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REVIEW ARTICLE

Assessing and coping with uncertainties in landscape planning: an overview

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Abstract

Context Although uncertainties are ubiquitous in landscape planning, so far, no systematic understanding exists regarding how they should be assessed, appropriately communicated and what impacts they yield on decision support. With increasing interest in the role of uncertainties in science and policy, a synthesis of relevant knowledge is needed to further promote uncertainty assessment in landscape planning practice.

Objectives The aim of this paper is to synthesize knowledge about types of uncertainties in landscape planning, of methods to assess these uncertainties, and of approaches for appropriately coping with them.

Methods The paper is based on a qualitative literature review of relevant papers identified in the ISI Web of Knowledge and supplemented by frequently cited publications. The identification and synthesis of relevant information was guided by a developed framework concerning uncertainty in landscape planning.

Results The main types of uncertainties identified in landscape planning are data-, model-, projection- and evaluation uncertainty. Various methods to address these uncertainties have been identified, including statistical methods for the assessment of uncertainties in planning approaches that help to cope with uncertainties. The integration of uncertainty assessments into landscape planning results is lacking.

Conclusions The assessment of uncertainties in landscape planning have been addressed by science, but what is missing are considerations and ideas on how to use this knowledge to foster uncertainty analysis in landscape planning practice. More research is needed on how the application of identified approaches into landscape planning practice can be achieved and how these results might affect decision makers.

Keywords Uncertainty · Landscape planning · Environmental planning · Uncertainty assessment · Communication of uncertainty

Introduction

Uncertainties are ubiquitous in spatial planning in general and landscape planning in particular. Knowledge of ecological, social and economic interrelations is fragmented and this strongly affects the certainty of projections about future landscape developments (von Haaren 2004). In addition, the sensitivity of stakeholders and the public for uncertainties in projections has been increasing since the introduction of more

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complex scientific models, especially climate models. Climate change reports now usually work with probability indicators and have a section devoted to the evaluation of the suitability of used models for different tasks. This is even the case in the summary for policy makers (IPCC 2013). Methods for landscape planning are generally aimed at practicability, not necessarily completeness and have inherent uncertainties in their results and management proposals. Uncertainty consideration in environmental assessments has been a rarity (Fischer 2007; Lees et al. 2016) and landscape planning has up to now—if at all—only indirectly addressed uncertainties or included general uncertainty considerations into flexible management design (Kato and Ahern 2008). What is missing is a systematic and transparent approach for identifying and describing uncertainties in a way that enables them to be appropriately included into planning propositions and communicated to decision makers. It is evident that uncertainties in landscape planning will have to be addressed in the future to avoid an impairment of the credibility of results with the public and stakeholders.

Some publications have already begun to assess uncertainties in planning or have explored approaches for dealing with them in planning proposals (Gallo and Goodchild 2012; Gret-Regamey et al. 2013a). A review by Refsgaard et al. (2007) summarizes methods for the assessment of uncertainties in environmental modelling processes but misses the important consideration of communicating uncertainties in planning. In a similar vein, Hou et al. (2013) provide a detailed overview of uncertainties in ecosystem service assessments and general strategies on how to address uncertainties in assessments processes. However, they do not propose application options in planning. Hamel and Bryant (2017) explore possible reasons for a lack of uncertainty analysis in ecosystem services analysis and propose solutions. Although not specifically addressed at landscape planning, their insights could also help to find solutions for uncertainty handling in planning practice. However, up until now, no comprehensive overview exists of the state of knowledge in assessing uncertainties and dealing with them in landscape planning. This is especially the case for knowledge which may be useful for introducing uncertainty analysis into actual landscape planning practice. A review of relevant knowledge could also contribute to the further development of landscape

planning theory and methods in three ways: by enhancing awareness of the role of uncertainties in planning, by identifying potential approaches for minimizing uncertainties in planning practice, and by highlighting areas for further research, to better address uncertainty that is especially important for landscape planning.

The aim of this paper is to synthesize current scientific knowledge on uncertainty assessment for application in landscape planning. To fulfill this aim, we developed a conceptual framework for uncertainty in landscape planning and conducted a literature review to answer the following questions:

- What relevant types of uncertainties and likely effects on landscape planning results are described in scientific literature?
- What suitable methods for addressing uncertainties in landscape planning can be identified?
- How can uncertainties be appropriately integrated into planning practice?

The remainder of the paper is structured as follows. First, we introduce a conceptual framework for uncertainty in landscape planning as derived from leading publications. This framework is subsequently used to structure a review of relevant literature concerning the above named questions. We then discuss the findings and possible implications, as well as challenges to further promote the use of uncertainty assessment in landscape planning practice. Finally, we identify knowledge gaps and opportunities for further research.

A conceptual framework concerning uncertainties in landscape planning

Landscape planning takes a multitude of different forms (Selman 2006). This paper follows the European Landscape Convention (ELC) in understanding landscape planning as a 'forward-looking action to enhance, restore or create landscapes' (Council of Europe 2000, Art. 1). The tasks to be executed by landscape planning differ with respect to the degree of its formalization and how landscape planning is embedded in a formalized planning system. In general, the tasks of landscape planning are relatively broad, such as including the generation of environmental information for decision making and the protection

and redevelopment of natural and cultural assets (Margules and Pressey 2000; Leitão and Ahern 2002). Some countries, including many member states of the European Union, have well-established planning systems in which landscape planning proposals may have direct or indirect legal consequences for land use decisions. In other countries or planning systems, as for example in many states of the US, landscape planning is applied more on a case basis and focuses on influencing decisions through information and persuasion. Regardless of the planning system in place, landscape planning recently is moving from a purely expert-based approach to more transdisciplinarity, involving different experts, stakeholders and decision-makers in participatory processes. These participatory approaches to landscape planning not only aim at generating relevant content but also at facilitating deliberation and social learning as well as moving towards landscape governance (cf. Beunen and Opdam 2011; Scott 2011; Albert et al. 2012; Opdam et al. 2015; Westerink et al. 2017). In all described variations of landscape planning, knowledge of uncertainty would be beneficial for improving transparent plausible decisions about landscape development.

