Global Change Biology

Global Change Biology (2017) 23, 28–41, doi: 10.1111/gcb.13457

RESEARCH REVIEW

Incorporating climate change into ecosystem service assessments and decisions: a review

REBECCA K. RUNTING[1,2], BRETT A. BRYAN[3], LAURA E. DEE[4], FLEUR J. F. MASEYK[2,5], LISA MANDLE[6], PERRINE HAMEL[6], KERRIE A. WILSON[2,5], KATHLEEN YETKA[1], HUGH P. POSSINGHAM[2,5] and JONATHAN R. RHODES[1,2]

[1]*School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane, 4072 Qld, Australia,* [2]*Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane, 4072 Qld, Australia,* [3]*CSIRO, Waite Campus, Urrbrae, SA 5064, Australia,* [4]*Institute on the Environment, University of Minnesota, St. Paul, MN 55108, USA,* [5]*School of Biological Sciences, The University of Queensland, Brisbane, 4072 Qld, Australia,* [6]*Natural Capital Project, Woods Institute for the Environment, Stanford University, Stanford, CA 94305, USA*

Abstract

Climate change is having a significant impact on ecosystem services and is likely to become increasingly important as this phenomenon intensifies. Future impacts can be difficult to assess as they often involve long timescales, dynamic systems with high uncertainties, and are typically confounded by other drivers of change. Despite a growing literature on climate change impacts on ecosystem services, no quantitative syntheses exist. Hence, we lack an overarching understanding of the impacts of climate change, how they are being assessed, and the extent to which other drivers, uncertainties, and decision making are incorporated. To address this, we systematically reviewed the peer-reviewed literature that assesses climate change impacts on ecosystem services at subglobal scales. We found that the impact of climate change on most types of services was predominantly negative (59% negative, 24% mixed, 4% neutral, 13% positive), but varied across services, drivers, and assessment methods. Although uncertainty was usually incorporated, there were substantial gaps in the sources of uncertainty included, along with the methods used to incorporate them. We found that relatively few studies integrated decision making, and even fewer studies aimed to identify solutions that were robust to uncertainty. For management or policy to ensure the delivery of ecosystem services, integrated approaches that incorporate multiple drivers of change and account for multiple sources of uncertainty are needed. This is undoubtedly a challenging task, but ignoring these complexities can result in misleading assessments of the impacts of climate change, suboptimal management outcomes, and the inefficient allocation of resources for climate adaptation.

Keywords: carbon sequestration, cumulative impacts, decision making, food provision, global change, global warming, land use change, uncertainty

Received 1 April 2016; revised version received 3 July 2016 and accepted 24 July 2016

Introduction

Climate change is a having a significant impact on ecosystem services, and these impacts are likely to increase as this phenomenon intensifies (Mooney *et al*., 2009). However, the impacts of climate change on ecosystem services can be difficult to assess as impacts often change over long timescales with high uncertainties (IPCC, 2014). Regional variation in climate drivers and pressures can create further challenges when assessing and managing their impacts (van Vuuren *et al*., 2007). Despite these challenges, integrating climate change and other drivers into assessments of ecosystem service provision is vital, because efforts to ensure supply of ecosystem services which ignore these impacts could lead to perverse outcomes. For instance, designing a coastal reserve system that ignored the impacts of sea level rise could lead to a decline in coastal wetlands and the ecosystem services they provide in the long run (Runting *et al*., 2016). To add to this challenge, future drivers of change of ecosystem services are not limited to the biophysical aspects of climate change but also include socioeconomic changes occurring in parallel, such as increases in population, food demand, and technology, as well as changes in policy and institutions (Millennium Ecosystem Assessment, 2005) (Fig. 1).

Assessing the impact of the different attributes of climate change on ecosystem services (e.g., changes in precipitation, temperature, CO_2, and sea level rise) individually is informative but does not necessarily capture

Correspondence: Rebecca K. Runting, tel. +61 7 336 56455, fax +61 7 336 56899, e-mail: r.runting@uq.edu.au

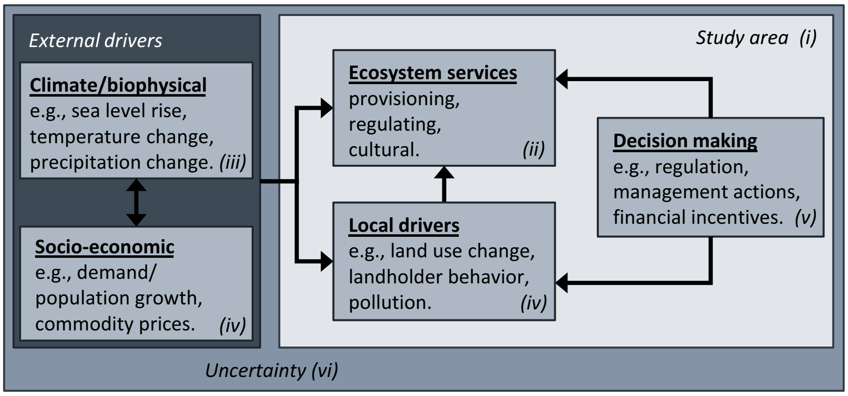

Fig. 1 A simplified conceptual framework illustrating how drivers of change impact ecosystem services. Ecosystem service provision is affected by climate change and other drivers (from global to local), along with decisions relating to their management. These decisions address the ecosystem service directly (e.g., through site-based management) or indirectly (by influencing local drivers). Uncertainty is inherent in all components of the framework and their interactions. This framework was used to structure our systematic literature review, with roman numerals indicating how each component relates to specific sections of the data extraction process (Table 1).

