Britain. The details of the assessment framework are explained in the next three research questions. The overall finding suggests that uncertainty has different meanings among the planners. First, surprisingly, the planners indicated low degrees of uncertainty with statements for the economic or social categories in contrast to high degrees of uncertainty with statements for the climate category. Second, the planners preferred to actively manage uncertainty associated with forest models and their outputs, while being aware of inaccuracies of these models. Finally, for the next 30 years, on the one hand planners perceived an increase in their concern and higher frequency of drought, pests, and wind risks, but on the other hand they believed in high levels of control and regulation through forest policies and management. This thorough empirical investigation of uncertainty in forest planning provides a new understanding of uncertainty and offers an original uncertainty assessment framework.

#### **First question: Which types of uncertainty do forest planners recognise in forest planning?**

To answer this question we prepared 27 statements from which composite measures were used to represent uncertainty types, categories, and sources. Ten uncertainty types such as action, goal, randomness of nature, and recognized ignorance were defined to explore each forest planner's recognition of uncertainty. These types were further classified to three sources of uncertainty being epistemic, stochastic, and ambiguity and also to one dimension representing a level of uncertainty. Additionally, we classified individual statements for uncertainty types into three categories (economic, social, and climate). Based on up to three statements for each of ten uncertainty types, only randomness of nature appeared to be a reliable measure of uncertainty assessed with Cronbach's alpha index (as a measure of reliability). The results show that from all different types and sources of uncertainty and across the three categories planners only recognised randomness of nature and uncertainty related to climate change. Other uncertainties were recognised on a

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<sup>4</sup> Employed by the Forestry Commission who is responsible for management of the public forest estate.

low level, being closer to “certainty”. Surprisingly, significant results were found for a lower uncertainty related to economic and social categories in contrast to a higher uncertainty associated with the climatic category. It is surprising because future economic and social issues should be more unpredictable and hence be more uncertain compared with climate change, because climate change can at least be partly explained by a good understanding of physics. Furthermore, due to societal randomness associated with people’s behaviour we should have a lesser understanding of how people might behave, for example, how and where people will use forests for recreation. This would imply that uncertainty should be higher. Other findings indicate that there are no differences in uncertainty recognition between the two types of forest planners, district and design planners, who make decisions at a regional or a local level, respectively. Also, we found no differences in uncertainty recognition among planners across Britain. Interestingly, this would mean that planners have similar knowledge about economic, social, and climate issues and also make similar decisions about them. However, although differences were expected among planners at least for climate issues, such as wind conditions and soil moisture because of climatic variability across Britain, these were not confirmed by this study.

Uncertainty was also evaluated by individual statements in our three categories, where the results show a higher variability in planners’ responses. Planners not only recognised high uncertainty for statements in the climatic category, i.e. soil moisture variability and wind variability, but also for some statements in the economic category, i.e. full costs of coupe rotation. On the other hand, the planners recognised a lower uncertainty or more ‘certainty’ in the social category, i.e. choice of suitable management options for forest recreation. The higher ‘certainty’ of issues in the social category can lead planners to choose these as a main forest objective, resulting in easier decision-making while avoiding more uncertain issues related to climate change. Therefore, uncertainty itself can be a reason for not adapting to climate change due to the recognised high degree of uncertainty within the forest planning community.

**Second question: How do forest planners prefer to manage uncertainty associated with forest models and their outcomes?**

By differentiating between active and passive types of uncertainty management we were able to assess how planners manage uncertainty related to forest models and their outputs. In this study active uncertainty management relates to a situation where planners acknowledge, share, and explore limitations of forest models and their outcomes. By contrast, passive uncertainty management relates to a situation where any uncertainty associated with forest models is ignored. The results indicate that planners are inclined to active uncertainty management but are neither for nor against passive uncertainty management.

Planners are therefore aware of the limitations of models and acknowledge them in their planning. On the whole, the results suggest that uncertainty associated with forest models and their outputs is not a barrier for their application in planning practice. Active management should then favour application of new climate change models in forest planning even with their inherent uncertainty.

**Third question: How do forest planners perceive climate change risks over time?**

Planners' risk perceptions, representing their intuitive judgment, offer a different view on climate change risks in forestry. This study used seven judgment scales and six hazards to interpret diverse risk perceptions among forest planners. As scales, representing risk characteristics, we used for example concern, predictability, and controllability of risk; and as hazards we used drought, fire, frost, pests, water-logging, and wind. The analysis of the changes in risk perceptions revealed that planners have a diverse understanding of risk for the next 30 years. The planners perceived an increase as well as a decrease for drought, pests, and wind risks depending on assessed judgment scale. On the other hand, they indicated no changes in perception for other risks. Therefore, a further analysis of risk perceptions was carried out for drought, pests, and wind. Only for drought risk this study found significant differences in the planners' perceptions among countries, with a higher drought concerns in England and Wales than in Scotland. This might imply a higher willingness by planners to address and react to drought in England and Wales as well as to consider drought related solutions, such as planting of drought resistant tree species. Surprisingly, on the one hand, the planners were concerned about risks and expected a higher frequency of risks in the future, but on the other hand they believed that greater control mechanisms and regulation by forestry policies and forest management would constrain risks. Therefore, the planners contrasting risk perceptions might support but also might hamper future adaptation actions.

**6.1.2 *Consequences of spatiotemporal climate change probabilities for drought risk induced reduction in potential forest production of the major tree species (chapter 3)***

This chapter investigates and evaluates with a new risk assessment approach impacts of drought on the major tree species across Britain. As described in chapter 2, the planners perceived drought of high concern and hence the knowledge about future drought is important for forest planning. Drought probability was calculated from the latest UKCP09 climate projections, which quantified climate change uncertainties and incorporated expert judgments into subjective probabilities using the best current evidence (see section 1.2 for

more details). The simulated probabilistic climate data were obtained from the UKCP09 Weather generator for seven decades (from the 2020s until 2080s) and for three emissions scenarios (B1, A1B, and A1FI). The tree growth responses of spruce, pine, and oak to different degrees of drought were evaluated with the Ecological Site Classification (ESC) model developed for British conditions. Due to the diverse British climatic conditions, forests were classified to the lowlands (warm dry and moist climate zones) and to the uplands (warm wet, and cool wet and moist climate zones). The main finding from the risk assessment show mostly negative drought impacts for forests across Britain. Spruce, as the dominant tree species in Britain, will mostly reduce its potential growth in both the lowlands and uplands, and also across all three emissions scenarios. However, depending on location, our results show smaller reductions or even a small increase of predicted growth rate for three species in west and north-west Britain. Of the three tree species spruce is the most sensitive to drought, whereas oak is the most resistant. By combining the predicted growth rate and the current spatial extent of each species, we conclude that total potential forest production will be decreasing on the public forest estate for the next 80 years. The forests in lowlands show greater relative reduction of production than in the uplands, hence forests in the uplands are more drought resistant. However, in absolute terms, a reduction in production in the uplands is up to 30% higher than in the lowlands, due to the greater area of forests planted on upland sites. Therefore, without any changes in the current forest extent, larger losses in forest production are to be expected in the uplands. If we are to minimise future drought impacts and to adapt to climate change, forest management might pursue a strategy of expanding the forest area in the uplands and also in the west and north-west Britain.

**Research question: How spatial and temporal climate change uncertainty affects the drought risk of three major tree species and their growth across Britain?**

In this study calculated drought risk is based on both drought's probability and drought's impacts on tree growth. Our results show a decline in the stand yield class for spruce, pine, and oak stands in the lowlands. Spruce - with the highest yield class - has the highest median reduction in yield class of 44% from the baseline (1961-1990) to the 2050 for the A1B emissions scenario. In the uplands, however, drought conditions will become favourable for pine and oak resulting mostly in an increased yield class, but with a reduced yield class for spruce. The most vulnerable sites to drought are forests in the south-east and east of Britain, where the predicted reduction in yield class is as high as up to 94% in the lowlands and is as high as up to 64% in the uplands in the 2080s for the A1FI scenario. More favourable sites for tree growth in respect to drought

are in the west and the north-west of Britain, and especially for forests in the uplands.

The changes in yield class translate to changes in the total potential forest production. Spruce represents the largest area and production in the baseline and will contribute the most to the total production losses in both the lowlands and uplands. From the total production loss of 42% in the lowlands in the 2080s for the A1FI scenario, spruce contributes to this loss with a 78% (equivalent to  $570 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ ). In the same scenario and time period for uplands, from the total production loss of 32% spruce contributes to this loss with a 96% (equivalent of  $987 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ ). A larger reduction in absolute forest production is predicted for the uplands, showing that timber production is potentially vulnerable to future drought.

### *6.1.3 Climate change impacts on key forest related ecosystem services: options for adaptation (chapter 4)*

Climate change adaptation helps to reduce future climate impacts on forest ecosystems. There is still a lack of knowledge about how large these impacts will be, and when and where adaptation is needed. In this study we move from the analysis across Britain to a more detailed analysis for the National Forest Estate in Scotland. We quantified drought impacts on the delivery of the traditional forest ecosystem services relevant to forest management: forest production, yield class, and sequestered carbon. Moreover, we assessed climate change impacts for one new service: potential tourism. Future climate was assessed with the data from the UKCP09 climate change projections. To propose options for adaptation, the method using dynamic adaptive policy pathways was discussed and modified to a forestry application. We expanded the method with forestry actions and with three emissions scenarios. Forestry actions represent possible management options suitable for providing forest ecosystem services. These actions were classified into three groups: forest management of the current tree species, potential for forest tourism, and forest area expansion. We used relative values of ecosystem services as changes from no climate change impacts to define when each action reaches its expiry date, i.e. fails to deliver a required amount of service. The findings show a decline in the traditional services (forest production, yield class, and carbon sequestration) due to drought over the next 80 years mainly for spruce and pine forests, and the decline become larger from the low (B1) to high (A1FI) emissions scenarios. However, forest tourism may benefit from climate change because of more favourable climate conditions during the summer months. Our results also show a reduction of 20% for the traditional services for spruce and pine actions in the lowlands by the 2050s for the A1FI scenario but we find no

reduction for the B1 scenario. Therefore, the recommended adaptation should focus on spruce and pine forest actions, especially in the lowlands. In the end, this study predicted a large decline in provision of the traditional forest ecosystem services depending on emissions scenarios.

**First research question: How much will drought and climate change reduce the delivery of forest ecosystem goods and services in the future under different emissions scenarios?**

Climate change and drought impacts will not only threaten but also improve the provision of forest ecosystem services in Scotland. We assessed two provisioning ecosystem services of forest production and stand yield class with the drought risk approach introduced in chapter 3; we assessed one regulating service of sequestered carbon in forest biomass with Woodland carbon code; and assessed one cultural service of potential tourism in forested areas with the Tourism Climatic Index. This index represents human comfort to climatic conditions related to light tourism. Drought reduces both yield class and forest production services for spruce and pine forests, while oak benefits from drier conditions and so production and yield class should increase. Furthermore, due to a faster yield class reduction rate for spruce and pine in the lowlands than in the uplands, the yield class for these two species will start to be higher in the uplands from the 2050s onward. The results also show a decline in sequestered carbon for the three species in contrast to no drought impacts in the 2080s. For spruce, this results in a high reduction of 31% in the lowlands and 41% in the uplands equal to 6,010,000 tCO<sub>2</sub>e year<sup>-1</sup> and to 11,492,000 tCO<sub>2</sub>e year<sup>-1</sup>, respectively, in the 2080s for the A1FI scenario. On the other hand, the potential for tourism may benefit from positive climate change impacts in summer in which the number of good days may increase by up to 16 or 19 days per month in the lowlands and uplands, respectively. Favourable climate conditions for forests located in both lowlands and uplands can possibly attract a higher number of forest visitors. Our results also show that forests will provide a smaller amount of ecosystem services for the A1FI scenario than for the B1 scenario.