In order to structure the literature review, we developed a conceptual framework for uncertainty in landscape planning (Fig. 1). Our framework shows the assessment and evaluation process as well as the forward-looking approach amended by its respective types of uncertainties. We decided to use the terms 'data uncertainty', 'model uncertainty' and 'projection uncertainty' as they complement the classifications used in landscape planning practice. These terms are recognizable and similar to the terms already used and found in the majority of approaches for standardizing uncertainty typologies in planning and ecology (Walker et al. 2003; Refsgaard et al. 2007; Kato and Ahern 2008; Hou et al. 2013; Larsen et al. 2013). We supplemented this set of uncertainties with 'evaluation uncertainty' as the evaluation process is an important step in landscape planning and inevitable for prioritizing the value and endangerment of landscape functions as well as the need for action. Evaluation uncertainty occurs when a descriptive statement about pressure or the landscape state is changed into a value judgement, which may be based on either legally prescribed standards (thresholds) or political, public preferences. The process of converting information into scales for the evaluation of different landscape functions (or ecosystem services), or prioritizing objectives with incomplete knowledge about the preferences of all affected people, give room for evaluation uncertainties.

Methods

The following results section is based on a qualitative literature review of publications that have been published from 1996 to the end of 2016 and been identified using the scientific literature database ISI Web of Knowledge, supplemented by much-cited publications not included in the search results.

The search parameters were as follows:

(i) The title, the keywords or the abstract of the paper should include the words 'landscape planning' or 'environmental planning' or 'ecosystem services'.

(ii) The word 'uncertainty' or 'uncertainties' must also appear in the title, the keywords or the abstract of the paper.

We reduced the amount of publications by conducting a relevance check of the title and the keywords and a subsequent review of the abstract of remaining publications to determine their relevance for landscape planning. An in-depth qualitative review was then conducted on the final publications with the aim to identify different focal points of the publications and to gain an overview of the concepts of uncertainty research. The review was conducted on the basis of the previously mentioned understanding of landscape planning.

Results

The search returned 707 unique records with the majority of papers being published in recent years (see Fig. 2). After the relevance check and the abstract review, papers that did not focus on uncertainty in combination with tasks of landscape planning were excluded, reducing the amount of publications to 65 for an in-depth review. The majority of the identified papers were published from the year 2010 and on, showing the emerging interest in uncertainty analysis in planning processes. Potential sources of uncertainty
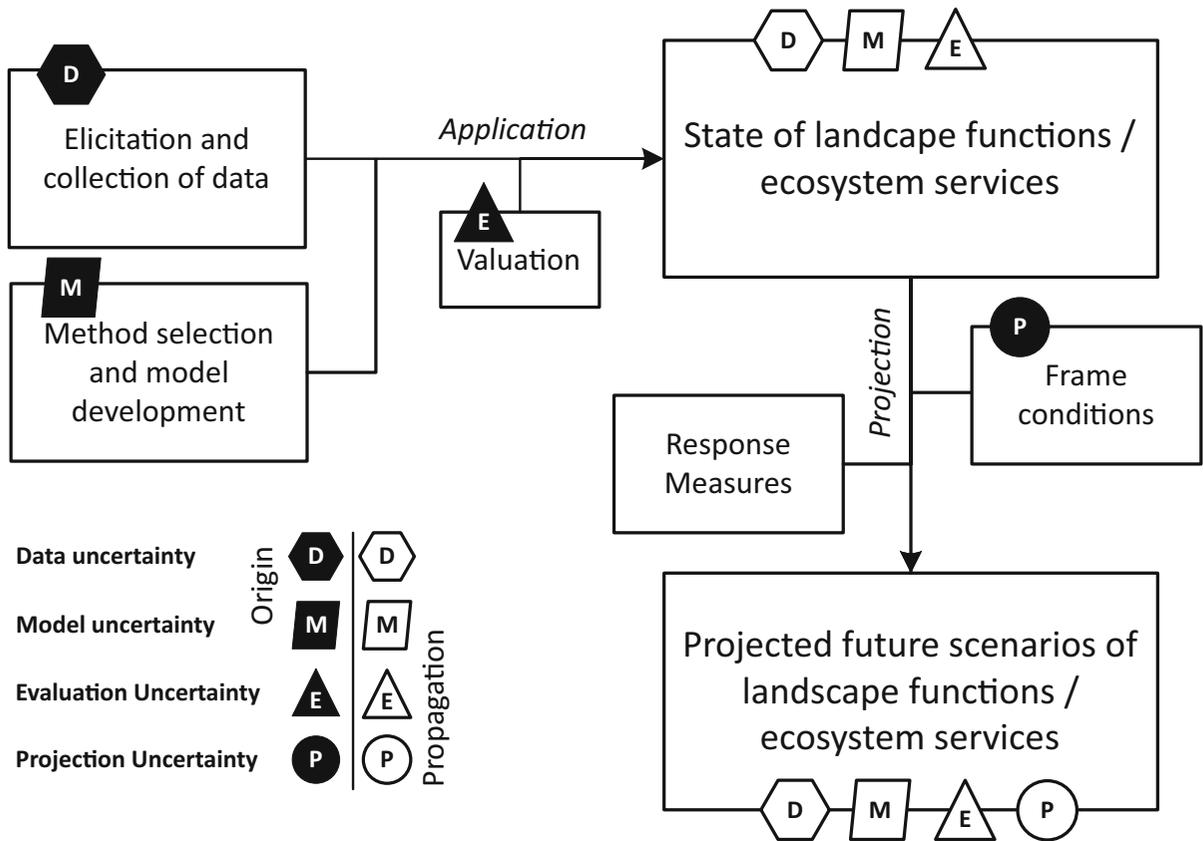
Fig. 1 Conceptual framework for uncertainty consideration in landscape planning. Origin (filled) and propagation (hollow) of relevant types of uncertainty in the frame of a simplified landscape planning process
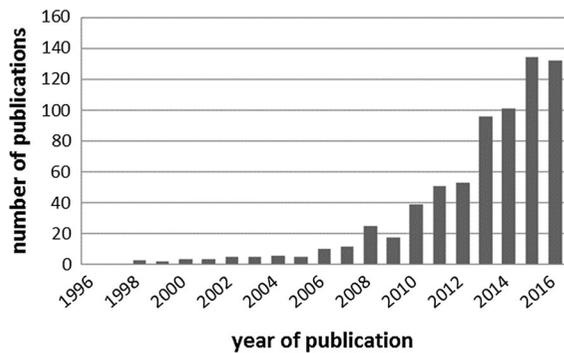

Fig. 2 Publications identified by the literature search by number (y-axis) and year of publication (x-axis)

and the communication of uncertainty were addressed by more than half of the publications (Fig. 3). Over 60% of the identified papers have ecosystem services as a focal point, with the majority of them also published within the last 5 years.

