HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Modelling climate and ecosystem services – an integrative literature review of the role of uncertainty, usefulness and boundary work

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Heidi Lehtiniemi
Supervisors: Nina Janasik & Riikka Paloniemi

HELSINGIN YLIOPISTO

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Heidi Lehtiniemi

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Mallintaminen on erittäin ajankohtainen tapa tuottaa tietoa kompleksisista ilmiöistä ja niihin liittyvistä kausaalisuhteista. Mallinnus nähdään parhaana saatavilla olevana työkaluna tarjota päättäjille tietoa lähitulevaisuuden skenaarioista ja tarvittavista toimista (Meah, 2019; Schirpke et al., 2020). Tässä tutkielmassa luodaan kokonaiskuva modernista ympäristömallinnuksesta vertaamalla globaaleja, objektiiviseen dataan pohjaavia ilmastomalleja paikallisiin, ekologista ja sosiaalista tietoa yhdistäviin ekosysteemipalvelumalleihin. Mallinnuksen lisäksi tarkastellaan tieteen ja päätöksenteon rajapintaa, joka on etenkin mallien yhteiskunnallisen käyttökelpoisuuden keskiössä.

Käyttökelpoista ja yhteiskunnallisesti relevanttia mallinnusta analysoidaan integroivan kirjallisuuskatsauksen (Whittemore & Knafl, 2005) kautta. Kirjallisuuden aiheina ovat ilmastonmuutos, ekosysteemipalvelut, mallinnus ja tieteen ja politiikan rajapinta, n=58. Eri tieteenalat ja näkökulmat ovat edustettuna aineistossa. Koska päämääränä on luoda kattava ymmärrys mallinnuksesta poikkitieteellisenä ilmiönä, tutkielma ei keskity mallinnuksen teknisiin näkökulmiin.

Kirjallisuudesta tyypitellään epävarmuuden lajeja sekä niiden hallintaan pyrkiviä strategioita (mm. van der Sluijs, 2005). Lisäksi tunnistetaan käyttökelpoisten mallien ja muiden tieteen muotojen tunnuspiirteitä (mm. Saltelli et al., 2020). Käyttökelpoisimpia ovat tilanteeseen sopivat, ratkaisukeskeiset ja saatavilla olevat mallit yhdistettynä riittävään vuorovaikutukseen ja luottamukseen mallien käyttäjien ja luojien välillä. Ilmastonmuutos ja ekosysteemipalvelut toimivat tapausesimerkkeinä, joita analysoidaan läpileikkaavasti kaikissa kappaleissa.

Keskustelu tieteen ja päätöksenteon suhteesta on erityisen tärkeää kestävyyskriisiä ratkaistaessa. Koska mallinnus sijoittuu tieteen ja päätöksenteon rajapinnalle (Duncan, Robson-Williams, & Edwards, 2020), rajapintatyön rooli epävarmuuden hallitsijana ja viestijänä sekä mallin käyttökelpoisuuden varmistajana on analyysin keskiössä.

Avainsanat - Nyckelord
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Faculty
Faculty of Biological and Environmental Sciences

Author
Heidi Lehtiniemi

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Abstract

Computing complex phenomena into models providing information of the causalities and future scenarios is a very topical way to present scientific information. Many claim models to be the best available tool to provide decision making with information about near-future scenarios and the action needed (Meah, 2019; Schirpke et al., 2020). This thesis studies global climate models based on objective data compared to local ecosystem services models combining ecological and societal data offer an extensive overview of modern environmental modelling. In addition to modelling, the science-policy boundary is important when analyzing the societal usefulness of models.

Useful and societally-relevant modelling is analyzed with an integrative literature review (Whittemore & Knafl, 2005) on the topics of climate change, ecosystem services, modelling and science-policy boundary, n=58. Literature from various disciplines and viewpoints is included in the material. Since the aim is to create a comprehensive understanding of the multidisciplinary phenomenon of modelling, the focus is not on the technical aspects of it.

Based on the literature, types of uncertainty in models and strategies to manage them are identified (e.g. van der Sluijs, 2005). Characteristics of useful models and other forms of scientific information are recognized (e.g. Saltelli et al., 2020). Usefulness can be achieved when models are fit for purpose, accessible and solution-oriented, and sufficient interaction and trust is established between the model users and developers. Climate change and ecosystem services are analyzed as case studies throughout the thesis.

The relationship of science and policy is an important discussion especially important when solving the sustainability crisis. Because modelling is a boundary object (Duncan et al., 2020), the role of boundary work in managing and communicating the uncertainties and ensuring the usefulness of models is at the center of the analysis.

Keywords
climate modelling; ecosystem services modelling; science-policy boundary; boundary work; uncertainty; complexity; modelling; impactful science; literature review

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This thesis was conducted as a commission for the Finnish Environmental institute SYKE.

Abbreviations

EU	European Union
ES	Ecosystem services
GCM	General Circulation model
IPCC	Intergovernmental Panel on Climate Change
IPBES	Intergovernmental Panel on Biodiversity and Ecosystem Services
UN	United Nations

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1 Introduction

During 2020, COVID-19 made the general public evermore familiar with scientific models, projections and other forms of computed representation of information (Stevens, 2020). Charts representing the number of confirmed cases and projections of possible scenarios became a daily content of media. Despite the increasing use of modelling, interpreting the model remains challenging (Saltelli et al., 2020). For example, understanding the uncertainties related to a model is often demanding even for scientists, let alone to decision makers or citizens (Larocque et al., 2011; Saltelli et al., 2020). This can partially be explained by the ontological aim of science and policy to remain separate; science should not create policy nor should policy influence science (McNie, 2007; Stevens, 2020).

In the era of sustainability crisis successful science-policy interaction is more important and pressing than ever (see Meah, 2019). The accelerating pace of biodiversity loss and anthropogenic climate change point out that social and ecological systems need to be understood and managed as a complex, dynamic whole with a number of feedback mechanisms (Chaffin, Gosnell, & Cosens, 2014). Many claim models to be the best available tool to provide decision making with information about near-future scenarios and the action needed to take today (Meah, 2019; Schirpke et al., 2020).

Models are created on a wide variety of subjects; economics, societal welfare, ecosystems, climate and so forth. However, science does not automatically transfer into applicable models (Funtowicz & Ravetz, 2003) and uncertainty is an essential part of modelling. There is no consensus on how models should be assessed or how to decide whether they are fit for the purpose (Hipsey et al., 2020; Larocque et al., 2011). The need for standards and protocols for modelling or mapping is identified in multiple papers (e.g. Crossman et al., 2013). While creating more accurate models and better data is important, knowledge alone is not enough to solve the sustainability crisis. Action is needed, and that cannot be sparked with mere knowledge (Funtowicz & Ravetz, 2003; Meah, 2019; Wesselink, Buchanan, Georgiadou, & Turnhout, 2013).

Action can be sparked at the science-policy boundary, and therefore the importance of boundary work should not be underestimated. After all, “getting things done in the policy arena involves more than providing the right science: it involves doing politics, that is, using power and influence strategically” (Wesselink & Hoppe 2011). Various approaches (see McNie, 2007; van Kerkhoff & Pilbeam, 2017) studying the boundary seek to better integrate scientific knowledge and societal action. Simply producing more and better science does not fix the issues in science-policy boundary (van der Sluijs, 2005).

Models are one way to present and communicate scientific information. Modelling has long traditions and a central role in environmental questions. The focus of this thesis is on the modelling of climate change and ecosystem services (ES). Climate models are important in the historical development of modelling (see chapter 2.1) and they have taken part in the discussion of defining climate change and sustainability crisis (Hoppe, Wesselink, & Cairns, 2013). Whereas climate models are global, based on biophysical data and have long traditions, ES modelling is a newer concept focusing on local scale modelling (see chapter 2.1.2) combining ecological and social data.

Other environmental models exist, but due to the differences and similarities between climate and ES models, they offer a rather comprehensive overview to current environmental modelling. Diversity of scale, data, policy-relevance, modelling practices and ways to do boundary work can be analyzed with these two cases. Due to complexity, uncertainty and its management are essential for modelling. For knowledge to spark action, the models need to be useful and policy-relevant. Therefore, *uncertainty* and *usefulness* of models is at the core of this thesis.

1.1 Importance of the topic

Regardless of the overwhelming amount of information of the cause and effects of climate change, the societal action is still lacking (Meah, 2019). Hence it is important to understand how information should be produced, communicated and presented for it to be applicable, societally relevant and to create action. Getting things done in the policy sphere is not just about information and knowledge (Wesselink et al., 2013), but a rather complicated process including also value judgement (Christl, 2018). Science is our most important epistemic tool (Potochnik, 2017) yet paradoxically science-led public policy often fails to reach consensus (Meah, 2019).

Science-based policy is a priority for the Finnish government (Valtioneuvosto, 2019), as it is in many other countries. Simultaneously, the integration of scientific information to decision making is lacking. Forum for Environmental Information[1] studied science-policy cooperation in Finland. They identified opportunities for improvement: researchers and politicians should be more strongly connected and the need for facilitated interaction is great. Especially the connection between universities and decision making is weak and the need for synthesized information pressing (Silfverberg, Huotari, & Kolehmainen, 2018). Reports and articles are not automatically scientifically or societally relevant (Lyytimäki, 2020).

Stakeholders recognized the opportunities of alternative means of communicating scientific information, mainly other than written reports, and are eager to participate in facilitated discussions. Challenges for politicians include lack of synthesized information and difficulties separating scientific information from other types of information. The selective use of information to support one's own claims is also recognized as a problem. (Silfverberg et al., 2018.) These issues have been recognized in many other articles and reports.

Knowledge and information might not be the core motives when making decisions relating to climate change mitigation or adaptation (see. Saltelli et al., 2020; Wesselink et al., 2013). Modelling provides an alternative for some written reports and articles. As a communicational tool, modelling is a promising alternative, but the process still needs to be perfected (Hipsey et al., 2020; Larocque et al., 2011; van der Sluijs, 2005). It is commonly used to communicate ecological, economic, social and other information to decision makers. While common, modelling as a communicational tool is not without its challenges (Duncan, 2008; Saltelli et al.,

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[1] Ympäristötiedon foorumi in Finnish

2020) such as misinterpretation due to the complexity or uncertainty related to modelling. This is further analyzed in chapter 4. However, by better communicating the stakes at hand, possible routes of action as well as the urgency of the situation it is possible to impact decision making (Lemos & Rood, 2010). Improving models and especially the integration of models into decision making is a way to do this.

Citizens' trust in science and the government are indicators of how rapidly political decisions are made towards climate mitigation (Jasanoff, 2005 according to van Kerkhoff & Pilbeam, 2017; Wesselink et al., 2013). By improving the trust and understanding between scientists, decision makers and the rest of society, action will simultaneously be sparked. Science-policy boundary is where models are put in action. Boundary work offers tools and approaches to study and further improve the process. Therefore, analyzing the modelling practices of climate and ES models as well as the process of knowledge transfer between models and decision making is highly topical and important.