**Second research question: Which forestry actions and when should forest planners choose to support climate change adaptation and sustainable forestry?**

This question was investigated through the assessment of eight forestry actions relevant to forest planning, such as keeping the current tree species or adjusting of forest facilities. Again, we used the same three emissions scenarios. Due to the accumulated reduction in forest production, yield class, and sequestered carbon for the national forest estate, two sets of threshold values were specified (a 10% and a 20%). The future increase in potential

tourism resulted in another set of threshold values (a 100% and a 200%). The results show that spruce and pine forestry actions in the lowlands are vulnerable to drought impacts reaching a 20% threshold with expiry date for all three services from the 2050s onward under the A1FI scenario. We see no expiry dates for these actions under the B1 scenario. At a 10% reduction values these actions reach their expiry dates even sooner, in the 2030s. However, in the uplands spruce and pine forests are less vulnerable to drought, providing forest ecosystem services without any constraints at a 20% reduction value. Only at a 10% reduction value spruce action reaches its expiry date by the 2040s for the A1FI scenario, whereas there are no expiry dates for the B1 scenario. Forest management can benefit from the improving climate conditions during summer months, which are more suitable for tourism across Scotland. A two time relative increase in the number of good days for tourism is estimated already from the 2020s. To summarise, climate change adaptation should be targeted on forests in the lowlands to sustain provision of forest services or to expand forest cover on more suitable uplands, and also to focus on forest tourism.

#### *6.1.4 New climate change information modifies decision-making of the forest planners under uncertainty and ambiguity (chapter 5)*

This chapter explores the forest planners' understanding of new climate change information which contains inherent uncertainty and how it influences or does not influence their decisions about forestry actions. Building upon the research results in the previous chapters, we presented the planners with an action expiration map with assessed four forest ecosystem services for their district. These ecosystem services are the provisioning services of forest production and stand yield class, the regulating service of sequestered carbon, and the cultural service of potential tourism. Due to different climate change impacts each action expiration map included two different threshold values. We ran the workshops with 10 forest planners in three forest districts in Scotland to observe and assess any changes in the planners' decisions first without and then with new climate change information. We measured changes in the planners' frames – interpretation of a reality – with expiry dates for forestry actions. The results show that with new climate information the forest planners changed expiry dates for forestry actions, resulting in them shifting expiry dates to earlier time periods. Other results confirmed that the planners perceive some ambiguity about forestry actions, because they defined different expiry dates without and with the climate information. Then, their frames of reference were either adjusted or superseded by new ones. When confronted with emissions scenarios uncertainty, as individuals or in a group, the planners made different

decisions and set different expiry dates. However, the group setting may also account for these differences.

**First research question: From which decade do forest planners believe climate change impacts will become serious?**

We used three different tasks to explore when the forest planners believed forestry actions might reach their expiry dates due to drought impacts. In the first task, the planners wrote down their own list of forestry actions and defined their possible expiry dates. In the second task, the planners wrote down expiry dates for our list of eight pre-defined forestry actions. Before the last task we explained and presented to the planners climate information in an action expiration map relevant to their district. With this new information the planners again wrote down expiry dates for the eight pre-defined forest actions. The results by districts for the planners' own forestry actions revealed that between 0 and 17 actions (from up to 28 forestry actions) would reach their expiry date by the 2050s. The variability in responses was due to different interpretations of drought impacts. Comparing planners' responses to the eight forestry actions without and with climate information, the results show a shift of expiry dates to earlier time periods. For example, the number of forestry actions with expiry dates by the 2050s increased from a range of 0 to 11 (from up to 40 actions) without climate information to a range from 4 to 14 with climate information. This shift indicates a higher urgency in the minds of planners to react and adapt.

**Second research question: Will planners change their initial frames about forestry actions suitable for climate change adaptation when confronted with new climate change information?**

To the same three previous tasks we added one new task for a group discussion among planners, in which the group of planners specified expiry dates. In the group discussions the planners had information in the form of action expiration maps for three emissions scenarios in contrast to only one scenario when they defined expiry dates as individuals. As we concluded with the first question, with new climate information the planners changed their frames about forestry actions, measured by changes in expiry dates. Other results show, for example, in the Moray district that new information increased ambiguity, as the planners were unable to specify expiry dates for 16 actions compared with 2 forestry actions (without climate information). In the group discussion the planners found it hard to define expiry dates in contrast to assessing actions as individuals. The results show that as individuals the planners specified no expiry dates between 3 and 12 forestry actions (representing 7.5% and 50% of all responses) compared with 5 forestry actions (62.5% of all responses) defined in the group discussion. One of the

explanations for these differences is that the planners were confronted with ambiguity about expiry dates for forestry actions.

**Third research question: Will forest planners make different decisions about a set of forest management actions when confronted with uncertainty about emissions scenarios?**

To answer this question we used tasks where the planners had to define expiry dates as individuals but also in a group setting. In the individual task we randomly assigned to each planner one action expiration map with results for one emissions scenario. In the group task the planners were given information for all three emissions scenarios in the form of an action expiration map. A higher degree of uncertainty represented by the three scenarios resulted in no expiry dates for 5 forestry actions (62.5% of all actions from a total of 8) as decided by planners in a group. With lower degree of uncertainty represented by one emissions scenario, only in Moray district the planners defined “not known” expiry dates for 16 forestry actions (from a total of 40 actions). However, with the high degree of uncertainty and in the group, the planners in Moray district were able to specify all expiry dates for forestry actions. These differences can be attributed to a group discussion in addition to uncertainty related to the three emissions scenarios. Other results show that expiry dates for spruce forestry actions were set much later in a group setting compared with individual decisions. Hence, we think that the planners are more cautious about their decisions when making decisions in a group.

### **6.1.5 Main conclusion**

The overall objective of this thesis was “*To explore climate change associated risks and uncertainties and their understanding in forest planning and management for making informed decisions about the future states of forests*”. This thesis demonstrates different understandings, quantifications, and applications of uncertainty within forest planning and climate change adaptation. High uncertainty recognition and diverse risk perceptions obtained from forest planners help us to understand how uncertainty can be a source of inertia to climate change adaptation. Quantified climate change uncertainty as drought risk enables us to locate where and when vulnerable hotspots for forest production losses may occur on the public forest estate. Lowland forest sites, especially in east and south-east Britain, are vulnerable hotspots. The findings from these results can support climate change adaptation and implementation at regional scales across Britain. By expanding the drought risk assessment with additional climate change data, and evaluating new forest ecosystem services, we identify which forest ecosystem services in Scotland would be vulnerable and where adaptation should be targeted. Assessed with different

emissions scenarios, the results identify that provisioning and regulating services from spruce and pine forests are the most vulnerable to drought on lowland sites. On the other hand, climate conditions may become better on forest sites for potential tourism as a cultural service. Combining knowledge and research outputs from the previous three studies, we explored whether climate change information and associated uncertainty presented to forest planners would modify their decisions about forestry actions. The findings suggest a time shift in expiry dates for forestry actions but also reveal ambiguity in decision-making when planners were confronted with multiple ecosystem services and emissions scenarios. To conclude, this thesis contributes to a better understanding of uncertainty and risk within forest planning, and also shows how quantified uncertainty can support informed forest planning and climate change adaptation.

## **6.2 Reflections**

Forest planners deal with many societal problems that address, among others, a range of contrasting public demands and values about forests (ambiguity). Climate change adds another degree of complexity to these problems, especially due to high unpredictability of its impacts. This unpredictability relates to stochastic and epistemic uncertainty sources. These sources of uncertainty are the reason why climate change adaptation is a complex or a wicked problem. Therefore, a new type of empirical and comprehensive uncertainty investigation is required. This study offers a new view and a better understanding of inherent uncertainties related to forest planning, climate change, and forest ecosystem services. Uncertainty was investigated from the two perspectives of a decision maker and a modeller, with each perspective focusing on different sources and types of uncertainty. The benefits of having two perspectives are a clearer identification of uncertainties and suitable assessment methods allowing us to better communicate uncertainty to model users (decision makers) and to model developers (modellers). The main sources of uncertainty investigated in this study are epistemic (limited knowledge), stochastic (variability of a system), and ambiguity (multiple representations of a problem). Depending on a problem under investigation, either a research or a decision problem, and the perspective, specific sources of uncertainty have to be dealt with.

For the investigation of uncertainty, diverse qualitative and quantitative methods were used. For the qualitative methods, we used survey analysis and a workshop experiment to explore how forest planners understand and make decisions with uncertainty. For the quantitative methods, we employed data analysis, drought risk assessments, and models to quantify climate change

impacts on forest ecosystem services. From a decision maker's perspective, qualitative methods enrich our knowledge about how forest planners think, understand, and manage the three uncertainty sources. From a modeller's perspective, quantitative methods allow us to translate uncertainty differently as a risk, or assess climate change impacts for different emissions scenarios offering another view on uncertainty. These methods mainly address epistemic and stochastic sources of uncertainty. This mix of qualitative and quantitative methods allowed the study of uncertainty from different perspectives or disciplines, contributing to an interdisciplinary research. This is one of the main strengths of this research, which would have been impossible if conducted only with qualitative or quantitative research methods alone. Furthermore, the used methods complement each other in a thorough investigation of uncertainty. The chosen approach of multiple methods helps to explain why uncertainty associated with climate change impacts remains a problem for forest planning.

This research contributed to current knowledge with a new understanding of uncertainty. With respect to the role of uncertainty in forest planning, diverse uncertainty types were hard to describe and explore. Moreover, no previous research studies offer a comprehensive typology of uncertainty related to forest planning and management. Hence, our newly developed uncertainty assessment framework based on an online questionnaire provides a novel method for empirical investigation of uncertainty. The framework was designed to explore types of uncertainty, uncertainty management and also climate change risk perceptions among forest planners. Furthermore, this framework is suitable for investigating uncertainty from a perspective of a decision maker and allows other scientific disciplines to explore types of uncertainty present in decision-making. To my knowledge no other study in environmental management has explored uncertainty in such a detail in relation to climate change.

To provide more confidence in decision-making, uncertainty about climate change and its impacts on forests was quantified through drought risk. In the drought risk assessment, uncertainty from climate models and an impact model was treated from a modeller's perspective, which addresses mainly epistemic and stochastic uncertainty. The traditional risk assessment combines probability of a hazard and its impacts (Blaikie 1994). This probability, also known as a frequentist, represents the statistical likelihood of a natural hazard from long-term measurements. However, our drought risk assessment is based on subjective probabilities, which combine both long-term observations but also expert judgments. Subjective probabilities are the essential component for this new drought risk assessment, with probabilities obtained from the latest UKCP09 climate change projections in the UK. These probabilities correspond

to degrees of likelihood for future climate based, for example, on a range of climate models and expert judgments. Additionally, these probabilities differ depending on specific locations in Britain and also the range of probabilities increase into the future. The drought risk outputs were translated to changes in tree growth rate and forest production, which offer more robust estimates to forest planners in contrast to estimates from a single climate model. The final outputs provide information about drought impacts across Britain with more spatial details for the lowland and upland forests and also at a higher spatial resolution - 5km by 5km. Furthermore, these drought impacts are available over the next 80 years and at seven decadal time steps from the 2020s until 2080s. These levels of high spatial and temporal resolutions from national climate models were not available in the UK before.

Forests provide multiple ecosystem services but how these services change due to climate change and what adaptation options exist is an unresolved issue at a national and a regional level. Uncertainty remains about potential climate change impacts due to a limited knowledge of scientific understanding translated into models, hence we addressed uncertainty from a modeller's perspective. Building upon the drought risk assessment, we assessed forest ecosystem services of forest production, stand yield class, and amount of sequestered carbon at a higher spatial detail. Another service is potential tourism, which was quantified to climate change impacts. Incorporation of these services into modified dynamic adaptive policy pathways as action expiration maps helps to provide a bigger picture of adaptation options for Scottish forestry. Moreover, the assessed services allow us and planners to define expiry dates for pre-defined forestry actions and then highlight where and when the action might be needed. At a national or a regional level forest planners can benefit from this information in evaluating their future forest objectives and targets, such as forest production relevant for timber industry. Additionally, forest policy makers can benefit from better knowledge about how much climate change might affect key forest ecosystem services. We believe that the added value of this research is in offering a new integrated assessment of four forest services at a national scale across Scotland in contrast to assessments of only one service or within a case study. Combined information about these services and forestry actions can help to direct feasible adaptation options where and when they might be needed.