Sources of uncertainty

The literature review identified a great diversity of sources of uncertainty that are of relevance in landscape planning. The framework presented earlier is used as the conceptual basis to structure the results of the literature review for potential sources of uncertainty in landscape planning. In more detail, possible sources of uncertainty in scaling and modelling are systemized in Fig. 4, which gives a comprehensive overview of essential elements of the more technical uncertainty in assessments. This framework is particularly suitable for landscape planning because it displays different levels of detail that can be transferred into different planning concepts.

Fig. 3 Thematic focal points (y-axis) and their share (x-axis) of the total number of identified publications distinguished between types of papers
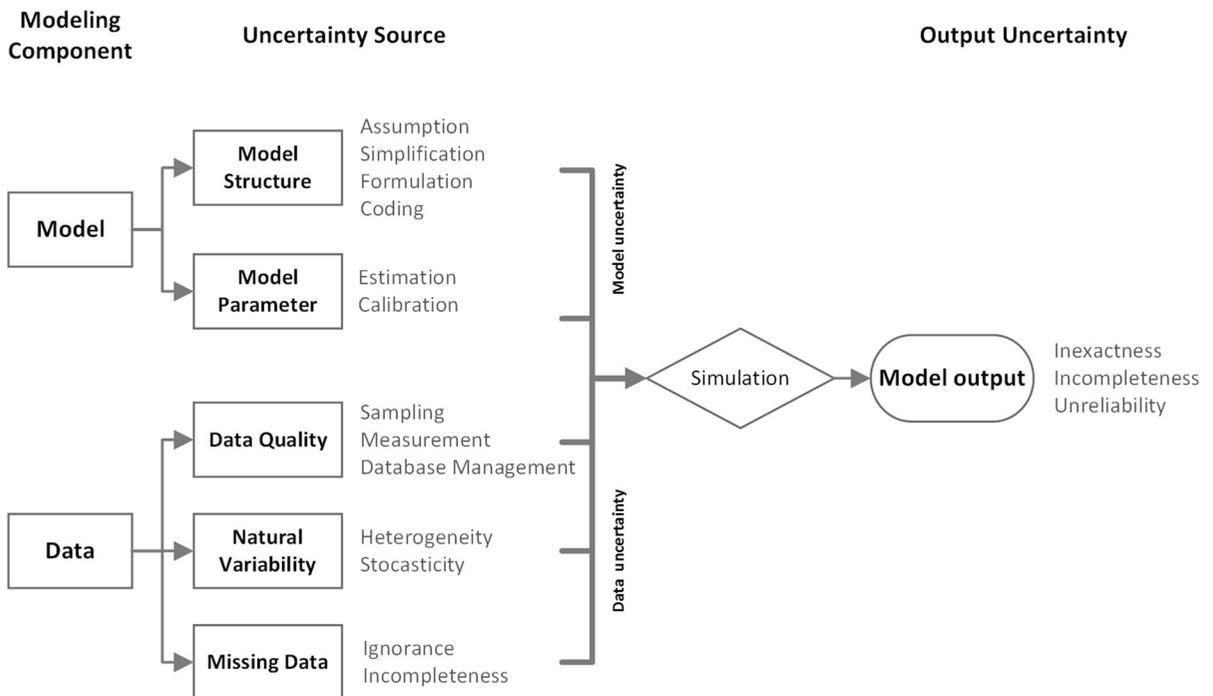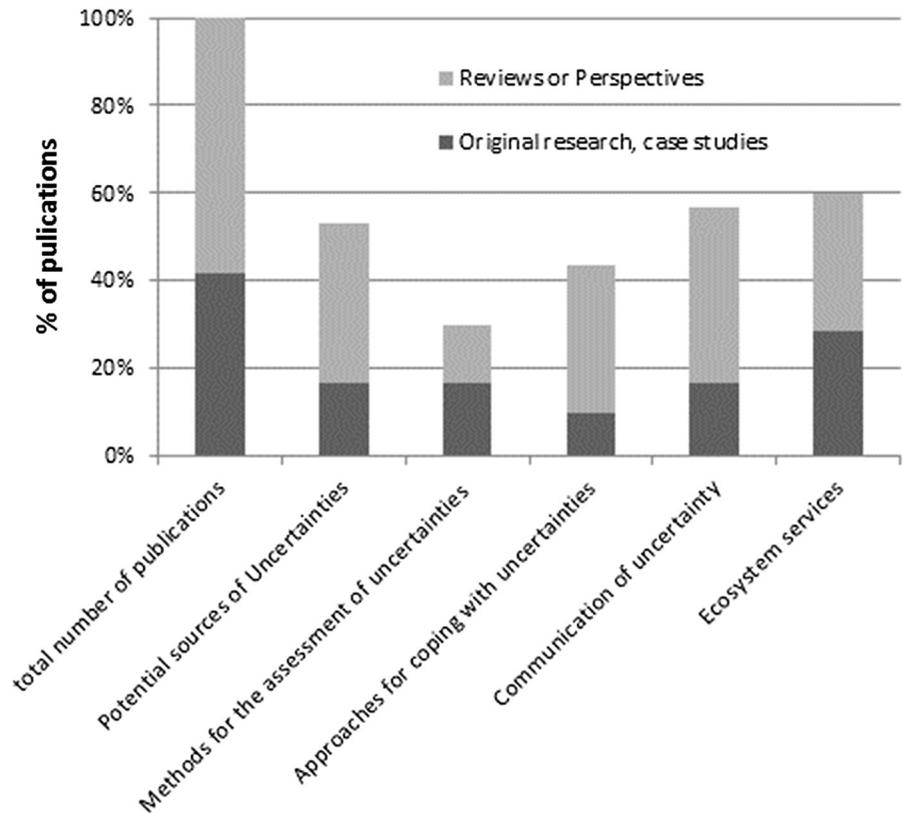

Fig. 4 Sources of uncertainty in scaling and modeling. Adapted from Li and Wu (2006)

Data uncertainty

Data uncertainty is of importance in landscape planning practice because of its implications in the transformation of information during the planning process. Data is usually illustrated spatially in landscape planning, allowing stakeholders to easily identify data flaws in those areas they are particularly knowledgeable of. If diverging perspectives and conflicts emerge in the planning process, stakeholders sometimes draw upon identified data flaws in order to question the appropriateness of the overall planning proposals and to promote their interests (cf. Maxim and van der Sluijs 2007).