1.2 Research questions and the aim of thesis

The aim of this thesis is twofold. Firstly, an overview of the phenomenon of modelling and its relevant historical development is created. Climate modelling and ES modelling are explained separately. Since the usefulness of models is the focus of this thesis, science-policy boundary and boundary work are also introduced. Based on the literature, definitions for complex, digital modelling as well as science-policy boundary are created. The aim is not to focus on the technical aspects of modelling but rather provide a synthesized overview of the multidisciplinary phenomenon (see chapter 2). Since the focus is on modelling as a phenomenon, no individual models are analyzed in detail.

Secondly, literature is analyzed regarding the *uncertainty* and *usefulness* of models. Chapter 4 offers analysis of the usefulness and uncertainty of models and reflection on how boundary work can be used to ensure the usefulness of the models. Types of uncertainty as well as strategies for uncertainty management are identified from the literature. Usefulness of models is analyzed by mirroring literature on both modelling and science-policy boundary. The two case studies, climate and ES modelling, are analyzed throughout the thesis.

My research questions are:

1. How do climate and ecosystem services models differ?
2. What is the role of uncertainty in climate and ecosystem services models in the literature?
3. How is usefulness of climate and ecosystem services models approached in the literature?
4. How can boundary work manage the uncertainties and improve the usefulness of models?

The overall aim is to create a comprehensive overview of useful and societally-relevant climate and ES modelling. The thesis is conducted as a commission for the Finnish Environmental Institute SYKE. However, ensuring that scientific information impacts decision making is important to all researchers, decision makers and even the general public.

2 Theoretical background

Creating mathematical forms and calculations in order to make nature measurable, understandable and predictable is not a new phenomenon at all but rather one of the foundations of science (Berry & Houston, 1995; Potochnik, 2017). However, models used today are significantly different from those of even a hundred years ago (Lahsen, 2005). The impact of digital technology has been extreme. For example, traditionally forests are analyzed from the viewpoint of forestry, with growth and yield tables and linear models (Blanco, Ameztegui, & Rodríguez, 2020). Currently hydrological factors, harvest area, ecological factors, vegetation, carbon cycles and timber volume are included in most forest models (Forsell et al., 2019). Global climate models are also an example of complex modelling including many uncertainties that could not be done without the help of computers.

Modelling has developed drastically with technological development, but for the aim of the thesis, it is not useful to provide a detailed overview of the historical development. The basic idea of quantitative science relies on statistically analyzing the data to find patterns, exceptions and correlations (Berry & Houston, 1995). By recognizing past patterns and trends, theories can be developed. On the basis of the theories, projections of the future development can be made (Berry & Houston, 1995). These projections are always uncertain, since it is impossible to know the factors affecting the parameters in the future. It is important to identify risks and projections are a good tool for that (Berry & Houston, 1995). With more data and quantitative analysis, the models started to comprehend a larger or more complex system.

Global systems, such as the climate, are so complex, that we cannot accurately model even the current state of them (Oppenheimer, O'Neill, Webster, & Agrawala, 2007). Regardless of the lack of certainty, these models are societally relevant. The ability to identify risks and causality is valuable for adaption and development (Berry & Houston, 1995; de Nijs, de Niet, & Crommentuijn, 2004; Hoppe et al., 2013).

The world cannot be understood with merely one lens but rather a comprehensive, broad view is needed. There is growing emphasis on including and assessing the influence social factors in the creation and content of science (Jasanoff, 2012). Approaches such as ecosystem services, cost-benefit analysis, life-cycle assessment and evident-based policy take a stand on normative values and should not hide their choices regarding modelling (Saltelli et al., 2020). They are also taking a step towards interdisciplinary, more comprehensive science that is not only based on absolute objectivity.

The role and responsibility of scientists ensuring usability and societal relevance of information and models is a common topic in the literature (e.g. Dilling & Lemos, 2011; Hoppe & Wesselink, 2014; Hoppe et al., 2013; Jasanoff, 2015; Lemos & Rood, 2010; Meah, 2019; Silfverberg et al., 2018; van der Sluijs, 2005; van Kerkhoff & Pilbeam, 2017). The traditional pipe-line model does not describe the interaction science and decision making have (Wesselink et al., 2013) and hence the discussion on how boundary work should be done is important.

2.1 The phenomenon of modelling

In this thesis, maps refer to geographically bound models that project the development of a phenomenon in the future. They can present e.g. land use change or the development of climate change on a certain area or the whole Earth. Both climate change and ES models are typically representations of a certain area, and hence maps. Models in this thesis refers to complex computations of a certain phenomenon. Static models are not included, since the ability to create projections is essential for both case studies.

Models aim to be (simplified) *representations of reality* (Hipsey et al., 2020) used to increase understanding of real-world phenomena, their behavior and functions (Brunet et al., 2018; Pohjola, Pohjola, Tainio, & Tuomisto, 2013). Scientific knowledge has shed light to many environmental problems (Hoppe et al., 2013). Instead of assessing whether the model provides the ‘truth’, it might often be more relevant to consider if it represents “a ‘good enough’ approximation of the truth” (Jasanoff, 2012; see also Lee et al., 2018). Theories and models are a common way to try to reach this ‘good enough’ truth.

Models represent *complex, synthesized* and, hence *policy-relevant*, information (Brunet et al., 2018). Literature emphasizes complexity and future-orientation, and hence they can be perceived as the most important qualities of modelling for decision making.

Modelling requires making *assumptions* which affect the political reality produced (Knol, 2011) and the results of the model (Forsell et al., 2019). Predictive computer modelling is a system represented by assumptions derived from theory or idealized representations (Duncan, 2008). Models are also a way to make uncertainty understandable with quantification or outsourcing the subjective, uncertain or value-loaded aspects into scenarios (van der Sluijs, 2005). Due to the chaotic dynamic of climate system and modelling, reproducing the exact climate model is impossible (Lahsen, 2005). I will further study models and uncertainty in chapter 4.1.

Computer modelling is often essential to the *legality* of a decision making since models and their results justify made decisions (Lee et al. 2018). Legal texts, strategies and agreements often create the need for knowledge production and define what the model represents (Lee, Natarajan, Lock, & Rydin, 2018) but models are also occasionally requested by decision makers (Duncan et al., 2020). Science answers these questions by creating a model, that decision makers then validate, misinterpret or refuse (Lee et al., 2018). Therefore, maps symbolize order and hierarchies, either consciously or unconsciously, and are bearers of information taking on constitutive and transformative roles (Knol, 2011). They visualize ecological value and vulnerability spatially, and as such, the ecosystem was made legible, measurable and manageable.

The increasing amount of data available due to *technological development,* e.g. satellite data, creates opportunities for better assessment of models. Remote data collecting is becoming more and more common (Blanco et al., 2020), since it saves time and money but also creates consistent data. For example, forest cover classifications, forest attributes, detection of changes and spatial modelling are usual outcomes from remote sensing (Blanco et al., 2020) and can reduce uncertainty in models. More and better data helps especially with describing uncertainty in ES and CC models (Hipsey et al., 2020) but due to complexity of the phenomenon in question, no amount of data can erase all uncertainty (van der Sluijs, 2005). Comprehensive, continuous information can improve model’s accuracy and especially identify known unknowns within the model (Meah, 2019). Given that models are simplifications of reality, used parameters are averaged values that are very unlikely to be represented by fixed constants in reality (Hipsey et al., 2020).

Models can be static or dynamic (Duncan, 2008). The *projection* of *causal*, consistent *scenarios* that take future transitions into consideration is an important function in both climate and ES models (de Nijs et al., 2004). A very famous example is the IPCC (the Intergovernmental Panel on Climate Change) and their warming scenarios (see IPCC, 2014). IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) has also had an expert group for modelling and scenarios since 2016 (IPBES, n.d.). I will study boundary organizations further in chapter 4.3. The ability to project future scenarios makes modelling highly relevant for decision making. Previously advances in technology have participated in the development of governing practices (Knol, 2011).

While modelling has certain advantages, if not properly explained to users, models can be *misused, misunderstood* and create lack of trust between decision makers and scientists (Saltelli et al., 2020). The importance of facilitated meetings between model developers and users, as well as other boundary work, is well represented in literature (see Blanco et al., 2020; Brunet et al., 2018; Duncan et al., 2020; Frantzeskaki & Kabisch, 2016).

There are no shared rules or guidelines on what to include in or exclude from models (Crossman et al., 2013; Hipsey et al., 2020; van der Sluijs, 2005). This is especially problematic for the transparency and legitimacy of modelling. For example, ‘the climategate’ challenging IPCC’s credibility in 2009 (Hoppe et al., 2013) clearly states the importance of public trust in sufficient transparency and legitimacy. Additionally, this trust indicates the speed of climate mitigation actions (van Kerkhoff & Pilbeam, 2017; Wesselink et al., 2013).

Climate change and ecosystem services are quite different and hence cannot be compared without challenges. Even though both are real-life phenomena, ES is mainly a concept created to communicate the importance of ecological factors and nature to policy making (Müller & Burkhard, 2012). ES aim to quantify the value of nature for human life. Climate change is altering the biogeochemical processes of the Earth and hence threatening our current way of life. Climate change can be seen either as an *impact* of human activities, or a *driver* of global change. Ecosystem services are typically understood as an *impact* of human activities reflecting the *state* of ecosystems (Müller & Burkhard, 2012).

Another way to understand the relationship of climate models and ES models is the global – local scale. Global climate models aim to create understanding of the whole phenomenon and identify synergies and interconnectedness within (Hoppe et al., 2013; IPCC, 2014). ES models, however, aim to bring this information on a local scale, where it becomes manageable (Blanco et al., 2020; Pohjola et al., 2013). This separation is not perfect, since ES modelling often includes the impact of climate change, but however, not always (Forsell et al., 2019). Another important difference is, that climate models rely on more objective, biophysical data, whereas ecosystem service models aim to integrate biophysical data to societally relevant factors (Blanco et al., 2020).

Modelling both phenomena usually focuses on causalities and projections. Future projections, or forecasts, can be divided in two types: deterministic ones that estimate what will happen, and probabilistic ones that asses the range of what is to be expected in the future (Lemos & Rood, 2010). Climate projections are typically the latter. Weather forecast is an example of a deterministic forecast, or prediction. Providing information of the causalities and possible future is essential in environmental models and the very feature that makes them policy-relevant.

2.1.1 Climate modelling

The history of climate modelling can be traced back as far as the 3rd century BCE when the first connections between climate and the inclination of the sun were made, and the role of heat-trapping gases in the geophysical cycles causing climatic changes was identified in 1861. (Edwards, 2011). Typically the first decades of modern climate modelling are placed between the 1960s and 1980s (Lahsen, 2005). Three types of models have played an important role in the development of climate modelling: conceptual models, analog models and energy balance and radiative-convective models. They are also the foundation of modern climatic modelling. The simplest ones do not need computers to be calculated but computers become necessary when complexity increases. (Edwards, 2011.)