Multiple forest ecosystem services not only provide information about the amount of goods or service they deliver, but in a decision-making process they can be used as ambiguity indicators. This view on ecosystem services is from a decision maker's perspective, with the main sources of uncertainty being epistemic and ambiguity. The ambiguity, in our case, represents multiple values

and interpretations of forests and its services by the forest planners. Evaluating expiry dates for a range of forestry actions with ecosystem services, the results show that the planners have different degrees of ambiguity. Applying the action expiration maps to forestry problems seems to be a good tool for exploring ambiguity within the climate change adaptation debate. But, forest planners' ambiguity can also increase when confronted with the three emissions scenarios, as was the case in our empirical study. Emphasis on the multiple ecosystem services in forest planning and management might lead to conflicts of interest and diverse values, hence to more ambiguity. In the end, ambiguity about values and use of ecosystem services can contribute to the wickedness of problems addressed in forest planning.

### **6.3 Recommendations**

This study evaluated many aspects of uncertainty, which should help other researchers and policy makers to better understand uncertainty and use the findings for better decision-making. Many unanswered questions and gaps still remain that should be addressed in the future. The first section discusses and recommends how the future research can expand and improve the new knowledge on uncertainty. The second section proposes the application of the results for forest planning and then suggests their benefits for the current and future analysis and development of forestry and climate change policies.

#### **6.3.1 For future research**

The following key points highlight where the future research can build upon and expand the achieved findings:

- Uncertainty assessment framework explores different types of uncertainty and climate change risk perceptions among the forest planners responsible for management of the public forest estate in Britain. However, other research should apply this framework with forest policy makers to find out whether their uncertainty understanding differs from the planners. Other research studies can evaluate the usability of the framework with other decision makers rather than planners, and also in a different environmental management.
- Forest planners showed a high variability in their climate change risk perceptions. The question remains whether planners in other countries with similar forest management objectives and types of forest will respond similarly to these risks. Of special interest to climate change adaptation research should be the difference between assessed risks on judgment scales. On the one hand, the planners perceive high concerns about risks,

but on the other hand, for the same risks they believe in their high controllability by forestry policies and forest management.

- Assessment of drought impacts and associated risks show mainly large reductions in forest production for the major tree species over the next 80 years in Britain. One limitation of drought risk assessment is the use of only one impact model which estimates tree growth response to drought. Multiple tree growth impact models will make the results more robust and can also validate the used impact model. Moreover, knowledge is missing about how the major tree species grow under extreme drought conditions. It was impossible in this study to incorporate tree response to extreme drought due to a lack of reliable data.
- Long-term assessment of climate change and specifically drought impacts on the main forest ecosystem services in Scotland offer a good indication how much these services may change. Moreover, the results show where forests may become vulnerable to climate change impacts in Scotland either in the lowlands or uplands. Other models of forest ecosystem services should validate the accuracy of our estimates for these services. Several ecosystem service models already exist that can quantify the amount of tree growth and sequestered carbon for the current climatic conditions, but these are not yet fully parameterised to the future climate.
- The novel approach of dynamic adaptive policy pathways modified for forestry application as action expiration maps has shown potential for climate change adaptation. These maps enable one to identify when and where adaptation measures can be taken. Still, many aspects of the expiration maps can be improved. For instance, defining and providing expiry dates for forestry actions on the continuum scale instead of two threshold values. This can help decision makers to decide precisely when expiry date for each action exists. Other improvements can focus on extending the list of forestry actions with other actions relevant to forest planning and management.
- The planners changed their decisions about forestry actions when new climate change information was available for forest districts in Scotland. A small sample of ten planners should be expanded with more planners to increase the reliability of the results and to explore other possible understanding of forestry actions. This should include additional data from the planners managing the national forest estate but also of private forest enterprises.
- The planners evaluated expiry dates for forestry actions with two pre-defined threshold values showing environmental limits on the time scale from the 2020s until 2080s. Due to diversity of actions and different responses of forest ecosystem services to climate change we pre-set two threshold values for all services. However, further research should

investigate how individual planners will define their own expiry dates for forestry actions, which will depend on their risk attitudes and perceptions.

### 6.3.2 *For forest planning, and policy analysis and development*

Information from this study can help forest planners in their decision-making and support practical climate change adaptation in forest management. In addition, information can support evaluation and development of forestry and climate change policies. The examples below illustrate the application of the key research results:

- Recommendations for forest planning in Great Britain and Scotland
  - o Knowing which tree species, where, and when can become vulnerable to drought provides valuable information for the national and regional climate change adaptation plans and strategies. Additionally, this information can feed into new forestry guidance, for example, on selection of drought resilient tree species and sustainable forest management systems under climate change.
  - o Our findings can help planners to locate whether adaptation is needed for forests in the lowlands or in uplands. Furthermore, to decide in which decade the adaptation measures should be taken supporting the urgency to act and adapt.
  - o The results can support the development of forest contingency plans for future drought events at the regional and national level. They can also help in prioritising of drought hotspots for the lowland or uplands forest sites.
  
- Recommendations for policy analysis and development in Great Britain and Scotland
  - o This study can assist policy makers to evaluate the feasibility of current policy targets, such as the provision of forest production, and to propose future achievable targets.
  - o Policy addressing future forest production targets should consider large potential reduction over the next 80 years, especially for Sitka spruce in Great Britain.
  - o Climate change mitigation policies should take into account reduction in the amount of sequestered carbon on the national forest estate in Scotland.
  - o A woodland expansion policy should consider future climate conditions for proposing suitable forest sites. The uplands are less vulnerable to drought impacts in Great Britain.

- Health and recreation forestry policies should think about the impact of more suitable climate conditions for recreation in the future in Scotland.
- New policies should target vulnerable hotspots for the four assessed forest ecosystem services to offset their potential future losses.
- Information about uncertainty types and their recognition by forest planners can aid policy makers to identify possible bottlenecks for an uptake of future forestry and climate change policies.
- Current understanding of uncertainty in forest planning can improve communication of new forestry policies. For example, awareness and recognition of climate change uncertainty by the planners should be recognised and acknowledged in the development and communication of new climate change forestry policies.

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## Chapter 7 Appendices

### 7.1 Supporting information for the Uncertainty Assessment Framework

**Table 7-1 All statements for the recognition of uncertainty**

Statements ID	Statements	Uncertainty type
S1_1	Among stakeholders involved in forest planning in my district, there is consensus about how forests provide economic benefits. <sup>f</sup>	multiple knowledge frames <sup>e</sup>
S1_2	I find it easy to choose the cost-effective silvicultural practices from a range of options. <sup>f</sup>	action <sup>e</sup>
S1_3	I know the full cost for a coupe rotation in advance. <sup>f</sup>	yield <sup>e</sup>
S1_4	I trust the data from the production forecasting which I use in my planning practice. <sup>f</sup>	model and monitoring <sup>e</sup>
S1_5	In my planning practice I consider different future timber demands.	scenario <sup>e</sup>
S1_6	In my forest district timber demand is predictable for the next 50 years. <sup>f</sup>	recognized ignorance <sup>e</sup>
S1_7	For me as a forest planner there are no doubts about the long term timber production goals. <sup>f</sup>	goal <sup>e</sup>
S1_8	The measured standing timber volume and harvested volume is not the same.	statistical <sup>e</sup>
S1_9	I know the effects of forest management practices on recreational use. <sup>f</sup>	yield <sup>s</sup>
S1_10	It is difficult to choose forest management options suitable for recreation use.	action <sup>s</sup>
S1_11	Among stakeholders involved in forest planning in my district, there is no consensus about how forests are used for recreation.	multiple knowledge frames <sup>s</sup>
S1_12	The number of visits to forests obtained from surveys accurately represent the annual number of visits. <sup>f</sup>	statistical <sup>s</sup>
S1_13	In my planning practice it is possible to know the relevant interests from all key stakeholders. <sup>f</sup>	recognized ignorance <sup>s</sup>
S1_14	I am aware of different objectives that local key stakeholders have for the forests. <sup>f</sup>	goal <sup>s</sup>
S1_15	In my forest district I consider different future recreation demands for forests.	scenario <sup>s</sup>
S1_16	In my planning practice I do anticipate unprecedented extreme weather events.	recognized ignorance <sup>c</sup>
S1_17	The choice of tree species resistant to climate change impacts is easy. <sup>f</sup>	action <sup>c</sup>
S1_18	In my forest district the surveyed and actual number of affected trees showing symptoms of drought is not the same.	statistical <sup>c</sup>
S1_19	Wind variability strongly affects my forest design planning.	randomness of nature <sup>c</sup>
S1_20	I trust current outputs from Ecological Site Classification or ForestGales models for climate change adaptation. <sup>f</sup>	model and monitoring <sup>c</sup>
S1_21	Temperature variability strongly affects my forest design planning.	randomness of nature <sup>c</sup>
S1_22	The forest district strategic plan objectives related to climate change adaptation are clear for forest design planning. <sup>f</sup>	goal <sup>c</sup>
S1_23	Given climate change, I anticipate different growth rates for each of the tree species in my planning practice.	scenario <sup>c</sup>

<b>S1_24</b>	I know what the benefits are of forest adaptation measures to extreme weather events. <sup>r</sup>	yield <sup>c</sup>
<b>S1_25</b>	Soil moisture variability strongly affects my forest design planning.	randomness of nature <sup>c</sup>
<b>S1_26</b>	Among stakeholders involved in forest planning in my district, there is consensus about how climate change will affects forests. <sup>r</sup>	multiple knowledge frames <sup>c</sup>
<b>S1_27</b>	I always know the effects of forestry policies relevant to my forest district. <sup>r</sup>	political

<sup>r</sup> – a statement with a reversed scale

Categories: <sup>e</sup> – economic, <sup>s</sup> – social, <sup>c</sup> – climatic

**Table 7-2 The statements used for the construction of composite scales with categories and uncertainty types**

Measures	Statements	Categories (e – economic, s – social, c – climatic)	Uncertainty types <sup>a</sup>
Randomness of nature	S1_19, S1_21, S1_25		
Economic category	S1_2 <sup>r</sup> , S1_3 <sup>r</sup> , S1_6 <sup>r</sup>		
Social category	S1_9 <sup>r</sup> , S1_10, S1_11, S1_12 <sup>r</sup> , S1_13 <sup>r</sup>		
Climatic category	S1_16, S1_19, S1_21, S1_25		
Epistemic uncertainty source	S1_2 <sup>r</sup> , S1_4 <sup>r</sup> , S1_20 <sup>r</sup> , S1_3 <sup>r</sup> , S1_9 <sup>r</sup>	e,e,c,e,s	a,mo,mo, y, y
Stochastic uncertainty source	S1_22 <sup>r</sup> , S1_1 <sup>r</sup> , S1_26 <sup>r</sup> , S1_27 <sup>r</sup>	c,e,c,no-category	g, mu, mu, p

Note: <sup>r</sup> - indicate a statement with a reversed scale

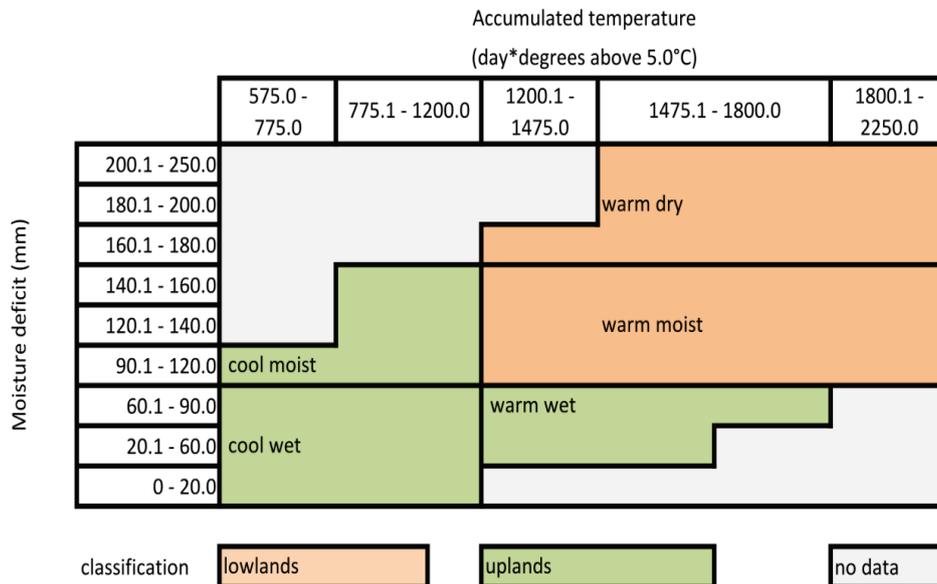
<sup>a</sup> : a – Action, g – Goal, mo - Model and monitoring, mu - Multiple knowledge frames, p – Political, ra - Randomness of nature, re - Recognized ignorance, sc – Scenario, st – Statistical, y - Yield

## 7.2 Supporting information for drought risk assessment

### 7.2.1 Methods

#### Definition of ESC climate zones and classification into the lowlands and uplands

We followed climate zones classification from (Pyatt et al. 2001) and divided British climate into 5 zones using accumulated temperature and moisture deficit values (Figure 7-1). These zones were the basis for the classification of British forests into the lowlands and the uplands sites.