Data uncertainty has been identified in the literature as a prevailing source of uncertainty in environmental assessments (Rae et al. 2007; Hou et al. 2013; Schulp et al. 2014). Potential uncertainties in the data will spread to the output, which in some cases leads to an outcome that can be rendered questionable (Heuvelink 2000; Huang et al. 2005). In science, the scale of the data should ideally match the processes that are being studied (Schulp and Alkemade 2011). This represents a condition that, although worth aspiring to, cannot be achieved in all cases of landscape planning. Commonly, data from data services, such as official soil maps, are being used as a substantial segment of the information for environmental assessments (Smith et al. 2011) and respective assessments of landscape functions. This data combined with acquired data can include sources of uncertainties, for example, measurement imprecisions and potential errors in subsequent data processing (Rae et al. 2007; Zhang et al. 2015). These sources of uncertainty will not only be confined to land cover data or biophysical data (see Schulp et al. 2014), but also be associated with social data (see Lechner et al. 2014). The development of models and the assessment of landscape functions is also often limited by the availability of adequate land cover data (Alvarez Martinez et al. 2011; Hou et al. 2013; Blennow et al. 2014; Schulp et al. 2014). In landscape planning the acquisition of additional data is limited by factors such as high costs or dependence on the responsible agents. Remote sensing data is sometimes an alternative to field work and has been used for ecosystem service assessments, for example data from the CORINE Land Cover Project (cf. Burkhard et al. 2010). Land cover maps, however, can contain uncertainties. One uncertainty is the shape and location of objects (geometric uncertainty), others are the values attributed to these objects (thematic uncertainty) (Schulp and Alkemade 2011). Geometric uncertainties arise mainly from spatial data resolution, for example, when using global land cover data that aims to map and monitor general spatial distribution. The resolution of such data can still be coarse. Consequently, there might be poor representation of small landscape elements (Ozdogan and Woodcock 2006) or the disappearance of minor land cover types (Ozdogan and Woodcock 2006; Verburg et al. 2011). Thematic uncertainties arise in the classification of land cover types from remote sensing data, for example from satellite images (Fang et al. 2006; Bargiel and Herrmann 2011). Land cover maps derived from remote sensing data also face accuracy issues that can be traced back to the satellite imagery equipment used for the data acquisition (Schulp and Alkemade 2011). Additionally, land use changes lead to the possibility of deviations between different maps that have been generated at different times (Schulp and Alkemade 2011). A fitting description for this is "no matter how visually convincing digital spatial data can be, it should always be noted that these data are in fact a model of the real world" (Rae et al. 2007, p. 216).

Model uncertainty

One feature that all modelling approaches have in common is that the variables have been chosen by the model's developers whose knowledge limits the validity of the model (Foley 2010). Many ecosystem processes are still poorly understood, regardless of the considerable scientific effort over the past decades (Barnaud and Antona 2014; Seidl 2014). The appropriate selection of indicators and variables for the assessment of landscape functions and ecosystem services is, therefore, a vast challenge in the development of new models (Foley 2010; Hou et al. 2013; Schulp et al. 2014). Some general limitations of models have long been identified and can be seen in Fig. 4. Empirical models, used to assess landscape functions, are parameterized on existing data and are generally limited to a smaller range of explanatory variables (Smith et al. 2011). They only contain information about conditions that have been observed in the past (Seidl 2014). These might not necessarily depict current conditions with high certainty. Additionally, empirical information can be deficient for

precise parameterization of a model (Williams and Johnson 2013), which adds to the overall uncertainty. Dynamic process models often aim to reflect a higher range of variables in order to give a more comprehensive overview of a wide variety of physical and biochemical processes. They also include a time component, for example when modeling plant growth or groundwater cleaning en route to a waterbody. This can translate into a tradeoff between precision and usefulness. Such a tradeoff can be seen when models increase in complexity because the data requirements will also become more demanding (McVittie et al. 2015). With ongoing technological evolution, the development of dynamic process models has increased while the validation of these models has become more scientifically challenging (Callaghan et al. 2004). Additionally, when evaluating the accuracies of land use based environmental assessments, researchers reach the conclusion that a "classification system with a very high level of detail is impractical and may lead to erroneous interpretations when the classification system is used by people other than its developers" (van der Biest et al. 2015, p. 42). In addition to the potential sources of uncertainty that have been mentioned, emerging concepts like ecosystem services and their respective assessment methods may include additional sources of uncertainty, particularly in the form of economic values. The quantification and ultimately the monetization of ecosystem service values can be relatively easily understood when looking at provisioning services. However, a valuation can be difficult and linked with high uncertainty when looking at non-market values such as regulation or cultural services (Smith et al. 2011; Johnson et al. 2012) presenting challenges for landscape planners when trying to use such concepts. Despite the best efforts to eliminate uncertainty in the development of methods for spatial modelling, it will always be present to some extent (Rae et al. 2007). Therefore, it is important that landscape planners acknowledge these uncertainties.