The first modern climate model a computerized *General circulation model* (GCM) by Norman Phillips in 1950s, providing the basis for current climate models (Edwards, 2011). After this the development and the amount competing models increases as more institutions and researchers tackle the challenge (Edwards, 2011, fig. 5; Lahsen, 2005). Since the 1990s other processes with significant climatic impacts have been modelled too. These include *Atmosphere-ocean GCM*, *Earth system model* and *Integrated Assessment models* (Edwards, 2011).

GCMs are grid-based mathematical computations used in climate dynamics modelling (Edwards, 2011; Lahsen, 2005). They “simulate complex interactions between the components of the earth system; time-dependent three-dimensional flows of mass, heat, and other fluid properties” (Lahsen, 2005). The more complex the model, the more anthropogenic effects such as oceanic, atmospheric and land-surface processes are included. Atmospheric flows and processes are the basis of climate modelling but with the development of models more factors, such as land surface and albedo, sulphates, aerosols and other chemical processes and carbon cycle, have been included (Edwards, 2011). However, e.g. migration and emission scenarios include social data as well (Oppenheimer et al., 2007).

One of the main uncertainties in climate models are the parameters of physical climate (Lemos & Rood, 2010). In GCM the three-dimensional grids make it impossible for the parameters to be accurate. Depending on the complexity of the model, the parameters included vary. Also, parameterization requires fully understanding the phenomena, which is rarely the case (Lahsen, 2005). Another uncertain parameter is for example, the amount and relation proportions of greenhouse gases in the atmosphere (Lemos & Rood, 2010)

The IPCC is the main international organization responsible of assessing and disseminating scientific climate projections (Lemos & Rood, 2010) but there are many other ways to assess models and their accuracy (Edwards, 2011). The IPCC does not conduct their own research but produces synthesized, consensus-based information based on scientific knowledge, including models (IPCC, 2014). In Assessment Report 5 (AR5) projected changes in climate system are based on over 30 individual models (IPCC, 2014). Even while consensus-based science has its benefits and challenges (Meah, 2019; Oppenheimer et al., 2007; Pearce et al., 2017), the political importance of IPCC has been and continues to be significant.

Scale issues are a common problem whilst integrating climate models and decision making. Since climate change was originally defined as a global issue (Hoppe et al., 2013) most of the models reinforce the narrative with their global scale. The global scale has been essential for climate models since GCMs were developed (Edwards, 2011). Understanding future climate trajectories is necessary for policy, and currently climate models are the best tool available (Meah, 2019). Although global climate models are important and useful, they are less applicable for national or regional decision making and planning. Regional and local models, such as the ES models, support decision making on regional and local scales. However, the information science and models offer on climate change is not utilized to its full potential (Dilling & Lemos, 2011).

As mentioned earlier, separating climate and ES models is not always simple. Modelling provides essential information for adaptation strategies, and they are also a science-based rationale for decision making (Machar et al., 2017). Since adaptation strategies are especially relevant on a national level, the models should focus on national and regional impacts. Modelling climate change effects on forestry and agriculture in Europe have unveiled the risk of drastic climatic changes with detrimental impacts on agricultural and forestry activities (Machar et al., 2017). Hence both global climate modelling as well as regional modelling on the effects of climate change are important.

2.1.2. Ecosystem services modelling

The difference between modelling ecosystems and ecosystem services is that the latter includes social and/or economic factors in addition to ecological data (Turnhout, Hisschemöller, & Eijsackers, 2007). Ecological indicators simplify complex human-environmental systems, and they are used managing said systems (Müller & Burkhard, 2012). Ecological indicators aim to provide measurable information for quality assessment of nature, which is essential for political decision making (Knol, 2011; Turnhout et al., 2007). Biophysical data of *ecosystem properties* and data of the functions of ecosystem or *ecosystem integrity* are the basis for the assessment of ecosystem services (Müller & Burkhard, 2012). Ecosystem services are built on the idea of combining ecosystem indicators and social indicators in a policy-relevant way.

The basis for ES modelling, similar to climate modelling, is in biophysical functions. ES modelling is a much younger tradition and hence a historical overview of the phenomenon cannot be established. The epistemological aim for ES models is to quantify and make the value of nature understandable (Knol, 2011; Müller & Burkhard, 2012; Turnhout et al., 2007), whereas the tradition of climate models starts from a more objective standpoint of gaining knowledge (Edwards, 2011). The trend of combining disciplines to create useful, applicable models from 2000 onwards, according to Edwards (2011), could hence play a role in the development of ES modelling too.

ES modelling is considered to be the most promising approach on creating maps to support decision making (Schirpke et al., 2020). Especially land use planning utilizes ES models (Castellazzi, Joannon, Brown, Gimona, & Poggio, 2010; Forsell et al., 2019; Machar et al., 2017). Policies aiming to conserve biodiversity through commodification of ES production, e.g. payments, biodiversity and wetland banking, carbon offset and trading, conservation auctions, often require ES modelling to support them (Crossman et al., 2013; see also Mazziotta et al., 2016). ES modelling is hence a topical and societally-relevant way to produce scientific information.

Since ES models are map-based models, it is essential for spatial units to include both ecological and socio-economic parameters (Schirpke et al., 2020). Mapped ES usually include *provisioning* ES such as water supply, amount of wood, food production and *regulating* ES such as carbon sequestration, provision of water, water quality, pollination, cultural values, erosion control and climate regulation (Crossman et al., 2013; Orsi, Ciolli, Primmer, Varumo, & Geneletti, 2020). ES mapping can be grid-based and deciding on the level of resolution is one of the key challenges when creating applicable maps (Brunet et al., 2018).

There are simultaneous and occasionally contradictory pressures to increase the production of wood and protect ecosystem services and biodiversity (Heinonen et al., 2017). Since forests are often managed by individuals or companies, the main motivation for management is income and profit, more specifically the kind that is traded on markets (Zanchi & Brady, 2019). More information on the impacts of different forestry practices is needed to achieve environmental and sustainability goals, and especially decision makers need more information regarding the effects ecosystem services have on the welfare of different groups (Zanchi & Brady, 2019). The importance of ES modelling can also be observed in the analysis based on these models, since similar analysis could not be done with mere biophysical data. Forests are a common topic in ES modelling. The understanding of ecological processes in forests at multiple scales is supported with the coexistence of empirical and process-based models (Blanco et al. 2020).

The societal perspective can be included and transformed into monetary value with Benefit-Cost Analysis (BCA) (Zanchi & Brady, 2019). By using BCA, tradeoffs between wood production and public-good services can be quantified. This essentially means that continuous-cover forestry provides the highest contribution to societal welfare (Zanchi & Brady, 2019). Even while translation to monetary value is not the same as measuring welfare, it is a useful tool to support decision making.

2.2 Science- policy boundary

ES are an example of framing a societal problem, destruction of ecosystems and their functions, into a societally-relevant language. The predominant framing of environmental problems as scientific also transfers the responsibility of solving them on science (Wesselink et al., 2013). Scientific consensus is often used to communicate the certainty and urgency for action regarding climate change (see Meah, 2019). However, consensus and using it as validation has received criticism (Oppenheimer et al., 2007; Pearce et al., 2017). The need for longer and deeper discussion is clear.

Since both science and policy are needed to solve these societal problems, the importance of boundary work becomes irreplaceable. To better analyze the role of boundary work when assessing the usefulness of climate and ES models, studying the boundary is necessary. The *boundary* can be understood to separate three territories: science, technology and society. Gieryn (1995). However, since especially with modelling, science and technology are deeply intertwined, this thesis views the boundary between science and policy.

The boundary is both ideological and structural. The boundary is not stable or clear, and often difficult to draw. On the contrary to earlier understanding, knowledge transfer is not one-directional, one-dimensional or linear from science to policy, but rather a system of multiple levels and interactive processes (Wesselink et al., 2013). The boundary is constructed by both overlapping elements and gaps. In practice this means, that sometimes drawing the boundary between science and policy is almost impossible, because they are too intertwined and overlapping, whilst occasionally active knowledge transfer and integration is needed to bridge the gap between the two (Duncan et al., 2020; McNie, 2007; Wesselink & Hoppe, 2010).

The structural boundary is upheld by the separation of institutions, that are scientific or political. Redesigning these structures is one of the strategies to uncertainty management mentioned in chapter 4.1. Universities and other research institutes are, or at least aim to be, politically independent, which ensures the quality of research (Wesselink et al., 2013) and the authority of science (Jasanoff, 2012). This structural separation is also the key to succeed in the aim of the boundary to protect the integrity of both; “science from becoming politicized and politics from becoming scientified” (McNie, 2007). The reality, however, is not as simple.

The boundary is also a result of discourses and practices given the interactive nature of science and policy (Duncan et al., 2020). Boundary can be drawn by the separation of the nature of information and issues in science and policy. Scientists tackle uncertainty while decision makers need solution-oriented information (Dilling & Lemos, 2011; McNie, 2007; Silfverberg et al., 2018). The information relevant for scientists and decision makers is not always the same (Lemos & Rood, 2010). The lack of integration, or the gap, between science and policy can be noticed as, e.g., scaling issues with models and the academic awarding systems not encouraging scientists to produce usable information (McNie, 2007).

The involvement of scientists in decision making is inevitable when aiming for science-based decision making. Science and policy are co-produced (Duncan et al., 2020) by the ongoing process of "scientization of politics and the politicization of science" (Weingart, 1999 according to Wesselink et al., 2013). Therefore, the aim of keeping science and policy completely separated by the boundary, cannot be achieved. This especially problematic with modelling. When a scientist creates a model for political reasons, for example since it is legally mandated, is the model science or policy? The need for support tools and structures linking models and decision making has been identified (Larocque et al., 2011)

Like the boundary itself, *boundary work* (see Gieryn, 1995) is complex, "full of paradoxes and dilemmas" (Hoppe et al., 2013). Boundary work needs to be able to both open up new discussions as close down policy debates (Wesselink et al., 2013). Politicians can perceive scientists to provide moral weight to define 'the right' opinions or views (Machen, 2018). This, however, is not the aim of boundary work but rather increase understanding of all parties.

Interaction aims to create connections where previously there were none (Jahn, Bergmann, & Keil, 2012). It is not merely science and policy that need to be convinced of the authority and legitimacy of boundary work but the general public too. One way towards this is coproducing a linear knowledge transfer story of the relationship of science and policy as the dominant narrative to assure legitimacy of boundary work (Hoppe et al., 2013). However, as stated earlier, there are many challenges with the idea of linear knowledge transfer that has historically been deemed as the only way to do boundary work. Other practical challenges identified regarding boundary work are lack of time, trust and/or synthesized information, and tendentious use of information (Silfverberg et al., 2018).