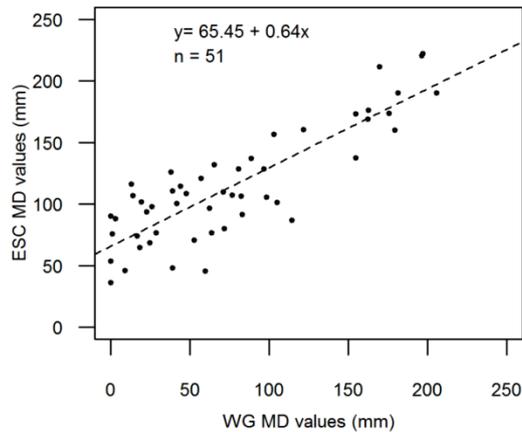
**Figure 7-1 Specification of climate zones in Britain using Accumulated temperature and Moisture deficit in the baseline (1961-1990) and the classification into the lowlands and uplands.**

#### The moisture index adjustment linear regression model

In the baseline (1961-1990), bias in Moisture deficits (MD) values exist between the UKCP09 Weather Generator (WG) data and MD from the MORECS dataset (Thompson et al. 1981) used in the ESC model (Pyatt et al. 2001). The MD values used in the ESC model were the base for the definition of trees' response to the moisture deficit and essentially to the drought. We corrected the bias between these two datasets with a linear regression model that used median MD values. We utilized median MD values to reduce the influence of MD extreme values from WG data. In addition median MD values were highly correlated with MD mean values ( $r=0.99$ ). The final linear regression model was:

$$\text{median\_MD\_ESC}_i = \alpha + \beta * \text{median\_MD\_WG}_i + \epsilon_i \quad [1]$$

where  $i$  is the WG site,  $\text{median\_MD\_WG}$  represents median MD value within each WG site and  $\epsilon$  represents the error term. Figure 7-2 shows the moisture deficit linear regression model with its equation and a model specification. We adjusted all MD values from WG up to 205mm, which is within model's limit using this linear regression model.



**Figure 7-2 Linear regression model for MD values between WG and ESC dataset with  $R^2 = 0.73$  and st. error = 0.05.**

### Drought risk calculation

The knowledge limits about trees' response to extreme drought represented by MD values within the ESC model constrain our risk assessment. These limits were for spruce (MD = 270mm), pine (MD = 400 mm), and oak (MD = 290) when trees response curves in the ESC model reached the zero stand yield class or a concave point. Beyond these limits we set trees' response to zero meaning no growth. This knowledge bounds also constrain the minimum future stand yield class.

To calculate the total probable stand yield class change, we first calculated the partial risk values within equal 100 MD bins. These partial risks represent the stand yield class change for each MD bin. We calculated partial risks as a multiplication of MD probability derived from the Empirical Cumulative Distribution Function (ECDF) by the future change of the stand yield class from the baseline stand yield class (reference point). Then we summed all these partial risk values into the risk measure of the total probable stand yield class change, following the method of total probable loss by (Smith 1992) (see [2] equation):

$$Risk_i = \sum_1^m \text{partial risks of stand yield class change} \quad [2]$$

where  $i$  is the WG site,  $m$  equals to 100 MD bins and partial risks of the stand yield class change represent individual stand yield class change from the future to the baseline stand yield class.

We used ArcGIS 10.1 (ESRI Inc. Redlands, California) and R (R Development Core Team 2012) for the spatial data management and to create maps.

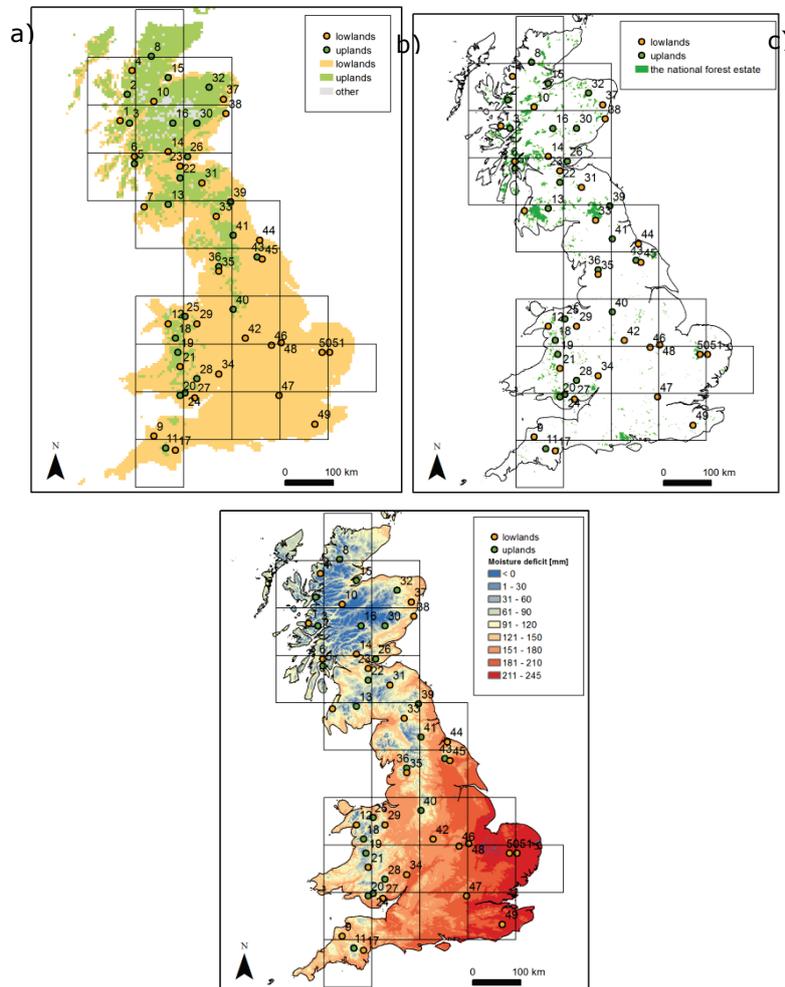


Figure 7-3 All twenty-nine 100km British National Grid cells covering at least 25% of landmass overlaying studied Weather generator sites with unique ID numbers (with “Map\_ID” in a lookup table Table 7-4) and a) showing the lowlands and uplands, b) the national forest estate, and c) the moisture deficit in the baseline (1961 – 1990).

**Table 7-3 Summary for all 51 Weather generator sites**

Map_ID	WG_site_id (UKCP09)	Latitude (°N)	Longitude (-°W, °E)	Mean MD +-sd (mm)	Lowlands / uplands	Map_ID	WG_site_id (UKCP09)	Latitude (°N)	Longitude (-°W, °E)	Mean MD +-sd (mm)	Lowlands / uplands
1	1700770	56.74	-5.81	101.8 +- 13.5	lowlands	27	3250190	51.57	-3.13	154.3 +- 15	lowlands
2	1850825	57.24	-5.61	76.9 +- 25.5	uplands	28	3300230	51.94	-3.05	73.5 +- 30.3	uplands
3	1900765	56.70	-5.47	32.7 +- 43.8	uplands	29	3300345	52.97	-3.08	133.3 +- 19.6	lowlands
4	1950875	57.70	-5.47	87.9 +- 37.2	lowlands	30	3300765	56.74	-3.18	47.2 +- 16.3	uplands
5	2000680	55.94	-5.24	54.5 +- 19	uplands	31	3400640	55.63	-3.00	84.8 +- 24.9	lowlands
6	2000695	56.08	-5.25	96.9 +- 23.5	lowlands	32	3550840	57.43	-2.78	103.3 +- 11.7	uplands
7	2200590	55.15	-4.86	103.4 +- 14.2	lowlands	33	3700570	54.99	-2.52	115.5 +- 6.4	lowlands
8	2350905	57.98	-4.83	69.5 +- 16.6	uplands	34	3750240	52.03	-2.42	160.6 +- 9.7	lowlands
9	2400110	50.84	-4.32	131.9 +- 5	lowlands	35	3750455	53.97	-2.42	125.4 +- 8.5	lowlands
10	2400810	57.12	-4.68	93.4 +- 29.9	lowlands	36	3750465	54.06	-2.43	94.4 +- 15.1	uplands
11	2650085	50.62	-3.95	48.3 +- 12	uplands	37	3850815	57.20	-2.29	126.4 +- 9.5	lowlands
12	2700345	52.96	-3.97	106.3 +- 41.7	lowlands	38	3900785	56.95	-2.22	137.4 +- 7.9	lowlands
13	2700595	55.21	-4.09	62 +- 15.7	uplands	39	4000600	55.27	-2.04	108.6 +- 23	uplands
14	2700705	56.19	-4.14	119.7 +- 6.4	lowlands	40	4050375	53.26	-1.98	77.1 +- 15.6	uplands
15	2700860	57.58	-4.22	99.7 +- 13.4	uplands	41	4050530	54.64	-1.97	79.7 +- 14.2	uplands
16	2800765	56.73	-4.00	50.5 +- 20	uplands	42	4300315	52.70	-1.60	173.4 +- 2.9	lowlands
17	2850080	50.59	-3.66	165.7 +- 10.7	lowlands	43	4550485	54.23	-1.20	132.5 +- 15.2	uplands
18	2850315	52.69	-3.73	87.1 +- 35.1	uplands	44	4600520	54.56	-1.12	158.5 +- 13.7	lowlands
19	2900285	52.43	-3.65	74.2 +- 14.7	uplands	45	4650480	54.19	-1.05	171.7 +- 8.6	lowlands
20	2950195	51.62	-3.54	87.1 +- 28.1	uplands	46	4850300	52.56	-0.79	176.3 +- 6.2	lowlands
21	2950255	52.16	-3.57	104.6 +- 15.9	lowlands	47	5000195	51.61	-0.60	189.7 +- 4.5	lowlands
22	2950650	55.71	-3.71	89.4 +- 6.3	uplands	48	5050305	52.61	-0.48	190.6 +- 2.9	lowlands
23	2950675	55.93	-3.72	106.5 +- 6.8	lowlands	49	5750135	51.07	0.46	211.3 +- 4.8	lowlands
24	3050200	51.67	-3.41	99.8 +- 22.4	uplands	50	5900285	52.41	0.74	222 +- 2.6	lowlands
25	3050360	53.10	-3.46	76.2 +- 18.2	uplands	51	6050285	52.40	0.97	220.7 +- 1.8	lowlands
26	3100695	56.11	-3.48	95.3 +- 10.5	uplands						

WG\_site\_id: based on UKCP09 classification, see [http://ukclimateprojections-ui.defra.gov.uk/ui/docs/grids/wg\\_5km/index.php](http://ukclimateprojections-ui.defra.gov.uk/ui/docs/grids/wg_5km/index.php)

Mean MD: represents mean Moisture Deficit value in the baseline used in the ESC model

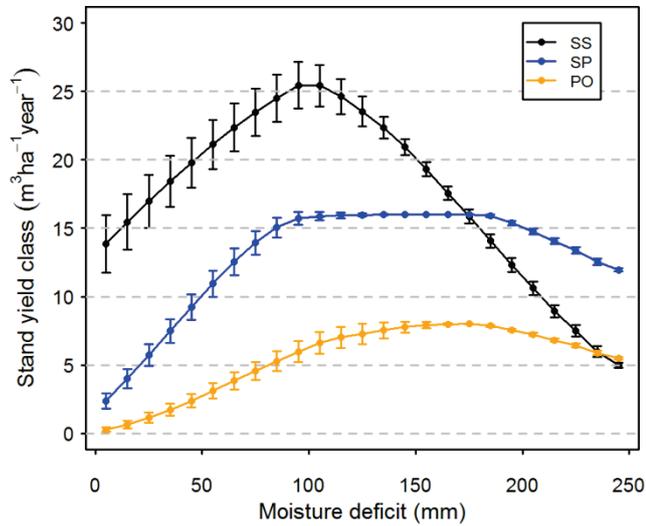


Figure 7-4 The vulnerability curves for Sitka spruce (SS), Scots pine (SP) and pedunculate oak (PO) using baseline (1961-1990) moisture deficit values from the ESC model. Error bars represent  $\pm$ SD. Curves specification in the Dataset S2.