Projection uncertainty

Landscape planning as a forward-looking approach is inherently laden with a multitude of uncertainties regarding the projection of future states of the environment (Shearer 2005; Gret-Regamey et al. 2013a). Ecosystems include a number of subsystems in which multiple processes, for instance the diversity of system components, temporal or spatial evolutions and other ecological arguments, should be considered by the planner and eventually the decision makers (You et al. 2014). Despite many decision problems in landscape planning and conservation practice having a dynamic nature with often long time horizons, they often are formulated as static problems and represented by plans that, for example, identify conservation areas or predicted future extension of habitats (Kubiszewski et al. 2013; Williams and Johnson 2013). The understanding of the various components of a dynamic environmental system does not necessarily imply understanding of the future behavior of the overall system (Foley 2010). Unfortunately planning results often give the contrary impression. Furthermore, long-term projections are prone to time-scale mismatches, when short policy lifespans meet with longer term perspectives for implementing policies (Dockerty et al. 2006). Changes in general drivers, in the form of political, technological, demographical and economic developments, make the prediction of land use change difficult and therefore introduces a large number of uncertainties into the planning process (Carter and White 2012; Gret-Regamey et al. 2013b; Seidl 2014). The introduction or the neglect of such drivers into landscape planning always relies on assumptions about the future that are bound to personal judgement and which may amplify uncertainty (Metzger et al. 2010). In addition, factors like climate change, land degradation and biodiversity loss are increasingly challenging environmental management (Schroeter et al. 2006). Projecting climate change, for example, can lead to very different results when using various climate models for the same area and time scale (Williams and Johnson 2013). This phenomenon can also be found in several other planning results (see Schulp et al. 2014).

Assuming that there always will be knowledge gaps, uncertainty may not only pose problems for management options but also may provide opportunities to rethink or reinvent them, leading to outcomes that are robust against a variety of possible futures (Bohensky et al. 2006; Seidl 2014).

Methods for the assessment of and coping with uncertainties

Several methods for the assessment of uncertainties and multiple approaches to cope with uncertainties in landscape planning have been identified while conducting this review (see Table 1). These methods differ in their aim and in their overall strategy. Statistical methods, summarized under 'Uncertainty assessment', aim to assess uncertainties and often give numerical results on which the uncertainty can be measured. Other strategies or planning approaches, summarized in the following under 'coping with uncertainty', address uncertainties within the planning process and offer opportunities to deal with them within the process.

Uncertainty assessment

Monte Carlo analysis (MCA) is one of, if not, *the* most commonly used technique for uncertainty analysis (Li and Wu 2006) and is used in both commercial and free software packages. It utilizes random samples of input data and variable model parameters as basis to generate output statistics through repeated simulations (Rastetter et al. 1992; Jansen 1998; Katz 2002). A main advantage of such a simulation is its general applicability and its possibility to be linked to any model code (Refsgaard et al. 2007). MCA may permit an effective mechanism for the assessment of model performance but lacks the ability to provide best system solutions (Huang et al. 2005). An example for the use of MCA in landscape planning would be the work by Pearson and Dawson (2005), which included a number of 10,000 Monte Carlo runs to create probability values on plant dispersal for the identification of conservation goals under climate change.

Fuzzy analysis (FA) approaches have been used for addressing uncertainties in situations where environmental decisions need to be made despite only vague information (You et al. 2014). FA is the grouping term for a variety of different methods based on the fuzzy set theory introduced by Zadeh (1965). A fuzzy set is a set of variables, in that for each variable, there is no 'true' or 'false' statement but anything between true and false (see Zimmermann 2001 for detail). This presents additional challenges for planners when results of FA need to be prepared for decision making exercises, as it has been identified that fuzzy

programming has its limitations when it comes to accounting for uncertainty in a non-fuzzy decision space (Li et al. 2009). Nevertheless, the modelling of uncertainty 'can (still) be considered to be the most important goal of fuzzy set theory' (Zimmermann 2001, p. 6) and can be seen in recent studies, where FA has been used to analyze uncertainty in pollination maps based on land cover data of different quality (see Schulp and Alkemade 2011 for detail). This concurs with the statement that 'Fuzzy numerical similarity', another derivate of FA, is considered one of the best methods when analyzing spatial differences or errors between different maps (Hagen-Zanker 2006).

Sensitivity analysis (SA) can be used to investigate how sensitive a model output is towards changes in the different input variables. With this, it is possible to understand the importance of different input parameters and their influence on the accuracy of the model output (Refsgaard et al. 2007). Rae et al. (2007) conducted a SA with the aim to add information on reliability for planning questions in the frame of area protection. The results of the SA show that with different assumptions and variations of parameters, results of the 'seemingly' same planning exercise can differ a lot (see Rae et al. 2007 for detail). SA can be used to communicate model behavior to experts and thus, can aid in the transparency of an assessment method for landscape functions or ecosystem services making it an important awareness raising tool for landscape planners.

Coping with uncertainty

The review identified structured planning methodologies with an integrated assessment and general planning proposals for coping with uncertainties.

In recent landscape planning and especially ecosystem service literature, Bayesian belief networks (BBNs) have become increasingly popular when considering uncertainty in modeling and planning tasks (Gret-Regamey et al. 2013a, b; Landuyt et al. 2014; McVittie et al. 2015). BBN present a strategy to reduce and simultaneously communicate uncertainty within the observed system parameters and eventually the outputs. BBN are multivariate statistical models consisting of a causal network (nodes and connectors) and conditional probability tables that quantify relations within the network. The creation of a BBN is a balance between complexity and intelligibility, when

Table 1 Overview of identified methodologies for the handling of uncertainties in landscape planning processes and identified potentials as well as challenges for the use in landscape planning practice