Boundary work is done by a diverse group of actors, including stakeholders and *boundary organizations* (Guston, 2001). Boundary organizations aim to act between science and policy facilitating the interaction on a specific matter, e.g. climate change or biodiversity. Boundary organizations resolve "*demands for political relevance, the integration* and *representation of diverse and distributed knowledge and calls for public accountability and participation*"[2] (Beck et al., 2014) Boundary organizations hold significant power in setting the topics and views for discussion and defining whose voice gets to be heard (Hoppe et al., 2013). IPCC and IPBES are both UN-lead boundary organizations, the first one focusing on climate change and the latter on biodiversity and ecosystem services (Beck et al., 2014).

A *boundary objects* are "scientific objects which both inhabit several intersecting social worlds … and satisfy the informational requirements of each of them" (Star & Griesemer, 1989). They are material or immaterial artefacts that adapt to the context at hand without losing their indistinct identities (Star & Griesemer, 1989). Hence, boundary objects can be models (Duncan et al., 2020), organizations (Guston, 2001) or societal problems (Jahn et al., 2012).

> "One example of an abstract boundary object is a concept like 'biodiversity'; a concrete boundary object, in contrast, can be, for example, a map of a specific nature conservation area. In the second step boundary objects are transformed into epistemic objects by means of developing or applying theories or concepts. These epistemic objects are, in turn, the basis from which research questions are derived. " Jahn et al. (2012.)

In this thesis, models are perceived as boundary objects that aim to solve societal problems such as climate change. Therefore, analyzing literature on the process is important, especially when analyzing the usefulness of models, or in other words, the success of boundary work.

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[2] original formatting of the source text.

3 Materials and methods

The literature regarding climate and ecosystem services modeling is inherently multidisciplinary (Clark & Harley, 2020). Merely studying the modelling practices requires studies from a variety of disciplines. Maps predicting past, present and the future created with species distribution models (also known as habitat models, niche-based models, habitat suitability models or climate envelope models) are used explaining the influences bioclimatic variables have on plants and pest distribution. Other promising approaches with a special interest in providing useful information for decision making include hierarchical niche models, evolutionary algorithms and the Bayesian meta-modelling framework. (Blanco et al., 2020.)

Natural sciences, e.g. biology, ecology, geology, physics, study how nature functions and how and what can be measured and projected. Computer sciences have an essential role in the development of digital modelling and other technical aspects relating to models. Science and Technology Studies (STS) and legal studies analyze the role and nature of facts (Jasanoff, 2012). Sustainability science studies and develops actionable, policy-relevant research and transdisciplinarity. Many other disciplines are relevant for the topic, since studying science-policy boundary inherently studies science as a whole. Especially political and social sciences have studied the boundary.

The role of science and society regarding sustainability is often perceived as science as a service for society (Wittmayer & Schäpke, 2014). Researchers are responsible of providing evidence, “transforming reality and putting sustainability into action” (Wittmayer & Schäpke, 2014). The same is not expected of conventional researchers. Because the expectations are fundamentally different, sustainability research should also be done differently (van Kerkhoff, 2014).

Sustainability science is action-oriented, transdisciplinary and complex. This thesis is a rather typical topic for sustainability research; it is transdisciplinary, societally relevant, action-oriented, complex and involves several uncertainties (Funtowicz & Ravetz, 2003; van Kerkhoff, 2014). Among the key approaches emerging in sustainability science research are integrative methods (see Clark & Harley, 2020; van Kerkhoff, 2014; Wittmayer & Schäpke, 2014). van Kerkhoff (2014) describes integrative research in sustainability science to be “research in the context of complexity, with an action imperative”. An integrative approach fits the topic of this thesis well and takes part in the trend of further developing integrative methods in sustainability science.

3.1 Method: Integrative literature review

The main characteristics separating sustainability science from conventional research are complexity, problem-orientation to spark action and the need for integration. Therefore, the methods for sustainability science are also different from conventional science (Wittmayer & Schäpke, 2014). van Kerkhoff (2014) presents an approach for integrative research in sustainability science that is based on four principles:

1. Embracing uncertainty
2. Engaging stakeholders
3. Transdisciplinarity
4. Learning.

The core idea is to address all of the criteria during the study rather than use them as a formula for the process (van Kerkhoff, 2014). This approach does not have systematic steps or hierarchy for conducting research. The process resembles a hermeneutic circle (see Mantzavinos, 2020).

Clark and Harley (2020) approach integration through viewing Anthropocene as a Complex Adaptive System. Analyzing and identifying nature-society interactions, governance, complexity and context dependence is essential for this approach. Based on this analysis they create a framework for sustainability science. The framework is dynamic and complex, but distinctive sub-processes are recognized.

An integrative literature review is “a specific review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon” (Whittemore & Knafl, 2005). Because it also allows different methodologies to be included and is more flexible than a systemic review or meta-analysis (Whittemore & Knafl, 2005), it is a suitable method for this thesis. Integrative literature review has a defined structure and it is constructed with the following steps:

1. Problem identification
2. Literature search
3. Data evaluation
4. Data analysis
5. Presentation (Whittemore & Knafl, 2005).

Synthesized scientific reviews are important and societally relevant. At its best, an integrative literature review can develop theory and be applicable to policy (Whittemore & Knafl, 2005). Every evidence synthesis should be based on four principles: inclusiveness, rigorousness, transparency and accessibility (Christl, 2018). Especially in medicine, evidence-based practices have been increasing (Whittemore & Knafl, 2005). Evidence synthesis is often targeting also non-scientists, mainly decision makers and stakeholders.

The aim of this thesis is to create a comprehensive overview of the role of modelling as a tool to integrate scientific knowledge and decision making. Ecosystem services and climate change are analyzed as case studies. Literature from a variety of fields and subjects is included in order to gain a broad understanding of related viewpoints.

The main method for this thesis is integrative literature review (see Whittemore & Knafl, 2005). However, given the characteristics of sustainability science, I will also include features of other methods designed for sustainability research. The four principles (embracing uncertainty, engaging stakeholders, transdisciplinarity and learning) by van Kerkhoff (2014) are considered throughout the thesis. I will tackle uncertainty and its role for the topic throughout the thesis but especially in chapter 4.1. Stakeholder engagement and transdisciplinarity are not at the core of the thesis but play a part in chapters 4.2 and 4.3. Learning and gaining understanding is the main motivation for the thesis.

3.2 Material

The material analyzed for this literature review consists of 56 scientific articles and 2 scientific books, n=58. In addition to these, there are 5 are political documents included. The reference list includes more articles (e.g. Chaffin et al., 2014; Gieryn, 1995; Guston, 2001; Mantzavinos, 2020; Star & Griesemer, 1989; Whittemore & Knafl, 2005) than Table 1 because the literature used for methods and other necessary references is not included in the literature review.

Since the topic, especially modelling, is developing with a rapid speed (Lahsen, 2005), literature published after 2010 was prioritized. Especially climate modelling has become increasingly standardized and organized and cooperation between disciplines increased since 2000 (Edwards, 2011). The material is published between 1992-2020. One scientific article and two political documents are published prior to 2000. Majority of the material, total of 48 of the scientific articles were published between 2010-2020.

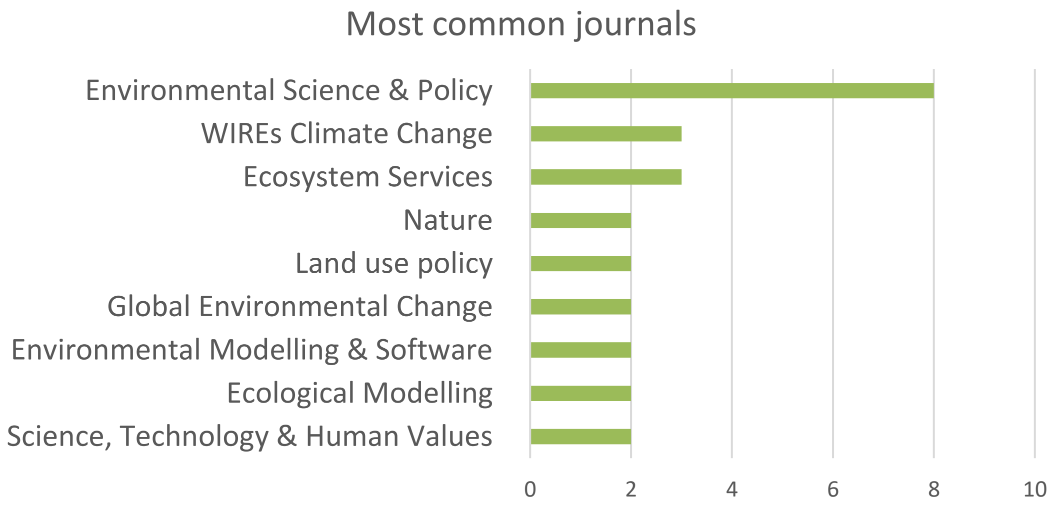
The literature search has been done using two data bases: Helka-online library and Google Scholar. Search was initially conducted with the following terms: “climate modelling”, “ecosystem services modelling”, “modelling AND boundary work”, “models AND decision making” “science-policy boundary”. However, some articles were searched for with a specific interest to confirm a finding of the analysis (see chapter 3.3). Majority of the material was identified in the initial literature search, but some complementary articles were included to improve the quality and coherence of the material. Additionally, some articles were included from the references of articles found through literature search. No systematic inclusion or exclusion criteria was established. Literature was chosen based on the relevance of the content. For the most part this could be done based on the abstract. The material has been chosen after careful consideration and after extensive background research on the subject.

Almost all the material is in English, with the following Finnish exceptions: Silfverberg et al. (2018), Lyytimäki (2020) and Valtioneuvosto (2019). Geographical distribution of the articles is challenging to define, since many of them have authors from multiple institutions and/or countries. By only observing the lead authors, literature can be placed on 5 continents and 19 countries; 38 from Europe, 12 from North-America, 6 from Oceania, 1 from South America and 1 from Asia. Therefore, the literature can be described as Western. Given the hegemonic Western narrative in climate questions (Machen, 2018; Wesselink et al., 2013), it can hardly be avoided in scientific literature either. Several articles are critical towards the dominant Western culture, but the lack of other views is a major disadvantage of the material. However, the material provides a rather vast geographical distribution of Western countries.

Since creating a comprehensive overview on the research question is a priority, efforts to include diverse views and disciplines were made. Due to the multidisciplinary nature of the topic, defining the disciplines the literature represents is challenging. However, the journals they are published in can give some indication. The 60 articles are published in 42 journals. The most common journals of the material are represented in Figure 1.

Figure 1

Material of the literature review organized by the publishing journal.



Note: The table includes 26 articles out of the total n=56. The remaining 30 articles are published in 30 different journals.

Another way to describe the material is according to the topic of the article. Table 1 present the literature thematically organized into four themes: climate change, ecosystem services, general (not climate or ES focused) modelling, and science-policy boundary. Many of the topics are overlapping and hence the list only indicative. Literature is only mentioned once even if it would be suited for another theme too.

Table 1

Analyzed literature grouped by topic of the content.