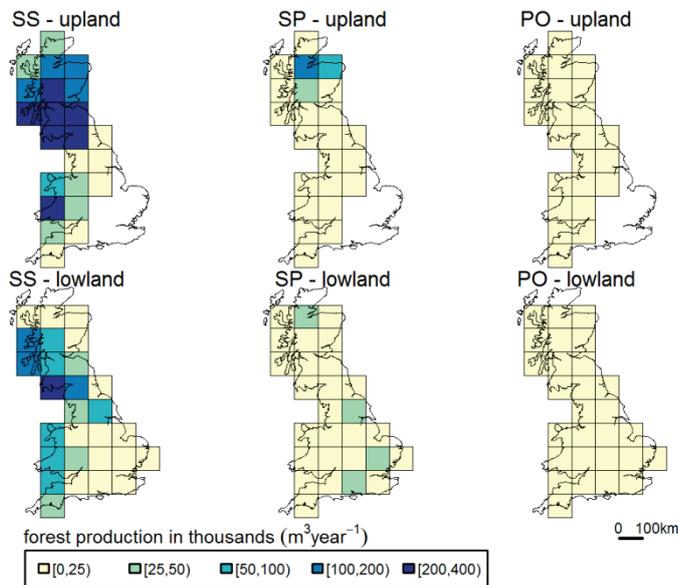
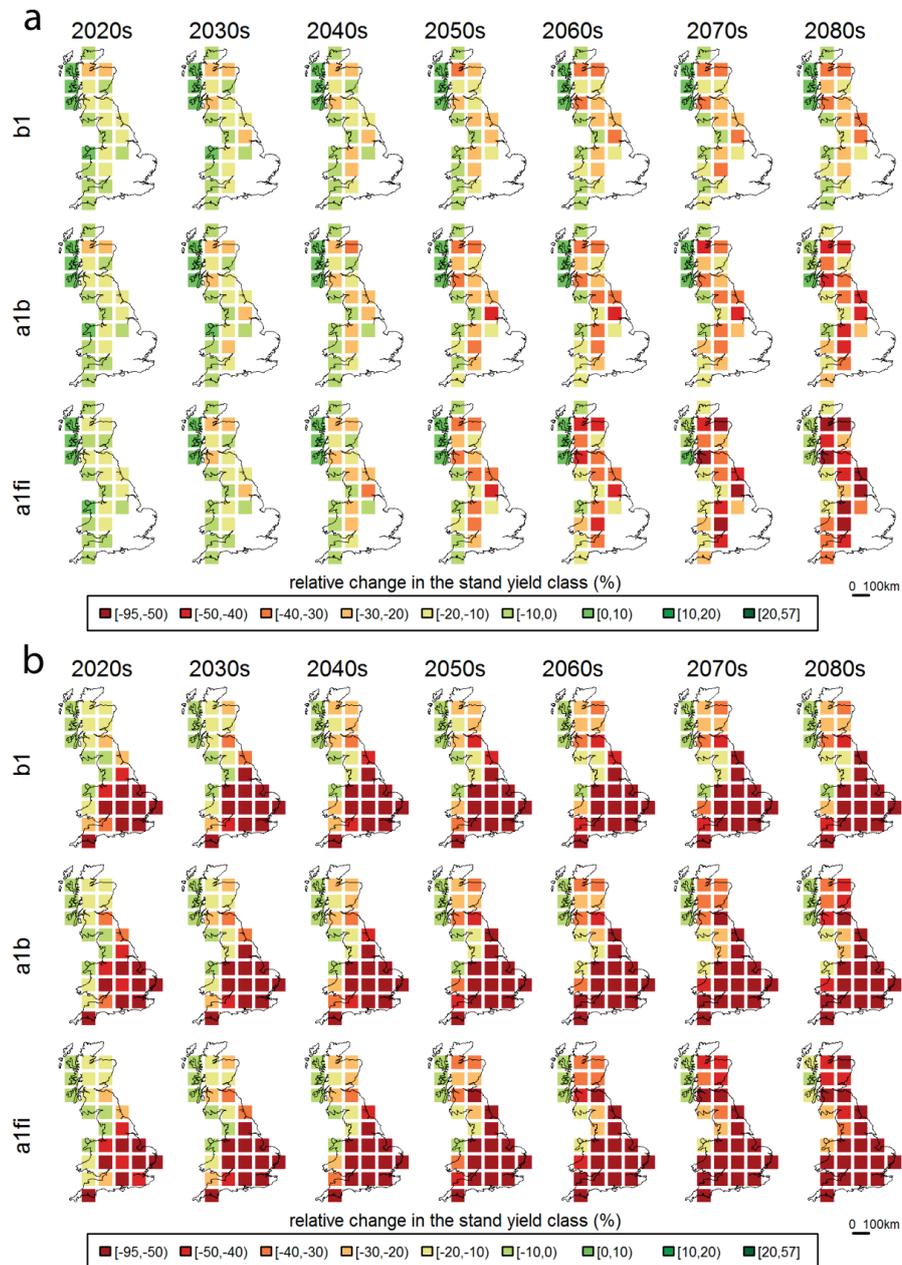
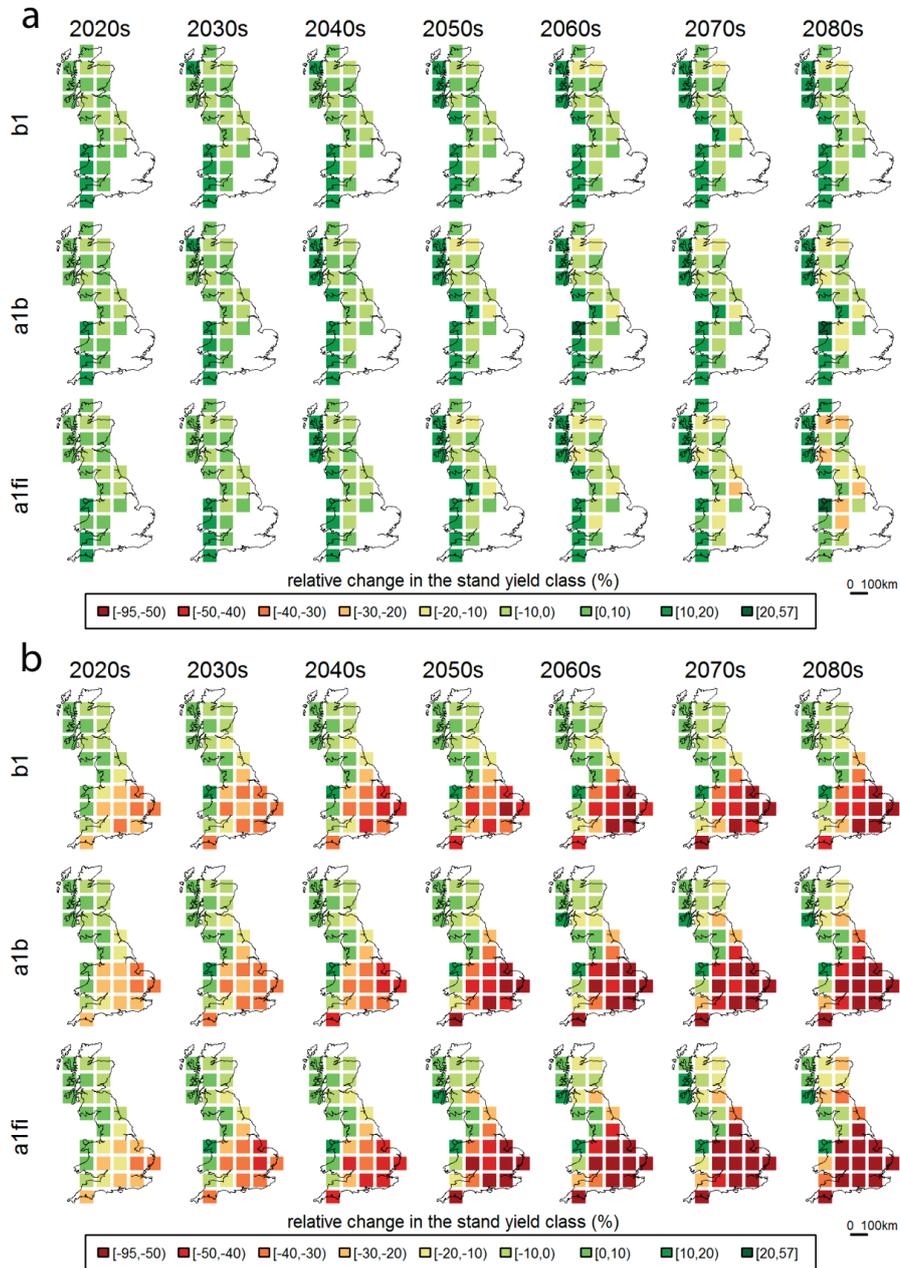


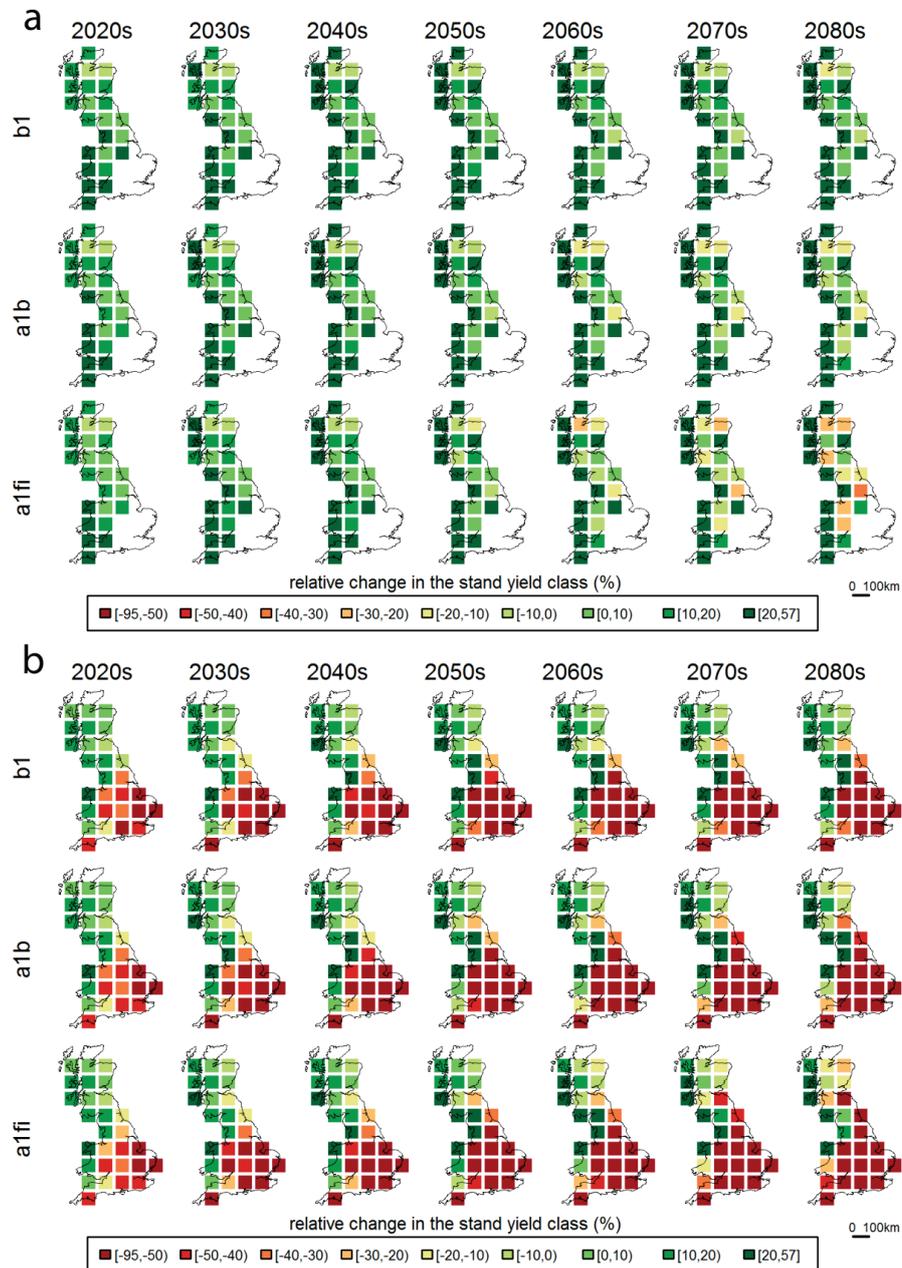
Figure 7-5 Baseline forest production within 100km grid cells based on stand yield classes and stand areas in the National Forest Estate dataset in Britain. SS – Sitka spruce, SP – Scots pine and PO – pedunculate oak.