Methods	Uncertainty handling approach	Uncertainty addressed	Potentials and challenges for the use in landscape planning practice
Uncertainty assessment			
Monte Carlo analysis (MCA)	Quantitative approach for assessing uncertainty values by generating output statistics with varying input and model parameters	DU, MU	+ General applicability + Viable assessment of model performance − can be time consuming with very high number of runs
Fuzzy analysis (FA)	Quantitative approach for assessing uncertainty values using fuzzy parameters	DU, MU	+ Addressing of uncertainty in situations where only vague information is available − No general applicability because different planning tasks might require different fuzzy analysis approaches − Problems when handling multiple data formats
Sensitivity analysis (SA)	Quantitative approach to assess model behavior and associated uncertainties by analyzing dependencies between input and output	MU	+ Communication of model performance and uncertainties (better transparency)
Coping with uncertainty in planning			
Bayesian belief networks (BBNs)	Semi-quantitative approach to make informed decisions in uncertain environments using stakeholder information and values	DU, PU	+ Communication and reduction of uncertainty + Integration of spatial and temporal scales + Combination of empirical data and expert knowledge − Generation of a BBN can be bound to uncertainty itself and can lack transparency − Limited comparability of the results between different regions/planning tasks
Adaptive planning	Qualitative approach to cope with uncertainties by using planning results of the past for adapted decision making	DU, MU, PU	+ Better informed management decisions based on decisions observed in the past + Encouragement to act + Interdisciplinary approach, promoting innovative measures ° Requires a mind shift in decision making, accepting failure − Requires monitoring
Scenario planning	Qualitative approach to cope with uncertainties by exploring different possible future states	PU	+ Incorporation of projection uncertainty through the exploring of multiple futures + Aids in robust decision making in cases where future states are uncertain − Can lack transparency if not conducted well

Table 1 continued

Methods	Uncertainty handling approach	Uncertainty addressed	Potentials and challenges for the use in landscape planning practice
Participation	Qualitative approach to cope with uncertainties by activating local knowledge	DU, MU, PU	+ Local knowledge can help in coping with uncertainty especially in task oriented landscape planning
			+ Improved transparency and acceptance of landscape planning results
			− Can also hinder the implementation of planning measures if not conducted well

Types of uncertainty: DU (data uncertainty), MU (model uncertainty), PU (projection uncertainty)

selecting variables that try to provide a realistic representation and while also keeping the model as simple as possible (McVittie et al. 2015). The core capability of a BBN lies in the possibility to use empirical data and expert estimations to define nodes and integrate uncertainties directly in the probability tables. Despite the usefulness of BBN when working in an environment where knowledge and data is of different quality or lacking (Landuyt et al. 2015), there are also some limitations with this approach. Knowledge based models can be seen as subjective and are often hard to validate (Landuyt et al. 2015). Additionally, the development of a BBN may be a difficult and time consuming procedure when integrating the knowledge of multiple experts or even stakeholder knowledge (Gret-Regamey et al. 2013b). Results of BBN are nevertheless seen less as providing final management suggestions but more as potential contributions to a more complete assessment or as part of a decision support tool that aims to develop a better understanding of processes and their interactions (Landuyt et al. 2014; McVittie et al. 2015). Studies investigating the effectiveness of the approach in mapping future ecosystem service provisions and coupled uncertainties are, however, still lacking (Gret-Regamey et al. 2013a).

Adaptive planning approaches have their origins in the adaptive management concept that was introduced and has been used since the late 1970s. Adaptive management was developed to deal with uncertainties that occur in complex systems (Holling 1978). In contrary to traditional management decisions that are often based on empirical studies, adaptive management treats decisions as experiments to promote a "learning by doing" process in a proactive way

(Holling 1978; Kato and Ahern 2008). The adaptive management approach expands traditional approaches by adding feedback loops where the effectiveness of planning decisions made and measures taken is monitored, generating new data to structure alternative or future decisions (Walters and Holling 1990; Ahern 2012). This approach has been commonly used in ecosystem and environmental management (Walters and Holling 1990; Rist et al. 2013), but has been rarely integrated into landscape planning (Ahern 2006). The use of adaptive planning can be beneficial because of the ability to cope with uncertainties that are inherent in natural and social systems (Kato and Ahern 2008). In recent years, the adaptive management concept has been expanded to include design principles into planning processes (Ahern 2012; Ahern et al. 2014). Adaptive design implies intentional, often experimental changes with a multifocal view on environmental and societal needs (see Nassauer and Opdam 2008). The changes, or "designed experiments" often take place in a small spatial extent with the aim to test innovative approaches in a "safe to fail" environment (Ahern et al. 2014). Designed experiments are developed in transdisciplinary processes including scientists, planners, design professionals and other stakeholders (Felson and Pickett 2005) amongst whom the risk of failure of such approaches is recognized (Ahern 2011). These principles of adaptive design fit especially well with the concept of resilience, which is defined by Walker and Salt (2006, p. 1) as the "ability of a system to absorb disturbance and still retain its basic function and structure". According to Ahern (2011), resilience capacity of a system can be achieved through multiple ways, amongst others being the multifunctionality of measures, and the adaptive

planning approach. To be effective, ecological limits, as well as economic and social limits need to be considered when constructing designed experiments (Pickett et al. 2004).

When envisioning future states of ecosystems, scenarios are a commonly used tool in landscape planning for coping with projection uncertainty. Scientists agree that scenarios are best used when information about the future under different policies is poorly defined and the knowledge is, at best, precarious (Shearer 2005; Biggs et al. 2007; Foley 2010; Metzger et al. 2010). Scenarios allow us to explore possible futures and illustrate how different policies can alter the landscape (Shearer 2005). Based on information of current and past conditions, scenarios are plausible stories about future states (Biggs et al. 2007). They can be divided into different types regarding their focus. These types are (i) predictive scenarios with a narrow focus on future developments answering the question "what will happen" (forecasting), (ii) explorative scenarios with a broader focus addressing potential impacts that can significantly alter future states (forecasting) and (iii) normative scenarios that start with a desired future state and explore pathways with conditions to achieve this future state (backcasting) (see Maier et al. 2016 for detail). Well-developed scenarios can be seen as an awareness raising tool that can help challenge the views of individuals about how a possible future may look like (Carter and White 2012). Through this it is possible to improve the robustness of planning through the incorporation of increasing amounts of uncertainty on the range from predictive scenarios to unframed exploratory scenarios (Maier et al. 2016).

To enhance understanding and raise the acceptance of landscape planning results, it is possible that scenarios and management options are developed in a participatory process. When developing scenarios or response measures, for example, it is possible to involve local stakeholders in the development process. This may lead to improved consensus building, strengthen the communication and can ultimately lead to decisions being made that are more acceptable amongst the general public (Biggs et al. 2007; Beach and Clark 2015). Participation can also present a way to cope with sources of uncertainties in landscape planning, especially on a local level where generic scientific knowledge needs to be reinterpreted to fit the local context (Beunen and Opdam 2011).