Topic	Literature
Climate change 11	Dilling and Lemos (2011); Edwards (2011); Hoppe and Wesselink (2014); Lahsen (2005); Lemos and Rood (2010); Machar et al. (2017); Machen (2018); Meah (2019); Norman, Read, Bar-Yam, and Taleb (2015); Oppenheimer et al. (2007); Pearce et al. (2017)
Ecosystem service 12	Blanco et al. (2020); Brunet et al. (2018); Castellazzi et al. (2010); Collalti et al. (2014); Crossman et al. (2013); de Nijs et al. (2004); Díaz et al. (2015); Larocque et al. (2011); Müller and Burkhard (2012); Orsi et al. (2020); Schirpke et al. (2020); Zanchi and Brady (2019)
General modelling literature 14	Berry and Houston (1995); Duncan (2008); Forsell et al. (2019); Gilliland and Laffoley (2008); Heinonen et al. (2017); Hipsey et al. (2020); Knol (2011); Lee et al. (2018); Mazziotta et al. (2016); Pohjola et al. (2013); Saltelli et al. (2020); Turnhout et al. (2007); van der Sluijs (2005); Vardas and Xepapadeas (2010)
Science – policy nter-face or boundary 21	Beck et al. (2014); Christl (2018); Duncan et al. (2020); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Funtowicz and Ravetz (2003); Hoppe et al. (2013); Jahn et al. (2012); Jasanoff (2012, 2015); Lyytimäki (2020); McNie (2007); Potochnik (2017); Sarewitz and Pielke (2007); Silfverberg et al. (2018); van der Hel (2016); van Kerkhoff and Pilbeam (2017); Weichselgartner and Kasperson (2010); Wesselink et al. (2013); Wesselink and Hoppe (2010); Wittmayer and Schäpke (2014)
Cited policy documents 5	"Consolidated version of the Treaty on the Functioning of the European Union " (2016); IPCC (2014; UN (1992a, 1992b); Valtioneuvosto (2019)

Note: While many are applicable to multiple topics, they only appear once. The total of literature sources is stated underneath the topic. N= 63.

The overview of the topic is based on *phenomena* rather than individual disciplines. Efforts to include both natural and social sciences were made. Both interdisciplinary and monodisciplinary views are represented. Additionally, research on the different actors, scientists, decision makers, knowledge brokers and other stakeholders, was included in the overview.

3.3 Conducting the analysis

The first steps of integrative literature review are problem identification and literature search (Whittemore & Knafl, 2005). For this thesis that meant defining the topic and aim of research. In the beginning three topics to study were identified: climate modelling, ES modelling, and models in the science-policy boundary. As already mentioned, the literature search was conducted using search terms (see chapter 3.2.). By analyzing the material, the importance and relevance of uncertainty and its management became evident, and therefore it was also included as a part of the thesis (see. *grounded theory* by Glaser and Strauss (1967)). Given the relevance of uncertainty for integrative literature reviews in sustainability science (van Kerkhoff, 2014), defining it as one distinct object of analysis is justified.

Evaluating and analyzing the data are the next steps in an integrative literature review (Whittemore & Knafl, 2005). Reading and summarizing the articles enabled the thematic categorization of the material (see Table 1.), as well as analyzing the content of them. Identification of similarities, differences, key arguments, connections and synergies is at the core of the analysis. When identifying connections or gaps, further literature search to confirm these findings was conducted. This is one of the efforts towards as coherent and relevant material as possible. However, the restrictions of the material need to be evaluated in order to ensure the legitimacy of the findings. These are better explained in chapter 3.2.

The final step of an integrative literature research is to present the findings (Whittemore & Knafl, 2005). Chapters 2, 4, 5 and 6 all analyze the material. The main integrative presentations are Tables 2, 3 and 4. Categorizing and separating the views of different disciplines is not the focus of an integrative literature review and hence the analysis focuses on synthesizing literature. Since the usefulness and impact of research is one of the main focuses of this thesis, ensuring the usefulness of the results was a factor when deciding on presentation style. Essential findings are presented in tables because this allows the reader to compare the material and possibly identify need for further research.

4 Results

4.1 Uncertainty and its management in models

Uncertainty, its management, communication and understanding in models are essential for successful decision making (van der Sluijs, 2005). For example, sensitivity and uncertainty analyzes can be used to numerically assess the uncertainties and errors in the outputs of the model (Larocque et al., 2011). Uncertainty is a key aspect in climate and ES modelling. Due to the complexity of these systems it is virtually impossible to remove all uncertainties, evermore so when using models to create projections (Lahsen, 2005). Especially the model users often struggle understanding the uncertainties related to models (Larocque et al., 2011).

There are many ways to describe and classify uncertainty (internal – external, structured-unstructured, known-unknown etc.) and many are present in literature. Understanding the source or reason for uncertainty is essential for the analysis and hence these types are identified and categorized. Managing uncertainty has also been studied from a variety of view points and categorized in many ways. Synthesizing both the types of uncertainty as well as the strategies for managing uncertainty is the focus of this chapter.

Uncertainties related to the parameters and structure of the model are the most commonly mentioned issues in the literature. By adjusting, including or excluding the parameters, the outcome can significantly change (Larocque et al., 2011).

This is an essential part of the models and hence the issue cannot be fixed entirely (Lahsen, 2005). In addition to the known unknowns, complex phenomenon include unknown unknowns (Saltelli et al., 2020). It also provides opportunities for intentional or unintentional misuse of the model since by adjusting the parameters one can aim for a output optimal for their motives (Saltelli et al., 2020). In addition to better communicating the logic behind chosen parameters, more accurate data is seen as a possible answer (Blanco et al., 2020).

Like in climate models, modelling choices and estimates made effect the results of ES models significantly (Forsell et al., 2019). Indicators are usually defined by scientists which steers the discussion merely on which indicators to include rather than analyzing the cause and effect relations of said indicators in the observed system (Turnhout et al., 2007). Furthermore, “especially among ecologists, there seems to be a fundamental and moral resistance against the entire concept of ecological indicators and ecological quality assessments” (Turnhout et al., 2007). Majority of this criticism is aimed at uncertainty of indicators trying to capture the essence of complex nature. However, when combining these ecological indicators with social or economic factors, the complexity and uncertainties increase (*uncertainty cascade*, see table 2).

The scale issues often refer to a situation, where the model is created on a scale that is not applicable to decision making. The scale can refer to temporal or spatial scale, but also systems, or to the complexity and accuracy of the model (Lemos & Rood, 2010). Scale issues are often caused by lack of understanding of both what decision makers need, and what scientists can produce. However, other reasons such as a disagreement between scientists solved by adapting resolution of the model (Brunet et al., 2018) can be responsible for scale issues. The importance of communication and boundary work is again pointed out.

The uncertainty cascade refers to a situation, where a parameter, or model, is used as a basis for other parameters accumulating the uncertainty. The Basslink project in Tasmania (Duncan, 2008) points out the problems of using another model as the basis for another’s parameters. Multiple assessments regarding a variety of environmental and economic impacts were created before the approval of the project. However, all the assessments were based on a single predictive economic model that turned out not to provide an accurate projection of the future. (Duncan, 2008.)

Modelling natural phenomenon is based on the idea that nature is quantifiable and predictable (Lahsen, 2005). While most scientists believe that certain predictions are possible, the climate system is agreed to be chaotic. Critical views regarding the predictability of climate change emerge from the literature (Lahsen, 2005; van der Sluijs, 2005).

This implies, that uncertainties play a key role in climate modelling. Especially uncertainty related to the parameters and models themselves are essential. In GCMs, grids contain averaged values. The models created by the IPCC are averaged from multiple different models (IPCC, 2014). As more parameters are included to create a more complex model, also the uncertainty accumulates into an uncertainty cascade (Saltelli et al., 2020).

The uncertainties within the model are also important for the accuracy of climate models. The global climate system is so complex, that not even the current state can be accurately modelled (Oppenheimer et al., 2007). With increasing temporal scale, the projections are also increasingly uncertain (Lahsen, 2005). Since there is a lack of guidelines for what to include or exclude from models (van der Sluijs, 2005), models are not always comparable with one another.

Similar uncertainties are a challenge for ES models too. Parameters are averaged values that are likely never to exist in nature (Hipsey et al., 2020). Also, the parameters included and excluded from the models play an important role for the outputs. LULUCF (land use, land use change and forestry) is an emission accounting practice of the EU. It requires all member countries to calculate a forest reference level to be able to calculate the change in emissions during the next years. Modelling choices impact the estimation of reference level significantly (Forsell et al., 2019). Yet again the importance of transparent documentation is made obvious.

ES models aim to present the projected natural values in a societally-relevant way. Since translating natural value into e.g. monetary value is problematic (Zanchi & Brady, 2019), it will increase the uncertainty of the results. Especially ES models often aim to quantify phenomenon that is difficult to measure. This can lead to the buildup of uncertainty, the uncertainty cascade (Saltelli et al., 2020). Quantifying nature has been criticized by especially ecologists due to the complexity and uncertainty related to it (Turnhout et al., 2007; see also van der Sluijs, 2005, monster-embracement). Additionally, when combined with societal data, estimates on rather unpredictable factors, such as the future development of citizens behavior, might provide the basis for the model (Saltelli et al., 2020).

The literature recognizes uncertainty as an essential part of modelling. Table 2 categorizes the types of uncertainty recognized in the analyzed literature. The list is not comprehensive but synthesizes the most important and common uncertainties mentioned in the material of this thesis. The literature is organized into topics by the same logic as in Table 1. While similar observations can be identified from literature in the 'science-policy boundary' topic in Table 1, it is excluded in Table 2. This is in order to offer a purely modelling focused analysis of uncertainty. The connection and synergies of the modelling and science-policy boundary are analyzed in chapters 4.2, 5 and 6.

Table 2

Types of uncertainty in models identified from the literature.

Type of uncertainty	**Literature that recognizes the type in**		
	climate models	**ecosystem services models**	**models in general**
Uncertainty within the model 24	Dilling and Lemos (2011); Edwards (2011); Lahsen (2005); Lemos and Rood (2010); Machar et al. (2017); Meah (2019);	Blanco et al. (2020); Brunet et al. (2018); Collalti et al. (2014); Crossman et al. (2013); de Nijs et al. (2004); Larocque et al. (2011); Müller	Berry and Houston (1995); Duncan (2008); Forsell et al. (2019); Hipsey et al. (2020); Lee et al. (2018); Mazziotta et al. (2016); Pohjola et

	Norman et al. (2015); Oppenheimer et al. (2007)	and Burkhard (2012); Schirpke et al. (2020)	al. (2013); Vardas and Xepapadeas (2010)
Uncertainty of the parameters 22	Edwards (2011); Lahsen (2005); Lemos and Rood (2010); Machar et al. (2017); Oppenheimer et al. (2007)	Brunet et al. (2018); Collalti et al. (2014); Crossman et al. (2013); Díaz et al. (2015); Larocque et al. (2011); Orsi et al. (2020); Schirpke et al. (2020); Zanchi and Brady (2019)	Berry and Houston (1995); Duncan (2008); Forsell et al. (2019); Heinonen et al. (2017); Hipsey et al. (2020); Mazziotta et al. (2016); Pohjola et al. (2013); Turnhout et al. (2007); Vardas and Xepapadeas (2010)
Uncertainty caused by scale issues 11	Dilling and Lemos (2011); Hoppe and Wesselink (2014); Lahsen (2005); Lemos and Rood (2010)	Blanco et al. (2020); Brunet et al. (2018); Crossman et al. (2013); Larocque et al. (2011); Schirpke et al. (2020); Zanchi and Brady (2019)	Duncan (2008)
Accumulation of uncertainty, *the uncertainty cascade* 6	Lahsen (2005); Lemos and Rood (2010); Meah (2019)	Larocque et al. (2011)	Duncan (2008); Saltelli et al. (2020)

Note: This list is based on the material of this thesis and is therefore not comprehensive. Table 2 synthesizes and presents the views and points of the material. The number of articles where the type is mentioned is stated underneath the type. n=37.