**Figure 7-6** Changes in a) the uplands and b) the lowlands for relative stand yield classes [%] from the baseline to the future due to drought for Sitka spruce, for emission scenarios (B1, A1B, A1FI) and seven time periods (from the 2020s till the 2080s) with red colour indicating reduction and green colour indicating increase of the stand yield class.



**Figure 7-7** Changes in a) the uplands and b) the lowlands for relative stand yield classes [%] from the baseline to the future due to drought for Scots pine, for emission scenarios (B1, A1B, A1FI) and seven time periods (from the 2020s till the 2080s) with red colour indicating reduction and green colour indicating increase of the stand yield class.



**Figure 7-8 Changes in a) the uplands and b) the lowlands for relative stand yield classes [%] from the baseline to the future due to drought for pedunculate oak, for emission scenarios (B1, A1B, A1FI) and seven time periods (from the 2020s till the 2080s) with red colour indicating reduction and green colour indicating increase of the stand yield class.**

### 7.3 Supporting information for the evaluation of forest ecosystem services

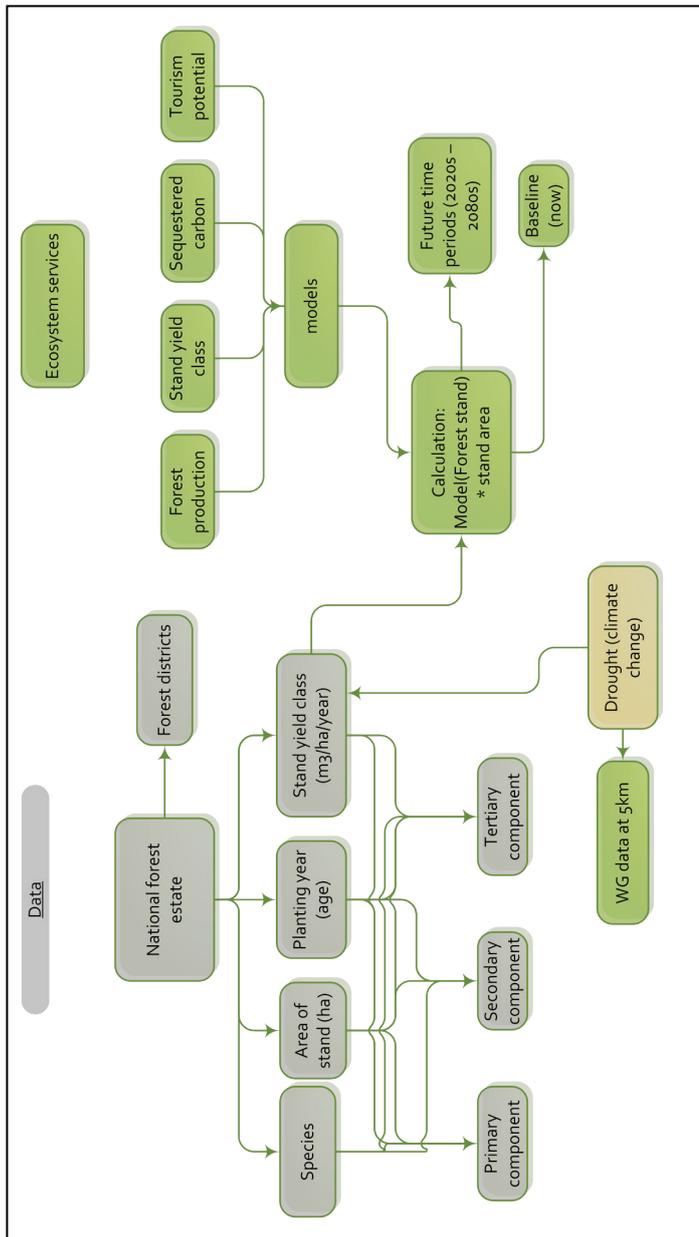


Figure 7-9 The modelling design for assessing forest ecosystem services

### Methods for assessing forest ecosystem services (outlined in Figure 7-9)

We calculated potential forest production for public forests in Scotland due to drought impacts using the national forest estate (NFE) dataset (<http://www.forestry.gov.uk/datadownload>). This dataset includes information about tree species, species components, stand area, and yield class. Future stand yield class was adjusted to the drought impacts described in Chapter 3. Production was calculated as the stand area multiplied by the stand yield class. The overall potential forest production was then calculated as the sum of production within forest stands. We assessed weighted mean stand yield class using information from the NFE dataset under drought conditions for Sitka spruce, Scots pine, and pedunculate oak. First, we adjusted the baseline yield class by a relative yield class change calculated under future drought conditions within each 25km grid cell by the lowlands and uplands. Second, we calculated mean stand yield by stand area.

We estimated sequestered carbon for three species using the Woodland Carbon Code (<http://www.forestry.gov.uk/carboncode>) described in Randle & Jenkins (2011) which uses the CSORT model (Morison et al. 2012). The Woodland Carbon Code provides information and parameters about tree species, tree spacing, stand yield class, forest management, age of crop in 5-year intervals from 0 to 200 years, and cumulative total sequestered carbon. Due to many possible options for parameters in the Woodland Carbon Code, we selected no forest management for all species; and a spacing of 2.0 m for spruce and pine, and 2.5 m for oak. Stand yield class in the Woodland Carbon Code are represented by even numbers, hence we adjusted our carbon calculation to be sensitive to yield classes with decimal places. Additionally, sequestered carbon for a yield class was a proportion of that sequestered between two even yield classes. For each species we adjusted stand yield class due to drought and also adjusted age available in the NFE dataset by the rotation period for every decade – from the 2020s until 2080s. The overall sequestered carbon was then calculated on a stand-by-stand basis for the baseline (1961-1990) and seven future decades with this equation:

$$\Delta YC_{calc} = \Delta YC_{min} + \frac{(\Delta YC_{max} - \Delta YC_{min})}{(YC_{max} - YC_{min})} * (YC_{calc} - YC_{min}) \quad [1]$$

where  $\Delta YC_{calc}$  is the cumulative carbon for the new stand yield class of a particular tree age,  $\Delta YC_{min}$  represents a cumulative carbon for the yield class directly below  $YC_{calc}$  in the particular tree age,  $YC_{min}$  represents stand yield class directly below  $YC_{calc}$ ,  $\Delta YC_{max}$  represents a cumulative carbon for the yield

class directly above  $YC_{calc}$  in the particular tree age, and  $YC_{max}$  represents stand yield class directly above  $YC_{calc}$ . As an example with  $YC_{calc} = 11.5$ , two even yield classes  $YC_{min} = 10$  and  $YC_{max} = 12$  form the limits. The sequestered carbon is tree age sensitive. To account for changes in the future tree growth we “harvested” trees when they reached the average rotation period, and restocked ‘like for like’ for the next rotation period. The average rotation periods in British conditions are 50 years for spruce, 60 years for pine, and 120 years for oak (Hart 1991; Kerr & Evans 1993). The final cumulative sequestered carbon was calculated at 5-year intervals. The limits for our calculations were: age of tree species to 200 years, and stand yield class range for spruce from 6 to 24, for pine from 4 to 14, and for oak from 4 to 8. We excluded stands outside these limits in our analysis, which removed less than 0.005% of all stands.

The last ecosystem service was tourism potential, which we assessed with Tourism Climatic Index (TCI) (Mieczkowski 1985) used in many studies (Perch-Nielsen et al. 2010; Hein et al. 2009; Nicholls & Amelung 2008). The formula for TCI is  $2*(4*CID + CIA + 2R + 2S + W)$  with five sub-indices: daytime comfort index (CID), daily comfort index (CIA), precipitation (R), sunshine (S), and wind (W). We calculated each sub-index using daily climate data and followed the method by Mieczkowski (1985). For the daytime and the daily comfort sub-indices we developed a look-up table based on a method for effective temperature (Mieczkowski 1985) to reclassify monthly temperature and relative humidity data into rates from 0 to 5. Precipitation sub-index was recoded to monthly precipitation values to rates from -5 to 5. For the sunshine hours sub-index daily sunshine hours were recoded to rates from 0 to 5. Finally, for the wind speed sub-index, we designed a lookup table that adjusted wind rates based on a wind chill rating system for temperature below 15°C and wind speed above 8 km h<sup>-1</sup>. To calculate TCI we used daily climate data from the UKCP09 weather generator (Jones et al. 2009) and these climate variables: sunshine hours [hours], precipitation [mm], minimum daily temperature [°C], maximum daily temperature [°C], relative humidity [%], and water vapour pressure [kPA]. For the missing mean wind speed we used MetOffice data available from <http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/available/monthly.html>. These data represent long term averages for the period 1971-2000, over 12 months, at 5km spatial resolution and are given in the unit ‘knots’.

## **7.4 Information used in the workshops in three Forest Districts in Scotland**

### **7.4.1 Questions for the free listing task and eight pre-defined forestry actions**

To stimulate planners thinking about possible forestry actions and their expiry dates we asked them a question:

1. For free listing task:
  - a. What actions are you doing or going to take in the future in a respect to drought in your district and when these actions reach their limits due to drought?
2. For the eight pre-defined forestry actions
  - a. When do you personally believe each action reaches its limits due to drought in your district?

### **7.4.2 Statements for exploring planners decisions in a group with new climate change information**

For the evaluation of new climate change information we asked planners four statements with responses on a 7-point Likert scale.