Emerging concepts like landscape stewardship specifically aim at the activation of local knowledge and involvement of local land owners in environmental protection for both, nature and people (see Brown and Mitchell 2000; Plieninger et al. 2015 for detail). To achieve better informed decisions and a reduction of uncertainties through collective knowledge, it is of high importance that inherent uncertainties are explicitly addressed within the participatory process (Newig et al. 2005).

Integration of uncertainty in planning

There has been a lack of integration of uncertainty information and limitations of certain models into planning results. Pe'er et al. (2014) believe that one main reason for this dearth is the simplification of model outputs for decision makers. This may be attributed to the belief that there is a considerable mismatch between information outcomes that scientists and practitioners produce and the expertise that policy and decision makers have. Even if science were freely available, it might remain inaccessible because of the level of detail desired by scientists and practitioners, which often conflicts with the time constraints imposed by policy makers (McInerny et al. 2014; McManus et al. 2015). Consequently, there is a call for simpler and more understandable decision supporting tools (Ruckelshaus et al. 2015). It is important to communicate how information for decision support has been generated and address any potential uncertainties. If this does not occur, there is a risk that information will be assumed to be part of reality even if this is virtually impossible. In conventional planning systems such uninformed decisions could result in long-term risks to both the environment and humans (Pe'er et al. 2014). In environmental assessment results uncertainties are usually not described. This is backed by the findings of studies that have focused on the consideration of uncertainties in such assessments (Larsen et al. 2013; Lees et al. 2016). The results of one study found that only 5 out of 87 planning cases considered climate change and mentioned associated uncertainties (see Larsen et al. 2013 for detail). Uncertainties can be described by values of probability, error percentages or by other formal concepts like the results of FAs (see Zhang et al. 2015) and BBN (see Gret-Regamey et al. 2013a). Other ways of displaying uncertainty information for

decision makers could be through the utilization of free graphical values or interactive representations in thematic maps (Griethe and Schumann 2005). As visualizations are bound to potential biases in audiences perception, it should be noted that particular information might be advocated if it is given prominence (Pidgeon and Fischhoff 2011; McInerny et al. 2014). Uncertainty values should be seen as additional information in a decision making process, one that does not detract from the actual thematic information (Ruckelshaus et al. 2015) but rather, contributes to the overall information basis on which decisions are made.

Discussion

Our findings show that, in general, uncertainty analysis in planning has gained increasing interest in corresponding scientific literature, potentially spurred also by emerging applications of more quantitative concepts such as ecosystem services. It seems that the development of new, and often more complex, methodologies in planning has given rise to an increased interest to assess uncertainties. This also may have a positive effect on the evaluation and further development of existing methodologies and processes in landscape planning.

While we are confident that we included the relevant publications in our review according to our search criteria, we acknowledge that we may have missed some differently labeled papers that could have potentially provided additional insights, if we had used more search terms. However, we took additional measures to ensure a comprehensive review by also adding new and relevant papers to our database once we became aware of them through reference lists. An important challenge for the transferability of our discussion findings is that we adopted the ELC's understanding of landscape planning which might divert from understandings on different continents. However, we expect our findings to be instructive also for planners in other contexts.

Challenges for landscape planning derived from identified types of uncertainty

Data and model uncertainties can be found in almost every landscape planning process as part of the assessment of the current state of the landscape or site. Landscape planners need to use the data that best fit the scale and detail required for solving the problems of the specific landscape planning exercises. When the standardized available input data from soil maps, habitat maps, topographical maps, and remote sensing seem to be incomplete many papers suggest acquiring further data through field work or the consultation of experts. However, generating such new empirical data is often challenged by the limited human, temporal and financial resources available in practical planning (Pourabdollah et al. 2014). Available standard data usually misses information concerning its inherent uncertainty. Providing this uncertainty information could help planners in estimating the overall uncertainty of their planning proposals. In order to qualify landscape planning for this uncertainty integration, it is necessary to first investigate the degree to which the data uncertainty actually discredits the assessment results. Information on the degree of uncertainty propagation throughout the planning process could help landscape planners to address critiques from stakeholders who use identified data flaws to question the appropriateness of the planning proposals.

Model uncertainty is at best handled within the model development process, with special consideration of the influence that model developers can have on the final model. Landscape planning often uses methodologies that have been developed decades ago and are still considered sufficient, but validation through uncertainty assessment has been missing (Gruehn 2010). It is conceivable that a validation of these models, with identified methods for uncertainty assessment, could aid in a more informed decision making process.

Our review shows that projection uncertainties have received less attention in uncertainty research. A reason for this might be that projection uncertainty addresses sources of uncertainty emerging mostly from human actions/-behavior or the dynamic of nature that are difficult to assess. It is seemingly easier to develop viable assessment methods for data- and model uncertainty. Landscape planning as a forward looking action is especially prone to these kinds of uncertainties.

Evaluation uncertainty that should be especially prominent in more formalized landscape planning has not been addressed explicitly by the identified

publications. The evaluation of assessment results by planners is prone to similar uncertainties as the actual model development itself, mainly being the influence of the planner on the final planning results through different evaluation methods. The legitimation of the different values used as starting point for evaluation could be used as reference for uncertainty assignment.

Potential use of different methodologies for handling uncertainty in landscape planning

Although each of the above mentioned methods for assessing uncertainty have been used in scientific studies, some of the identified approaches seem to be better suited for the practical application on landscape planning uncertainties.

When reviewing statistical methods for the assessment, MCA has the major advantage of a general applicability, but further interpretation and reprocessing of the results from such an analysis might open up new sources of uncertainty. It is conceivable that uncertainty can be avoided when predefined procedures and interpretation guidelines are being used. This would add to the transparency of uncertainty assessments with MCA. However, this would require further research as such guidelines do not already exist. Simpler fuzzy methods, like fuzzy numerical similarity statistics, could be used for uncertainty analysis in landscape planning processes when dealing with different forms of spatial data but we do not foresee the integration of more complex fuzzy programming into landscape planning practice as we struggle to see a fit for purpose.