Uncertainty is an essential part of modelling and does not stand in the way of usefulness. Efforts to minimize and manage uncertainty are common and distinct strategies can be identified. The most common ones in the literature are analyzed next.

Managing uncertainty is a way to ensure the usefulness of the information, regardless the lack of certainty (Hoppe & Wesselink, 2014). The traditional strategy, so called *uncertainty fallacy,* is the one relying on more and better research to increase accuracy. This is often the case with climate and ES models, since no amount of objective research can erase all uncertainties (Lahsen, 2005). Like simpler weather forecasts, climate and ES can never be modelled and predicted with absolute certainty (Lemos & Rood, 2010; Oppenheimer et al., 2007), nor should this be the aim (Jasanoff, 2012). However, the role of satellite data improving the accuracy and capabilities of models should not be forgotten (Edwards, 2011). While often aimed for the complexity of the model is no guarantee of the accuracy of it (Saltelli et al., 2020).

Another common strategy is to assess, quantify or outsource the uncertainty of models to better understand it. Uncertainty assessments are becoming a standard part of climate modelling (IPCC, 2014; Lahsen, 2005) and efforts to implement them in ES modelling are also taking place (IPBES, n.d.). However, quantifying the range of uncertainty might not provide the necessary explanation for model users trying to develop understanding of it. Communicating the uncertainty is an important part of this strategy. Drawing boundaries between science and policy is related to this strategy (van der Sluijs, 2005). Creating various scenarios of the future can be understood as one way to both outsource the uncertainties and stress the causality of actions taken today.

An opposing strategy is to try to hide uncertainty in the model. It is typical, that uncertainty and its assessment is explained in the technical reports but not in the impact assessment statements or final determinations (Duncan, 2008). Since all uncertainty cannot be excluded from the model, efforts to hide the remaining uncertainties are sometimes made (Lahsen, 2005). Uncertainty does not support the idea of science providing objective knowledge and it is hence efforts to delete uncertainty are made. Main motivations for hiding uncertainty are usually related to political agendas or avoiding disputes. (van der Sluijs, 2005.) Hidden uncertainty has been described as a Russian doll with not just one black box but many inside the other (MacKenzie, 1990 according to Duncan, 2008).

Using complexity of the phenomenon to explain the uncertainties in models is a strategy that can be implemented in two ways; either embracing complexity with uncertainty as its essential character or deny the existence of the phenomenon due to the complexity and uncertainties related to it (van der Sluijs, 2005). The latter strategy has been mainly used by climate sceptics to undermine the existence of the risks (van der Sluijs, 2005). This strategy was not evident in ES literature, which could be an indication that it is no longer as relevant. Embracing the complexity is a more commonly mentioned strategy in the literature, although it is often complemented with other strategies. It is often used as an argument for

why the remaining uncertainties in the models do not make it unusable or irrelevant.

The last strategy, redesigning the structures, is a rather popular one in the boundary literature (see e.g. McNie, 2007) but can also be identified from modelling literature. It is related to the boundary between science and policy and redefining that boundary, and often executed by redefining science and/or policy. Even though these theories are not analyzed by name, many of them are included in the literature. Chapter 4.2 analyzes literature and offers synthesized information on the characteristics of usefulness of information.

The literature recognizes uncertainty as an essential part of modelling. Table 3 categorizes the strategies for managing uncertainty recognized in the analyzed literature. Classification is applied from the list provided by van der Sluijs (2005) but also supported by the literature. The list is not comprehensive but synthesizes the most important and common strategies mentioned in the material of this thesis. Due to the differences between climate and ES models as well as the restrictions of material, all these qualities could not be recognized from ES literature. This can be a result of various factors; newer practices and traditions, more technically focused literature, different level of interaction between model users and developers, scale of the models, learning from previous efforts in modelling etc. All strategies that were recognized in at least climate or ES modelling and the general modelling literature are included. This provides information about the similarities and differences between the two case studies, climate and ES models. The literature is organized into topics by the same logic as in Table 1.

Table 3

Strategies for managing uncertainty identified from the analyzed literature.

Strategy for managing uncertainty	Literature that recognizes the strategy in		
	climate modelling	ecosystem services modelling	modelling in general
Assessing, quantifying and outsourcing the uncertainty to make it understandable 22	Dilling and Lemos (2011); Edwards (2011); Lahsen (2005); Lemos and Rood (2010); Machar et al. (2017); Meah (2019); Oppenheimer et al. (2007)	Brunet et al. (2018); Castellazzi et al. (2010); Collalti et al. (2014); Crossman et al. (2013); de Nijs et al. (2004); Díaz et al. (2015); Larocque et al. (2011)	Duncan (2008); Forsell et al. (2019); Hipsey et al. (2020); Mazziotta et al. (2016); Pohjola et al. (2013); Saltelli et al. (2020); van der Sluijs (2005); Vardas and Xepapadeas (2010)
Embracement of complexity 9	Lahsen (2005); Lemos and Rood (2010); Meah (2019)	Blanco et al. (2020); Crossman et al. (2013); Larocque et al. (2011)	Saltelli et al. (2020); Turnhout et al. (2007); van der Sluijs (2005)
Uncertainty is reduced by more objective research, *the uncertainty fallacy* 9	Dilling and Lemos (2011); Edwards (2011); Lahsen (2005); Lemos and Rood (2010); Meah (2019)	Blanco et al. (2020)	Hipsey et al. (2020); Lee et al. (2018); van der Sluijs (2005)
Denying the existence of complexity due to the uncertainties related to it 6	Lahsen (2005); Meah (2019); Oppenheimer et al. (2007)		Saltelli et al. (2020); Turnhout et al. (2007); van der Sluijs (2005)

Redesigning the structures supporting complexity and uncertainty 5	Lemos and Rood (2010); Machen (2018); Pearce et al. (2017)		van der Sluijs (2005)
Uncertainty is managed by hiding or downplaying it 5	Lahsen (2005)		Duncan (2008); Pohjola et al. (2013); Saltelli et al. (2020); van der Sluijs (2005)

Note: These strategies have previously been listed by van der Sluijs (2005) and this classification provided the frame for the analysis, but it has been applied to fit this purpose, and hence table 3 offers a synthesis of the literature. The number of articles where the strategy is identified is stated underneath the strategy. n=37.

4.1.1 The implications and relevancy of uncertainty

While uncertainty is an important part of modelling, it does not stand in the way of usefulness. Information provided by modelling can be useful and policy-relevant, or ‘good enough’, even if it is uncertain. Uncertainty should also not stand in the way of action or demine the message of these model. One of the legal grounds the literature mentions is the precautionary principle (Hoppe & Wesselink, 2014; Vardas & Xepapadeas, 2010).

The *precautionary principle* was first in the Rio Declaration in 1992:

> “Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as reason for postponing cost-effective measures to prevent environmental degradation” (UN, 1992a).

By 1993, 166 countries had signed the Framework Convention on Climate Change and currently[3] there are 197 Parties on it (UN, 1992b). The EU has also adopted this principle into their legislation to prevent taking unnecessary and irreversible risks to human and environmental health ("Treaty on the Functioning of the European Union ", 2016). According to the precautionary principle, harmful

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[3] Refers to 10/2020.

activities should be prohibited and reconsidered after sufficient scientific information is available. The uncertainties related to climate and ecosystem services models concern the *scale* of the impacts, not whether there will be harmful consequences. In conclusion, there are legal grounds to prevent further advancement of these harmful activities, and models rather support than resign this claim (Norman et al., 2015).

The precautionary principle has historically been an inadequate tool to prevent harmful activities even when the risk they pose has been known to be significant. The lack of scientific certainty has historically been used to undermine the message and legitimacy of science (Meah, 2019; Oppenheimer et al., 2007; van der Sluijs, 2005). Paradoxically, it is typical that the decisions with huge error potential need to be made before science is conclusive (van der Sluijs, 2005). Assessing the uncertainty or certainty of science is important but to successfully do so, one needs to fully understand *what* the uncertainties are and *why* they exist. While development of legal measures is also needed, many scientists have tackled this issue (see Tables 2 & 3).

Boundary organizations and models have had a great role in understanding and acknowledging phenomenon such as climate change and biodiversity loss. In addition to better understanding, managing uncertainty is important in order to maintain legitimacy (see also Table 4). Historically, sceptics have denied the information in the models based on uncertainty and due to the urgency of sustainability crisis, time can no longer be wasted on misinterpreting the models that severely. There are connections between the uncertainty, its management and usefulness of models, and the next chapter will analyze these relationships in more detail.

4.2 Usefulness and models

Given that models are boundary objects, analyzing the process of information flow from the viewpoint of *usefulness* of the models to decision making is important. There are many concepts that aim to redefine the boundary between science and policy, e.g. new social contract of science, mode 2, socially robust science, well-ordered science, use-inspired research, post-normal science, sustainability science, adaptive governance and social-ecological systems analysis (McNie, 2007; van Kerkhoff & Pilbeam, 2017). These concepts are one of the mentioned strategies for managing uncertainty. Additionally, various other ways to identify and assess the usefulness of science have been established. Typically, the assessment of models focuses on improving technical features and modelling practices. Literature on useful science often emphasizes the importance of boundary work and the integration of the producers and users of information. Instead of going into detail describing these concepts and classification, I will synthesize literature on the characteristics that useful information has.

Societally-relevant information in solution-oriented (Dunn & Laing, 2017). Modelling can identify and analyze causalities and create scenarios to be solution-oriented. Especially the ability to explore outcomes of decisions is beneficial for decision makers (Brunet et al., 2018). Solution-orientation and actionable research are typical for sustainability science (van Kerkhoff, 2014).

To be accessible and applicable, information needs to be available when decision making needs it (Duncan et al., 2020; Dunn & Laing, 2017). Time is also essential for successful boundary work: time to have discussions and do boundary work (Duncan et al., 2020). To be applicable, the users' need to be identified and local context taken into consideration, and adjustments made throughout the research (Brunet et al., 2018).