1. Presented pathway maps (action expiration maps) should be helpful for our forest planning. (1 – completely helpful; 7 – completely unhelpful, or DN for don't know)
2. With information from pathway maps for our district it was easy to define threshold values or limits (expiry dates) for presented actions. (1 – very easy; 7 – very hard, or DN for don't know)
3. It was easy to draw pathways under three emissions scenarios/different futures. (1 – very easy; 7 – very hard, or DN for don't know)
4. It was easy to make decisions about actions having two different percentage reduction values. (1 – very easy; 7 – very hard, or DN for don't know)

### 7.4.3 Action expiration maps for three Forest Districts

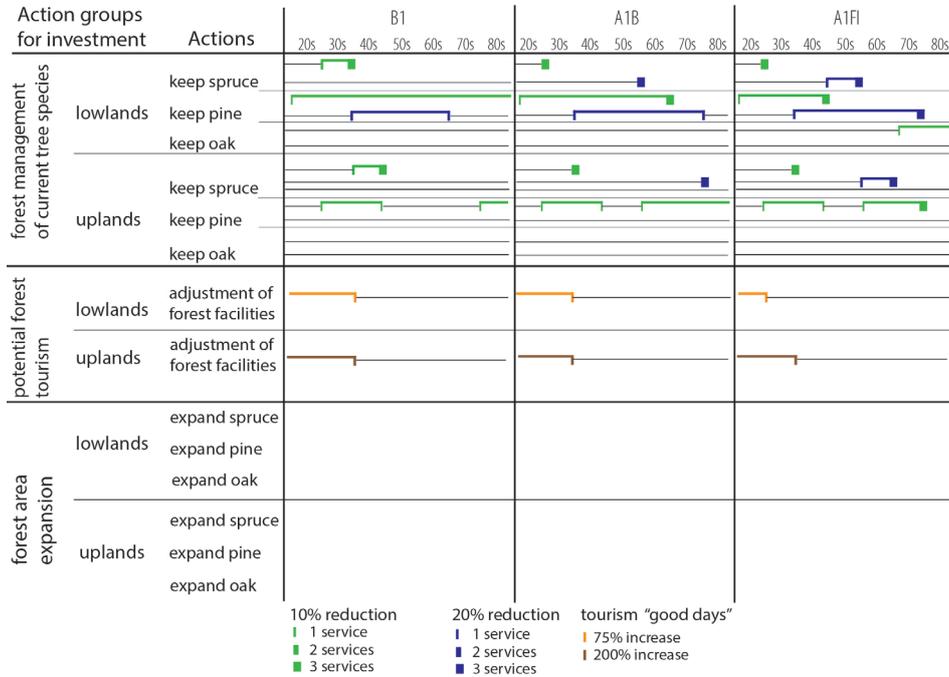


Figure 7-10 Action expiration map for Dumfries and Borders Forest District

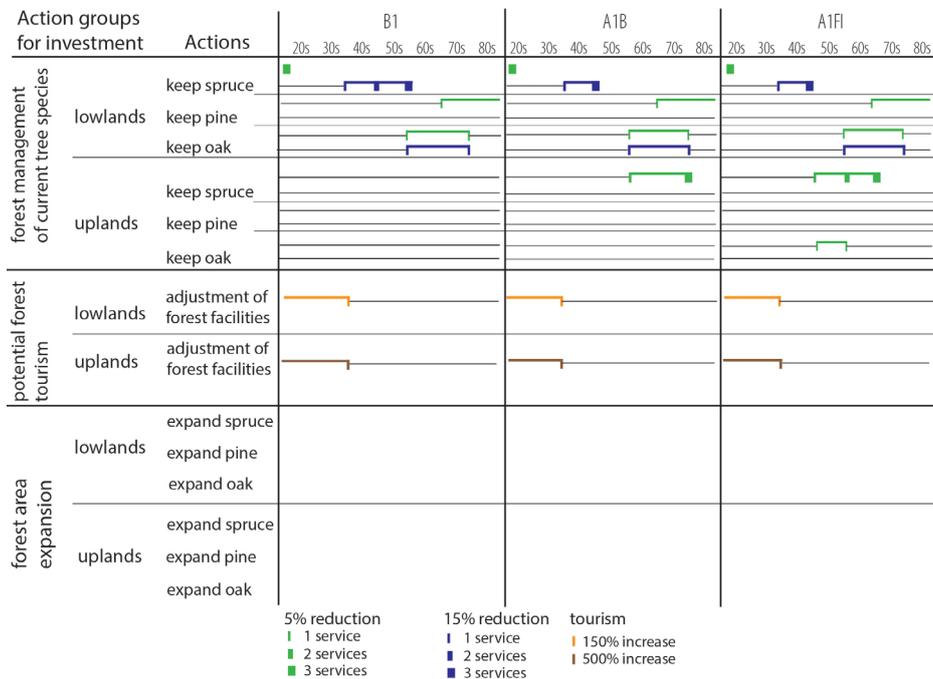


Figure 7-11 Action expiration map for Galloway Forest District

Appendices

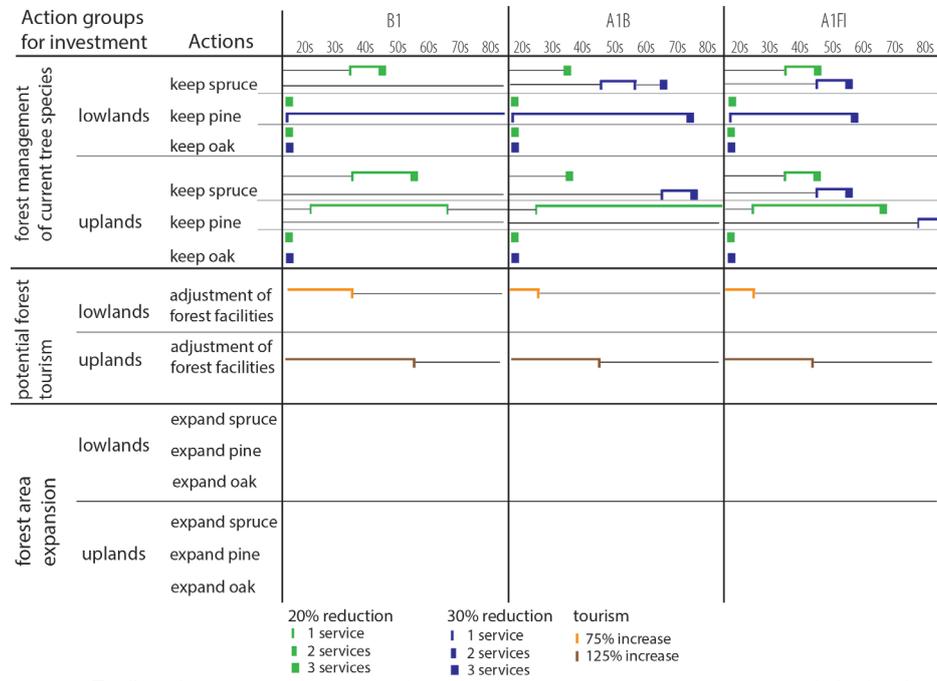


Figure 7-12 Action expiration map for Moray and Aberdeenshire Forest District

## Summary

A complete understanding of societal or wicked problems common in environmental management is unachievable. One of the reasons is uncertainty, which is represented by three sources: limited knowledge (epistemic), natural variability in human or natural systems (stochastic), and a different or conflicting interpretation of a reality (ambiguity). Forest planning, as well as climate change adaptation strategies have to address all these uncertainties. For example, uncertainty exists about the future timber demand, about the response of a stand of trees to the future climate, and about the future public use of forests. Hence, this study explores uncertainty within forest planning, in relation to climate change and its impacts. It also attempts to understand how this uncertainty might be managed in forestry, supporting implementation of climate change adaptation measures. In the future, to sustain or even to maximise the provision of forest ecosystem services, forest planners should foresee the climate change impacts and adapt forest management systems accordingly.

Expanding on the typology of uncertainty, this study has classified uncertainty into three sources and complemented two perspectives (Chapter 1). Epistemic uncertainty can be reduced with new knowledge, such as new accurate measurements, whereas stochastic uncertainty cannot be reduced due to its unpredictability, such as people's behaviour. Furthermore, uncertainty associated with ambiguity can be reduced when different interpretations of a problem are communicated and agreed among decision makers. The two perspectives relate either to a decision maker, who deals with uncertainties affecting his or her decisions, or to a modeller, who attempts to reduce the uncertainty with models. These two perspectives provide a new and more complete view of uncertainty that have been mainly rarely considered in research before. Detailed analysis and empirical research of uncertainty in forestry and climate change adaptation has been lacking. Both perspectives and three uncertainty sources were used to investigate and to address knowledge gaps of uncertainty in forest planning and in climate change impacts on forest ecosystem services.

The uncertainty investigation started with examining the different sources of uncertainty, with uncertainty management, and also with climate change risk perceptions in forest planning (Chapter 2). Essentially, understanding and thinking about uncertainty was approached from a decision maker's perspective – the viewpoint of a forest planner. Forest planners are exposed to many different types of uncertainty hence they should be familiar with handling uncertainty when it occurs. These types include uncertainty about what action to take, what goal to set, and having multiple interpretations of a problem. These

uncertainties can influence what forest planners might do, such as defining a clear goal helps to identify suitable actions that might otherwise lead to inaction. 33 planners across Britain, representing more than 50% of all planners<sup>5</sup>, involved in this study show diverse understandings of uncertainty. They indicated high levels of uncertainty related to climate problems and low uncertainty to social and economic problems. Management of uncertainty defines whether a planner prefers an active or a passive method to manage uncertainty of forest models and their outcomes. With an active method a planner acknowledges model limits and inaccuracies, whereas for a passive method a planner avoids using models because of uncertainty. The planners preferred an active method for managing uncertainty hence they should be keen to apply incomplete or inaccurate information from new models. The investigated planners' feelings and intuitive judgments about forest related risks show their diverse perceptions and worries. From a range of six risks, only for drought, pests, and wind the planners were concerned and worried with regard to their impacts on the forests they manage. However, the planners also believed that higher impacts of these three risks might be controlled or attenuated by forestry policies and management.

Uncertainty about climate change and its impacts on trees can be quantified in a risk assessment (chapter 3). Uncertainty was then explored from a modeller's perspective instead of a decision maker's, focusing on the quantification of climate change uncertainty. This leads to providing results that are as accurate as possible through the modelling of climate change impacts. The new type of drought risk assessment benefited from subjective probabilities available from the latest UKCP09 probabilistic climate change projections. These probabilities are based on multiple climate models and also on expert judgments. Probabilities then offer a sense of 'certainty' about the future climate, however, some uncertainty about a climate system still remains. The risk assessment quantified drought impacts for three major production tree species in Britain being Sitka spruce, Scots pine, and pedunculate oak over the next 80 years. The estimated combined provision of potential forest production for these species was shown to decline up to 42% due to drought impacts across Britain. Drought vulnerable hotspots were located mainly in the lowlands and in the south-east part of Britain. Less vulnerable forest areas were located in the uplands, and in the west and north-west part of Britain. To conclude, the findings reduce epistemic uncertainty about drought impacts on forests in Britain with use of the probabilistic climate change projections.

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<sup>5</sup> Employed by the Forestry Commission who is responsible for management of the public forest estate.

Building upon the drought risk assessment, additional forest ecosystem services were assessed in response to climate change impacts, and new adaptation options were evaluated (Chapter 4). Hence, uncertainty was treated from a modeller's perspective instead of a decision maker's, with an emphasis on quantifying climate change uncertainty on four forest ecosystem services. Forests provide multiple ecosystem services, however, information about their changes under climate change across Scotland has been lacking. The high spatial (5km) and temporal (from the 2020s until 2080s) resolution of UKCP09 climate data simulated with the Weather Generator allowed us a detailed assessment of drought and climate change impacts for the provisioning, regulating, and cultural ecosystem services. The provisioning services of forest production and stand yield class, and regulating service of sequestered carbon was shown to decline over the next 80 years for spruce, pine, and oak forests. For example, estimated forest production can result in the lowlands in loss up to 270,000 m<sup>3</sup> year<sup>-1</sup> (28.3% of total production) and in the uplands in loss up to 450,000 m<sup>3</sup> year<sup>-1</sup> (18.5%) in the 2080s. On the other hand, climate change may have positive impacts on potential tourism, representing a cultural service, with an increase in favourable conditions for tourism. To benefit from knowledge about these services in the actual climate change adaptation, these services were used to evaluate the forestry actions. Forestry actions represent traditional forest management actions, such as species choice. Each individual action was assessed under climate change and compared with no climate change impacts. Additionally, expiry dates were set for actions, representing a point in time when an action stops delivering the required amount of service. The final action expiration map for the Scotland containing all forestry actions shows which, when, and where adaptation measures should be taken using expiry dates. The most vulnerable forestry actions were found for spruce and pine forests in the lowlands.

The uncertainty investigation ended by evaluating ambiguity in forest planning, where planners were confronted with new climate change information (Chapter 5). Uncertainty was then addressed from a decision maker's perspective, as forest planners have to make decisions with uncertainty they are exposed to. The planners' understanding of uncertainty is important for their decision making and should be influenced by their multiple values and interpretations of a problem (ambiguity). Ambiguity also occurs due to a conflict of interests among stakeholders, who are involved in decision-making. To empirically investigate ambiguity, the planners were exposed to new climate change information during workshops across Scotland. Their frames about expiry dates for forestry actions changed with new information. Therefore, their frames about forestry actions changed or new ones appeared. Moreover, in a group setting with uncertainty represented by emissions scenarios, the planners made

different decisions in a group than they made individually. These findings confirm that new climate change information can change the decision makers' frames and also their decisions. This can imply that some climate change adaptation measures in forest management might be taken whereas some not.