When developing models and assessment methods for landscape planning purposes, a SA should not only be recommended, but should be mandatory in our opinion. The different indicators define the method and should therefore be checked for influence on the model outcome. If this is the case and the results of the SA are communicated together with the model output, a major contribution to the transparency of assessment methods in landscape planning could be achieved. It is also imaginable that additional information is gathered using SA to assess the uncertainty of established methods and document the results in databases. However, the question remains of how such databases need to be structured and which methods should be included for the assessment of different landscape functions.

BBN can be tailored to fit specific landscape planning tasks, which is a main advantage of this concept. Landscape planning according to the ELC is often only a part of the whole decision making process where the results are not decisions themselves but propositions for realizing environmental friendly and resource sparing developments. This is where BBN can help to clarify interrelations between different functions. Due to validation limitations and concerns regarding the time it can take to set up an appropriate BBN it might be, at this point, still questionable if BBN can be used in landscape planning practice the way they have been used in science.

The concept of adaptive management (Holling 1978) is a promising approach for incorporating and coping with uncertainty in planning processes and also for the support of management implementation to reduce uncertainty. One reason for the still limited use of adaptive planning in landscape planning practice may be that in former times analog maps, approved by local or regional governments, were not easy to change. Therefore, the biggest challenge may be the implementation of adaptive planning approaches into existing planning systems. Such implementation also requires the rethinking of planning traditions that might have already been in existence for decades (Kato and Ahern 2008). One way to apply adaptive planning in existing landscape planning procedures would be to intensify monitoring of management implementations and communicating associated findings and limitations for other planning processes. This feedback loop would make it possible to enrich the further planning processes with knowledge derived from success or failure of earlier decisions. Integration can be achieved by municipalities through monitoring (at least periodically) and by decisions on adaptive planning approvals. In situations where development measures can be more freely chosen, it is conceivable to accompany them by small scale designed experiments to test novel and innovative approaches for generating knowledge and coping with uncertainty. Although multifunctional approaches are not new to landscape planning, it is conceivable that in combination with the resilience approach, adaptive design can be used to especially promote innovative ways of establishing multifunctional measures that are robust against a wide variety of uncertainties.

Scenarios are already commonly used in landscape planning and provide an easy to use approach for

making uncertainties transparent within the landscape planning process. The integration of uncertainties happens implicitly in the majority of cases but without mentioning actual sources of uncertainty and solely addresses projection uncertainties. Uncertainties in data sources and assessment are still bound to the data and methods used, which makes an additional assessments of these uncertainties mandatory to cover the majority of the systems uncertainty. Nevertheless, we see in scenario planning a very good approach for buffering projection uncertainty by showing different results for different preconditions whilst not pretending to be a prognosis but instead a picture of possible future states.

Participation concepts as presented in recent literature (Beunen and Opdam 2011) are increasingly discussed in case oriented landscape planning tasks. Participation and co-generation of knowledge on the local level can be seen as both, assessment and coping with uncertainty and therefore presents a good way for landscape planning to handle uncertainty and for the results to be transparent. It should be noted that participatory systems have limitations as well and that participatory processes can also have a negative effect on the broad acceptance of landscape planning results, for example when the structure of the process and the time frame makes it unlikely for participants to attend every meeting (see Beach and Clark 2015). The aim in knowledge generation for landscape planning should be a balance between scientific research and participation, which is well perceived by the public, stakeholders, politicians and planners altogether.

Principles for the integration of uncertainties in landscape planning

As identified in the literature, the integration of uncertainty information in planning is lacking (Lees et al. 2016). The communication of uncertainty is the most important part in the process of integrating uncertainties into planning practice. Whether we use methods or innovative planning approaches to assess and cope with uncertainties, the usefulness of this uncertainty analysis is defined by the appropriate integration of the associated uncertainties by decision-makers. It is therefore mandatory to present uncertainty information in a way that both fits planning results while keeping a scientific standard and also fulfilling the desire of decision-makers for information

that is easily understood. This should help landscape planning results to maintain credibility amongst stakeholders and the public. It becomes obvious that in order to appropriately cope with inherent uncertainties, a dialogue between scientists, planners and decision makers is needed. This is important, for example, for the deriving of criteria to judge which uncertainty is acceptable with respect to the consequences of the implementation of planning proposals. When considered in innovative planning approaches like adaptive design, "uninformed decisions" can act as a starting point for the generation of knowledge through designed experiments. In such cases uncertainty can be seen as a catalyst.

Conclusion

Our findings show that assessing uncertainties in landscape planning could provide highly relevant information for supporting discussions and decision making. Landscape ecological modelling can already provide much experience in approaches for uncertainty estimation. However, little guidance can be found in the literature so far of how this information can be appropriately transferred to the field of landscape planning for decision support. Consequently, further research on uncertainty in landscape planning should focus on the challenges of actual implementation options (cf. Hamel and Bryant 2017). Potential reservations of practitioners against the communication of uncertainties should be identified, and ways to reduce these should be explored. Another area for research could be to investigate politicians' perceptions of uncertainty information and potential impacts of these perceptions on their decision-making. Finally, it should be explored how different kinds of uncertainty descriptions and illustrations influence decision support processes.

As a way forward, we propose landscape planners to collaborate with landscape ecologists and other natural scientists to explore ways for assessing and integrating uncertainty information in planning practice in ways that are both accurate enough to better inform decision making and doable given the limited temporal and financial resources in planning processes. It is conceivable that this might be achieved, for example, through readily available uncertainty information for different types of input data and

different models. This would enable landscape planners to use predefined values for the estimation of inherent uncertainties with little additional effort. The uncertainty assessments should also be fit for purpose in different landscape planning applications, ranging from simple estimations up to more specific assessments that deliver reliable results, especially in cases where a high level of transparency in the actual planning information is needed. In the end, landscape planning needs to act, no matter how uncertain the system under investigation might be. Uncertainties in a decision can be well accepted, if the consequences of a wrong decision will not be serious, if the decision can be easily readjusted after some time and if there is a lot of experience available as to the outcome. To maintain credibility in times of increased public sensitivity to uncertainties in expert recommendations, landscape planners should take active measures to ensure a transparent and understandable communication of landscape planning proposals to its audiences, including an appropriate communication of the inherent uncertainties as well as pointing out their meaning for the projected landscape development, financial risks and the life of people.

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