The need for scientists to understand decision makers needs was recognized in many of the articles. Producers and users need different things (Lemos & Rood, 2010). Therefore, identifying the users' needs should be the first step of creating models (Brunet et al., 2018). This also needs to be done case-by-case, since no "one-size-fits-all model" exists (Beck et al., 2014).

Successful framing is another way to emphasize the importance of mutual understanding and cooperation. Model producers and users need to agree on the same scale and context of its use (McNie, 2007). Users also need to understand, what the model presents, since e.g. climate models cannot predict weather (Lahsen, 2005). Transparency on the normative choices made is also important (Saltelli et al., 2020). Framing can also refer to participation and inclusion; for example “IPBES plenary discusses the relevance and credibility of different forms and sources of knowledge and experience” (Beck et al., 2014). Framing can be one way to define authority and legitimacy. As mentioned in chapter 4.1.1, uncertainties can be the enemy of legitimacy, and therefore managing them is important.

Iterative information can be communicated without jargon to minimize misunderstandings (Dunn & Laing, 2017). Prevention of misuse or tendentious use of information is at the heart of iterativity (Dilling & Lemos, 2011). However, communication of information is not always simple. Knowledge brokers have to make difficult decision on what is communicated and what is let out: often many technical details are left out while they would make the broker seem more honest and legitimate (Duncan et al., 2020). Iterativity and legitimacy on information are often connected.

Authority plays an important role when assessing legitimacy, credibility or integrity. Lee et al. (2018) identify legal, scientific and political authority, that are all mutually reinforcing. All three are relevant for the topic for modelling and their use in decision making. Legitimacy is especially important for the impact of research since “the uptake of facts and data in policy discourses depends on who provides them” (Wesselink et al., 2013). This indicates that the information provider has a central role to the perceived legality of it (see Silfverberg et al., 2018). Usefulness and legitimacy are subjective and should therefore be better communicated and discussed. Providing all necessary information still does not guarantee political action (Wesselink & Hoppe, 2010) and hence dialogue between model developers and users is important (Larocque et al., 2011).

Cooperation between scientists and decision makers is important for improvement of the perceived legitimacy of research, but it can also create trust, respect and means for cooperation (Frantzeskaki & Kabisch, 2016). Science cannot tell us what we ought to do but rather offer information of the possibilities at hand (Jasanoff, 2015). Useful science-policy interaction offers decision makers the information they need to consider when addressing the issue at hand (Meah, 2019).

Adjustment, discussion and learning have been identified increase the success of boundary work (Brunet et al., 2018). Deciding who is included in policy-making might be at its center (Wesselink & Hoppe, 2010). Co-production of knowledge, transdisciplinarity and stakeholder participation are examples of attempts to include more people and views into decision making.

One of the main expectations and key differences to other forms of scientific information, is models' ability to present comprehensive and integrated information (Brunet et al., 2018). As already explained, synthesizing and creating comprehensive information is not without its challenges. Integrating information is an act of power. There is always has a risk of epistemological hierarchy regarding the types or sources of information. In the case of climate change, geophysical sciences and economics are often promoted while other types of knowledge marginalized (Hoppe et al., 2013).

The literature recognizes uncertainty as an essential part of modelling. Table 3 categorizes the strategies for managing uncertainty recognized in the analyzed literature. Classification is applied from the list provided by van der Sluijs (2005) but also supported by the literature. The list is not comprehensive but synthesizes the most important and common strategies mentioned in the material of this thesis. Due to the differences between climate and ES models as well as the restrictions of material, all these qualities could not be recognized from ES literature. This can be a result of various factors; newer practices and traditions, more technically focused literature, different level of interaction between model users and developers, scale of the models, learning from previous efforts in modelling etc. All strategies that were recognized in at least climate or ES modelling and the general modelling literature are included. This provides information about the similarities and differences between the two case studies, climate and ES models. The literature is organized into topics by the same logic as in Table 1.

Table 4 presents the aforementioned characteristics of usefulness in both modelling literature and boundary literature. The classification is based on the characteristics identified from the analyzed literature. The list is not comprehensive but synthesizes the most important and common characteristics mentioned in the material. The literature is organized into topics by the same logic as in Table 1, modelling literature including the topics of climate change, ecosystem services and general modelling literature.

Table 4

Characteristics of societally useful science and/or models identified from the literature.

Characteristic	Modelling literature that recognizes the characteristic	Science – policy boundary literature that recognizes the characteristic
Applicable and accessible 26	Brunet et al. (2018); Castellazzi et al. (2010); Collalti et al. (2014); Dilling and Lemos (2011); Hipsey et al. (2020); Lee et al. (2018); Lemos and Rood (2010); Machar et al. (2017); Orsi et al. (2020); Saltelli et al. (2020); Turnhout et al. (2007)	Beck et al. (2014); Christl (2018); Duncan et al. (2020); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Hoppe et al. (2013); Jasanoff (2012); Lyytimäki (2020); McNie (2007); Sarewitz and Pielke (2007); Silfverberg et al. (2018); van der Hel (2016); van Kerkhoff (2014); Weichselgartner and Kasperson (2010); Wesselink et al. (2013)
Trust, respect and cooperation between model developers and model users 21	Brunet et al. (2018); Dilling and Lemos (2011); Gilliland and Laffoley (2008); Larocque et al. (2011); Lemos and Rood (2010); Müller and Burkhard (2012); Oppenheimer et al. (2007); Pohjola et al. (2013); Saltelli et al. (2020)	Beck et al. (2014); Christl (2018); Duncan et al. (2020); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Hoppe et al. (2013); McNie (2007); Sarewitz and Pielke (2007); Silfverberg et al. (2018); Turnhout et al. (2007); van der Hel (2016); Weichselgartner and Kasperson (2010)
Comprehensive and integrated information 19	Blanco et al. (2020); Brunet et al. (2018); Castellazzi et al. (2010); de Nijs et al. (2004); Díaz et al. (2015); Dunn and Laing (2017); Forsell et al. (2019); Knol (2011); Lemos and Rood (2010)	Christl (2018); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Funtowicz and Ravetz (2003); Hoppe et al. (2013); McNie (2007); Silfverberg et al. (2018); van der Hel (2016); van Kerkhoff (2014); Weichselgartner and Kasperson (2010)

Successful framing 18	Brunet et al. (2018); Crossman et al. (2013); Dilling and Lemos (2011); Gilliland and Laffoley (2008); Hoppe and Wesselink (2014); Lee et al. (2018); Lemos and Rood (2010); Müller and Burkhard (2012); Saltelli et al. (2020)	Beck et al. (2014); Dunn and Laing (2017); Funtowicz and Ravetz (2003); Hoppe et al. (2013); McNie (2007); Sarewitz and Pielke (2007); Silfverberg et al. (2018); van der Hel (2016); Wesselink and Hoppe (2010)
Legitimate 17	Dilling and Lemos (2011); Hoppe and Wesselink (2014); Knol (2011); Lee et al. (2018); Lemos and Rood (2010)	Duncan et al. (2020); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Hoppe et al. (2013); Jahn et al. (2012); Jasanoff (2015); McNie (2007); Pearce et al. (2017); Silfverberg et al. (2018); van der Hel (2016); van Kerkhoff and Pilbeam (2017); Wesselink et al. (2013)
Iterative 14	Dilling and Lemos (2011); Larocque et al. (2011); Lemos and Rood (2010); Müller and Burkhard (2012); Saltelli et al. (2020); Zanchi and Brady (2019)	Christl (2018); Duncan et al. (2020); Dunn and Laing (2017); McNie (2007); Sarewitz and Pielke (2007); Silfverberg et al. (2018); van Kerkhoff (2014); Wittmayer and Schäpke (2014)
Solution-oriented; Introducing options for action 13	Brunet et al. (2018); de Nijs et al. (2004); Dilling and Lemos (2011); Lemos and Rood (2010); Pearce et al. (2017)	Duncan et al. (2020); Dunn and Laing (2017); Frantzeskaki and Kabisch (2016); Hoppe et al. (2013); McNie (2007); Silfverberg et al. (2018); van Kerkhoff (2014); Wittmayer and Schäpke (2014)
Scientists understand decision makers' needs 10	Duncan (2008); Larocque et al. (2011); Lemos and Rood (2010)	Christl (2018); Duncan et al. (2020); Dunn and Laing (2017); McNie (2007); Sarewitz and Pielke (2007); Silfverberg et al. (2018); Weichselgartner and Kasperson (2010)

Note: These are the qualities ensuring the societal impact and usefulness of scientific information, both in models and other forms of information. Many classifications already exist, and Table 4 provides a synthesis of the key views in the material of this thesis. The number of articles where the character is identified is stated underneath the name. n=58.

Useful, impactful and societally-relevant model can be described with the same characteristics as other forms of scientific information. The main difference is the ability to present comprehensive, synthesized information and the following role of uncertainty and its management. Chapter 4.1 analyzed the ways uncertainty can be identified, communicated and managed. Essential for all forms of useful science is to understand what the users want or even can utilize (e.g. Dunn & Laing, 2017; Larocque et al., 2011), and how to successfully communicate the key points of research to create trust and legitimacy. Since model users is a "diverse group that includes stakeholders, environmental managers, decision makers, academics and the general public" (Larocque et al., 2011) successful development, presentation and communication has its challenges. This is where boundary work can be useful.

4.3 Negotiating uncertainty and usefulness in science-policy boundary

The interaction of science and decision making has been studied through the idea of science-policy boundary (see chapter 2.2). Since modelling is a boundary object integrating science and decision making, analyzing what literature says about the process is important. The role of both decision makers and model developers is critical for the quality of the decisions (Larocque et al., 2011). As already stated, models are complex and often challenging to understand and interpret. Therefore, boundary work is important for ensuring the usefulness of models.

Boundary work can be done by a *knowledge broker*. Quite often knowledge brokers are scientists, but also boundary organizations can act as knowledge brokers.

> "The broker needs to be able to do boundary work horizontally and vertically, i.e., horizontal between disciplines, knowledge sources, values and audiences and vertical to orient decision-makers not only into the depths of the technical work and the uncertainties and unknowns but back out and skyward" Duncan et al. (2020.)

In other words, knowledge brokers are expected to do the boundary work and the receivers to remain passive. Successful boundary work requires more than packaging the information.

The outdated idea of one-way information flow from science to policy (Wesselink et al., 2013) is still visible in knowledge brokering practices. Knowledge brokers are expected to act as objective and unbiased merely translating the information without advocating their views (Duncan et al., 2020). The same unrealistic requirement of objectivity is often cast on research. After all, translation is an act of power and defines the hegemonic claim silencing alternative and critical discourses (Machen, 2018). The idea of ‘good enough’ truth (Jasanoff, 2012) is applicable for knowledge brokering too: instead of expecting knowledge brokers to offer ‘the truth’, the aim should be offering understandable, useful and usable information (Dilling & Lemos, 2011).