Examining and evaluating uncertainty from two diverse perspectives and for three sources offers a comprehensive overview of uncertainty associated with forest planning and climate change impacts. This study shows the complexity of assessing and addressing uncertainty with qualitative and quantitative methods. The uncertainty of climate change should not be seen as a barrier to forest planning but also as an opportunity. For example, knowing about more favourable climate conditions for tourism in the future can help forest planners to take action now. Our findings show that quantified uncertainty provides valuable information about climate change impacts while providing more confidence to forest planners' decisions. Additionally, new information about climate change impacts on forest ecosystem services reduces epistemic uncertainty or limited knowledge of forest planners but possibly increases their ambiguity. In the end, depending on a source and view on uncertainty, they can offer many opportunities for future decision-making.

## Samenvatting

Een volledig begrip van maatschappelijke of venijnige ("wicked") vraagstukken, die veelvoorkomend zijn in milieubeheer, is onmogelijk. Een van de redenen is onzekerheid, die uit drie bronnen voorkomt: beperkte kennis (epistemisch), natuurlijke variabiliteit in maatschappelijke en natuurlijke systemen (stochastisch), en verschillende, mogelijk conflicterend, interpretatie van de werkelijkheid (ambigüiteit). Planning van bossen en de strategieën voor aanpassing aan klimaatverandering dienen al deze onzekerheden in aanmerking te nemen. Voorbeelden van deze onzekerheden zijn de toekomstige vraag naar hout voor de bouw, de reactie van bomen op toekomstige klimaatverandering, en het toekomstig maatschappelijk nut van bossen. Deze studie onderzoekt onzekerheid in de planning van bossen, gerelateerd aan klimaatverandering en de gevolgen van deze verandering. Ze poogt ook te begrijpen hoe deze onzekerheid in bosbouw beheert kan worden, om daarmee uitvoering van aanpassingsmaatregelen aan klimaatverandering te ondersteunen. Om in de toekomst ecosysteemdiensten van bossen te handhaven of te maximaliseren, moeten bosbeheerders het toekomstige effect van klimaatverandering kennen en naargelang het bosbeheer aanpassen.

Door op bestaande typologieën van onzekerheid voort te bouwen, heeft deze studie een classificatie van onzekerheid kunnen maken van drie bronnen en twee perspectieven van onzekerheid (Hoofdstuk 1). Epistemische onzekerheid kan verminderd worden met behulp van nieuwe kennis, zoals meer accurate metingen, terwijl dat voor stochastische onzekerheid niet mogelijk is vanwege haar onvoorspelbaarheid, bijvoorbeeld van menselijk gedrag. Onzekerheid door ambigüiteit kan wel gereduceerd worden als bijvoorbeeld beslissers verschillende interpretaties van een probleem bespreken en tot overeenstemming komen. De twee perspectieven betreffen de beslisser, die handelt met onzekerheid welke zijn beslissing beïnvloed, of de modelleur, die poogt onzekerheid in modellen te reduceren. Deze twee perspectieven verschaffen een nieuw en completer beeld van onzekerheid dat tot dusverre niet vaak onderzocht is. Gedetailleerde analyse van een empirisch onderzoek naar onzekerheid in bosbeheer en klimaatadaptatie ontbreekt. Beide perspectieven en de drie bronnen van onzekerheid zijn gebruikt om tekortkoming in kennis ten aanzien van onzekerheid in zowel planning van bossen als het effect van klimaatverandering op ecosysteemdiensten te onderzoeken.

Deze studie begon met het onderzoeken van verschillende bronnen van onzekerheid, met beheer van onzekerheid, en met risicopercepties over klimaatverandering in de planning van bossen (hoofdstuk 2). In essentie werden begrip en overwegingen ten aanzien van onzekerheid vanuit een

beslissersperspectief benaderd – het perspectief van de planner van bossen. Deze planners worden geconfronteerd met verschillende types onzekerheid. Ze moeten daarom al bekend zijn met het omgaan met onzekerheid. De types van onzekerheid betreffen welke actie ondernomen moet worden, welk doel gezet moet worden, en hoe problemen geïnterpreteerd moeten worden. Ze beïnvloeden acties van planners van bossen, zoals het definiëren van een duidelijk doel helpt geschikte acties te identificeren, zonder welke anders geen actie ondernemen zou worden. 33 planners uit heel Groot Brittannië, die 50% van alle planners vertegenwoordigen<sup>6</sup>, lieten verschillend begrip van onzekerheid zien. De planners gaven een hoog onzekerheidsniveau ten aanzien van klimaatveranderingsproblemen, en een laag onzekerheidsniveau ten aanzien van sociale en economische problemen. Beheer van onzekerheid meet of planners de voorkeur geven aan actieve of passieve methoden voor het beheer van onzekerheid ten aanzien van bosmodellen en hun resultaten. Met een actieve methode erkent de planner beperkingen en onnauwkeurigheden van een model, terwijl met een passieve methode de planner het gebruik van modellen vermijdt vanwege hun onzekerheid. De planners prefereerden een actieve methode van beheer van onzekerheid en zouden derhalve graag incomplete en inaccurate informatie van modellen gebruiken. Het onderzochte gevoel en intuïtieve oordeel van planners ten aanzien van risico's voor bossen, toonden uiteenlopende percepties en zorgen. Van een reeks van zes risico's, waren planners met name bezorgd over het effect van droogte, ziekten en wind op de bossen die ze beheren. Ze geloven echter ook dat grotere effecten van deze drie risico's onder controle kunnen worden gebracht of kunnen afzwakken door bosbeleid en bosbeheer.

Onzekerheid over klimaatverandering en het effect op bomen kan worden gekwantificeerd in een risicobepaling (hoofdstuk 3). Onzekerheid werd nu onderzocht vanuit het perspectief van de modelleur in plaats van de beslisser, waarbij de aandacht uitging naar het kwantificeren van onzekerheid van klimaatverandering. Dit leidde tot resultaten die zo nauwkeurig mogelijk waren gegeven de modellen voor berekening van het effect van klimaatverandering. Een nieuwe droogterisicoberekening profiteerde van subjectieve waarschijnlijkheden beschikbaar van de meest recente UKCP09 probabilistische klimaatveranderingsprojecties. Deze waarschijnlijkheden zijn gebaseerd op meerdere klimaatmodellen en beoordelingen van die modellen door experts. Waarschijnlijkheden geven zo zekerheid over toekomstig klimaat, maar enige onzekerheid over het klimaatsysteem blijft bestaan. De risicoberekening kwantificeerde het effect van droogte op de drie belangrijkste productieboomsoorten in Groot Brittannië, Sitka spar, Grove den, en zomereik voor de komende 80 jaar. De

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<sup>6</sup> In dienst van de Forestry Commission, verantwoordelijk voor het beheer van bos in publiek beheer.

geschatte totale potentiële productie voor deze soorten liet een reductie tot 42% zien ten gevolge van droogte over heel Brittannië. Kritieke locaties, kwetsbaar voor droogte, lagen vooral in lagere gebieden en het Zuidoosten van Brittannië. Minder kwetsbare locaties waren de hogere gebieden en in het Westen en Noordwesten van Brittannië. Concluderend, de bevindingen reduceren epistemische onzekerheid over het effect van droogte op de bossen in Groot Brittannië met behulp van probabilistische projecties van klimaatverandering.

Op basis van deze risicoberekening van droogte, zijn de consequenties op additionele ecosysteemdiensten van bossen berekend ten gevolge van klimaatverandering. Tevens werden nieuwe adaptatieopties geëvalueerd (hoofdstuk 4). Derhalve werd onzekerheid vanuit het perspectief van de modelleur in plaats van de beslisser benaderd, met nadruk op het kwantificeren van onzekerheid van klimaatsverandering met betrekking tot vier ecosysteemdiensten geleverd door bossen. Bossen voorzien in meerdere ecosysteemdiensten. Echter, informatie over de verandering deze diensten ten gevolge van klimaatverandering over heel Schotland ontbreekt.

De hoge ruimtelijke (5 km) en temporele (van de decaden 2020 tot 2080) resolutie van de UKCP09 klimaatdata, gesimuleerd door de Weergenerator, hebben het mogelijk gemaakt het effect van droogte door klimaatverandering te berekenen voor voorzienende, regulerende en culturele ecosysteem diensten. De voorzienende diensten bosproductie en de oogstklasse van de bos opstand, en de regulerende dienst van koolstof opslag gaven een daling te zien voor de komende 80 jaar voor spar, den en eik bossen. Bijvoorbeeld, de geschatte productie kan tot een verlies oplopen van  $270,000 \text{ m}^3 \text{ year}^{-1}$  (28.3% van de totale productie) in het laagland, en  $450,000 \text{ m}^3 \text{ year}^{-1}$  (18.5%) in het hoogland in de jaren 2080. Aan de andere kant, heeft klimaatverandering mogelijke een positief effect op potentieel toerisme, hetgeen een culturele dienst betreft, door toenemende geschikte condities voor toerisme. Om van de kennis over deze diensten te profiteren in actuele adaptatie aan klimaatverandering, werden deze diensten gebuikte om bosbouwacties te evalueren. Bosbouwacties zijn traditionele bosbeheeracties zoals soortkeuze. De gevolgen van Iedere individuele actie zijn berekend en vergeleken met en zonder klimaatverandering. Ook zijn adaptatieknipunten gedefinieerd voor de acties, die aangeven dat op een bepaald moment de actie de gewenste hoeveelheid diensten niet meer levert. De uiteindelijke kaart van Schotland met adaptatieknipunten voor alle bosbouw acties, toont waar en wanneer adaptatiemaatregelen genomen moeten worden, gebruikmakend van deze adaptatieknipunten. De meest kwetsbare bosbouw acties waren het verbouwen van spar en den in de laaglanden.

Dit onderzoek naar onzekerheid sloot af met een evaluatie van ambiguïteit in bosplanning. Daarbij kregen planners de nieuwe klimaatveranderingsinformatie te zien (hoofdstuk 5). Onzekerheid werd toen vanuit het beslissersperspectief benaderd, aangezien planners van bossen beslissingen namen met de onzekerheden waar ze mee te maken konden krijgen. Het begrip van onzekerheid bij planners is belangrijk voor hun besluitvorming en zou beïnvloed moeten worden door hun waarden en interpretaties ten aanzien van het probleem (ambiguïteit). Ambiguïteit is ook een gevolg van belangentegenstellingen tussen belanghebbenden die betrokken zijn in de besluitvorming. Om ambiguïteit empirisch te onderzoeken, werd aan planners de nieuwe klimaatveranderingsinformatie getoond in workshops in heel Schotland. Hun denkraam ofwel 'frame' over adaptatieknipunten veranderde ten gevolge van de nieuwe informatie. Derhalve veranderde hun frames over bosbouwacties en nieuwe frames kwamen tevoorschijn. Bovendien, toen onzekerheid werd getoond met emissie scenario's, maakten planners verschillende beslissingen als groep dan als individu. Deze bevindingen bevestigen dat de nieuwe klimaatveranderingsinformatie, frames en beslissingen van beslissers kunnen veranderen. Dit impliceert dat sommige aanpassingsmaatregelen in bosbouw kunnen worden genomen, en andere niet.

Het onderzoeken en evalueren van onzekerheid van uit twee uiteenlopende perspectieven en drie bronnen van onzekerheid biedt een veelomvattend overzicht over onzekerheid die samenhangt met bosplanning en de effecten van klimaatverandering. Deze studie toont de complexiteit van het berekenen en aanpakken van onzekerheid middels kwalitatieve en kwantitatieve methoden. Onzekerheid van klimaatverandering moet niet enkel gezien worden barrière voor bosplanning maar ook als kans. Bijvoorbeeld, de kennis over gunstigere toekomstige klimaatcondities voor toerisme, kan planners helpen nu actie te ondernemen. Onze bevindingen tonen dat gekwantificeerde onzekerheid waardevolle informatie over effecten van klimaatverandering geeft, en meer vertrouwen in beslissingen van planners van bossen. Tevens reduceert nieuwe informatie over effect van klimaatverandering op ecosysteemdiensten van bossen de epistemische onzekerheid, of de beperkte kennis van bosplanners, maar vergroot mogelijk hun ambiguïteit. Uiteindelijk kunnen, afhankelijk van de bron en het perspectief op onzekerheid, veel mogelijkheden bieden voor toekomstige besluitvorming.

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