Knowledge brokers have been successful with climate science (Dilling & Lemos, 2011), and the role of boundary organizations in discussion is great (Hoppe et al., 2013). Boundary organizations tackling climate change are, for example, are the IPCC (Hoppe et al., 2013; IPCC, 2014) and ClimateXChange (Machen, 2018). The IPCC relies heavily on consensus producing comprehensive, global reports at a relatively slow pace. Being an international organization operating under the UN, they aim to create global cooperation and climate action. ClimateXChange operates on a national scale, producing nationally-relevant information.

IPBES is the equivalent for IPCC in biodiversity and ES matters, founded in 2012. The goal is to ensure the conservation of biodiversity by improving science-policy interaction and to develop policy-relevance assessments. As a boundary organization IPBES implements a rather transdisciplinary approach: transparency and inclusiveness combined with a multitude of knowledge systems are essential. The IPBES framework is based on six elements (nature, Anthropogenic assets, nature’s benefits to people, institutions and governance systems, direct drivers, and good quality of life) and their interactions. (Díaz et al., 2015.)

Forum for Environmental Information (Silfverberg et al., 2018) is an example of a boundary organization that does not further specify its topic, but aims to be the knowledge broker for all environmental information. On a global scale this would be quite demanding, but the Forum only aims to bridge Finnish policy and science. Since they only aim to impact on a national scale, boundary work is done differently too, e.g. organizing facilitated discussions.

There is a need for interaction but also integration (Dilling & Lemos, 2011). Boundary work can increase understanding of both model creators and users of each other's needs. By better acknowledging the supply and demand of information, scale issues could be solved, and successful framing and applicability achieved. Case-by-case solutions (Beck et al., 2014) regarding both modelling and boundary work are needed. Since climate models are often global, the importance of boundary organizations is highlighted, since model developers and users have no means to interact with one another.

Models have unique opportunities for doing boundary work too. Because maps and scenarios can be created, techniques for boundary work arise. Data of the ecosystem and its functions can be quantified presenting the areal differences of the state of ES (Orsi et al., 2020), or synthesized bundles (Brunet et al., 2018). Maps can provide legitimacy for decision making but they can also be difficult to interpret. Scale and resolution need to be appropriate, and the interconnectedness of areas explained to avoid ranking the areas based on the amount of ES they provide (Brunet et al., 2018). Other forms of visualizing, such as photos or impact-assessment reports can also be useful for planners and decision makers. Photos are considered a good way to make models tangible, while impact-assessments help categorize the results. These alternatives are important, since text-format is not always the best way to communicate large amounts of information. (Brunet et al., 2018.) By building trust, the legitimacy of produced models can improve.

Scenarios can be used for the outsourcing of either uncertainty of values but also to frame uncertainty in an understandable way (van der Sluijs, 2005). However, scenarios can be useful in identifying trade-offs and bundles while they do not always replace other forms of stakeholder inclusion (Brunet et al., 2018; Silfverberg et al., 2018). Gamification of models can be used as a pedagogic tool to spark discussion and create collective culture among decision makers and other stakeholders (Brunet et al., 2018).

However, not all the issues can be solved with boundary work. Boundary work benefits from interaction within the domains, so within science and within policy (Dilling & Lemos, 2011; Duncan et al., 2020).

5 Discussion

Models are often seen as the best available tool for knowledge transfer between science and policy (Meah, 2019; Schirpke et al., 2020). Modelling is a promising alternative to written reports, and it has potential to produce actionable research and integrate science and decision making, as chapter 4 points out. Even if models and their uncertainty are now more widely accepted, the necessary action is still lacking.

Because modelling is a boundary object, the actions towards useful science need to happen in both institutions. Therefore, no universal instruction can be established on how to create a useful model. This also explains, why the importance of trust, respect and cooperation between model developers and users was emphasized in the literature (e.g. Frantzeskaki & Kabisch, 2016). As a boundary object, modelling is inherently rooted in both sides of the boundary. Therefore, the importance of boundary work in translating and bringing together these two institutions cannot be downplayed. This requires model developers and users to understand each other; users to understand the outputs of the model, and developers to understand what the users need.

The boundary between institutions of science and policy is established to protect them from one another. Science is supposed to have an objective stand and provide facts whereas policy offers value judgement (see Jasanoff, 2012). There is an ongoing discussion of the relationship and boundary of science and policy, that is ever more relevant in the era of sustainability crisis. There is no consensus over what *sustainability* entails nor for it being a priority in our societies (Silfverberg et al., 2018; Wesselink & Hoppe, 2010). Even if scientific evidence is accepted, it still does not create a consensus on what *should* be done (Meah, 2019). Science studies what *is* whereas policy defines what *should* be, and therefore the role of boundary work is central in sustainability questions.

For example, the framing of climate change has resulted in political challenges to solve it. Emphasizing the globality of climate change instantaneously results in challenges of defining who is responsible of mitigation actions. Combining social, environmental and economic concerns into the discourse of sustainable development and creating an illusion of an easy *techno-fix* to be possible is very appealing and has hence become the dominant discourse (Wesselink et al., 2013). This global, technical framing of climate change takes part in maintaining the exclusive discourse favoring the Northern policy makers (Hoppe et al., 2013). In reality the solutions are much more complex due to the wicked nature of the issues (Wesselink & Hoppe, 2010). Short-term solutions or techno-fixes are not enough to maintain a habitable planet.

Authority is often separated in three, mutually reinforcing types: scientific, legal and political authority (e.g. Lee et al., 2018). The lack of action to solve sustainability crisis cannot be explained by the lack of evidence or knowledge. Modelling has played an important role communicating science and increasing public understanding of the issue. The legal grounds, e.g. precautionary principle (UN, 1992a), should also spark action towards sustainability. If scientific or legal authorities cannot take the blame for inaction, policy must be responsible. While policy and societal action are widely studied, science has been unable to create a rigorous strategy to spark political action. This indicates, that the problem cannot be solved with science, at least not science alone. This could further indicate that our political institutions are incapable of handling phenomena as complex, uncertain and urgent as sustainability crisis. The need for system level change is well recognized in sustainability science:

> “in order to develop robust sustainability learning feedbacks between knowledge and action we need the coupling of Human Information and

> Knowledge Systems (HIKS) with social– ecological systems (SES) dynamics” (Tàbara & Chabay, 2013).

The need for more interaction and cooperation is emphasized both in the literature on modelling and science-policy boundary. Systemic change is not a solitary effort but requires the participation of the surrounding and supporting systems too. Therefore, it is important to create that action in all sub-systems, including science. Further research regarding the role and possibilities of science to nudge policy towards necessary change is needed, even while science alone cannot provide the solutions. A variety of participatory methods and transdisciplinary approaches provide promising alternatives to be studied.

6 Conclusions

The main differences of climate and ES modelling relate to the technical aspects and the aim of the models. Technical differences relate to the data used and the scale of the model. Climate models tend to be global and include more objective data on the functions of the climate system (Edwards, 2011) whereas ES models focus on local or regional scale and combine ecological and social data (Brunet et al., 2018). This separation is only indicative, since ES models can include the impact of climate change too (Forsell et al., 2019), and likewise global ES models could be created. Climate models rely on environmental data (Lahsen, 2005), whereas ES models integrate environmental and social data (Blanco et al., 2020).

The ontological aim of climate models is originally to identify synergies, trade-offs and connections within the climate system (Hoppe et al., 2013), or in other words, understand the phenomenon of anthropogenic climate change. During the 21st century, the aim is increasing shifting towards societally-relevant, actionable information (Edwards, 2011). ES modelling aims to create societally relevant and useful information for regional or local decision making (Blanco et al., 2020). The ways to utilize ES models are various, e.g. wetland banking, carbon offset or conservation auctions (Crossman et al., 2013). The aim of both models is increasingly similar regardless of the historical differences.

Modelling traditionally approaches uncertainty from a technical view point; the source, scope and impact of the uncertainty (e.g. Hipsey et al., 2020). Assessing and decreasing uncertainty has been an essential part of the development of modelling and its practices. Essential in the uncertainty of climate and ES modelling is whether it stands in the way of applying and utilizing the information provided the model. Uncertainty and its management affect the legitimacy and furthermore the societal usefulness of the model. Especially with climate change, uncertainty and complexity related to the phenomenon itself has historically been misinterpret as uncertainty of whether climate change is real (Hoppe et al., 2013; Oppenheimer et al., 2007). Since communicating the uncertainties and restrictions of the models is crucial for the usefulness of them, ignoring or burying uncertainty is unlikely a suitable tactic for managing uncertainty in models. The importance of identifying, managing and communicating the uncertainties is evident in the literature. Scenarios are one way to communicate causality and need for action, while understanding and explaining the uncertainty involved. Scenario-making is unique for models and further development and research on the possibilities should be conducted to improve the practices of managing and communicating uncertainty.

The characteristics of societally useful scientific information are similar between models and other forms of information. Science that is available and accessible, understandable and fit for the purpose, is often also useful. Useful modelling emphasizes the comprehensiveness and integration of information from different sources or disciplines, causality and solution-orientation, and cooperation and open discourse between model users and developers. Key difference between models and other forms of scientific information is the models’ ability to represent synthesized information and scenarios. Usefulness can be achieved when models are fit for purpose, accessible and solution-oriented, and sufficient interaction and trust is established between the model users and developers (e.g. Saltelli et al., 2020). While the technical and ontological features of climate and ES modelling vary, uncertainty and usefulness of these models has no significant differences.

The importance of facilitated meetings when presenting complex information has been widely acknowledged (Frantzeskaki & Kabisch, 2016). As boundary objects, climate and ES models require boundary work to be iterated and become applicable for policy. Since the misuse of models is rather easy, whether it is intentional or not, model-users should receive support on using and interpreting the model (Gilliland & Laffoley, 2008; Larocque et al., 2011). Ensuring that the model is fit for the purpose requires boundary work and is essential for the usefulness of the model. Weather cannot be forecasted from a climate model, and vice versa. While politics often urge for numerical answers, it is important to be able to communicate, when the results cannot or should not be quantified (Oppenheimer et al., 2007; Turnhout et al., 2007).

van Kerkhoff (2014) named four principles that integrative research in sustainability science should be based on: embracing uncertainty, engaging stakeholders, transdisciplinarity and learning. While the material was not analyzed based on these principles, all of them can be found from the analysis. The importance of acknowledging and managing uncertainty and inclusion of stakeholders is very evident when studying the uncertainty and usefulness of models. By emphasizing the need for interaction between model creators and model users throughout the modelling process indicates the importance participatory methods. Climate and ES modelling are highly multidisciplinary processes. The principle of transdisciplinarity is analyzed through the participatory and multidisciplinary nature of these phenomena. Further transdisciplinary research as well as research on transdisciplinarity should be conducted. Learning, continuous improvement and assessment is the foundation of modelling, as well as the main aim of this integrative literature review.

In conclusion, boundary work can improve and ensure the usefulness of the models. However, since the lack of information is not the main issue with sustainability crises, more and better models can only get us so far. Cooperation and systemic change are needed.

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8 Appendices

Appendix 1

Material of the literature review

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