all the information needed for a comprehensive assessment. It is important to consider the impact of multiple attributes of climate change simultaneously within the socioeconomic context that together drive the relative supply of and demand for ecosystem services. To illustrate, climate change may decrease agricultural production through declines in rainfall, increases in evaporative demand, and shorter growing seasons, despite the positive effects of CO_2 fertilization on productivity (Rosenzweig *et al*., 2014). However, increases in global population and demand for agricultural commodities may facilitate agricultural expansion or intensification (Foley *et al*., 2005), which could result in an overall increase in food provision. Because of these complex interactions, assessing the relative and cumulative impact of these drivers is essential for a thorough understanding of ecosystem service change.

It is also important to incorporate the impacts of key local drivers of change, alongside global drivers such as climate change, as this could impact both the outcome of the assessment and how the service is managed (Fig. 1). For example, efforts to secure freshwater supply in South Africa's fynbos ecosystem in a drying climate may be thwarted by invasive alien woody plant species, as these species have higher rates of evapotranspiration than the native fynbos plants (Pejchar & Mooney, 2009). After considering these key impacts, policy to secure freshwater supply in the region is now focused on the removal of these invasive species (Buch & Dixon, 2009). Furthermore, both local and external drivers may alter the relationships between services, particularly where each service reacts differently to the same driver (Bennett *et al*., 2009). Identifying and incorporating these key drivers of change in ecosystem services is essential for designing context appropriate management strategies.

However, even if all major drivers are incorporated into ecosystem service assessments, there may still be considerable uncertainty associated with the results. First, there is substantial uncertainty involved in projections of climate change and its potential impacts (IPCC, 2014). This is further confounded by the uncertainty in the magnitude of other drivers of change (such as varying demand and commodity prices), which can also alter the demand for and supply of ecosystem services (Bryan, 2013) (Fig. 1). Other potential uncertainties, such as those associated with the measurement or modeling of ecosystem services, may also be important to consider (P. Hamel & B. Bryant, in review). Quantifying this uncertainty is not only important for determining the range of impacts on ecosystem services but is especially important to include in designing robust policy and management strategies.

Despite a growing number of studies assessing the impacts of climate change on ecosystem services, there are no quantitative syntheses of this information. Consequently, we lack a broad understanding of these impacts, how they are being assessed, and the extent to which other drivers, uncertainties, and decision making are included. To address these gaps, we systematically reviewed the peer-reviewed literature that assesses climate change impacts on ecosystem services at sub-global scales. This allowed us to quantify the impacts of climate change and other drivers on ecosystem services and determine how these impacts were measured or modeled. In doing so, we determine how uncertainty was incorporated in these assessments, and the extent to which decision making (actions, policies, or other interventions) was considered. We also identify gaps in the literature relating to the contexts of the assessments and recommend key directions for future research.

Materials and Methods

To address these aims, we designed a conceptual framework to structure our literature review (Fig. 1). Climate change, along with a range of other drivers and decisions, can impact ecosystem service provision. Non-climate drivers of change (e.g., land use change) can vary in scale from local drivers (which originate within or proximate to the study site) to external drivers (which operate at a scale larger than the study site). Whether a particular driver is local or external can depend on the scale and context of the study. For instance, commodity prices for food and raw materials are set globally for crops like wheat, corn, or cotton, but set locally for some non-timber forest products such as some medicinal plants, forage, and resin (Shackleton *et al.*, 2007). Additionally, a driver that is external at the patch scale (e.g., fertilizer runoff) may be within the study area at regional or national scales. These drivers of change are often interrelated as external drivers can influence local ones, such as global commodity prices influencing local land use change. Decisions made at the local scale can directly improve ecosystem service provision or influence local drivers, but they generally do not have a significant impact on the magnitude of external drivers. Decision making can also occur well outside the location and scale of the study area [e.g., the national and global level decision making inherent in the IPCC emissions scenarios (IPCC, 2013)], but here we focus on the decisions that can be made by local and regional actors to *adapt* to the impacts.

We compiled a set of peer-reviewed journal articles on ecosystem services and climate change (Fig. 2). A list of research articles published between 1990 and 2014 was generated using selective key words under 'TOPIC' in the database of ISI Web of Science Core Collection. Articles published in 2014 were only included if they appeared in the database before November 2014. We applied the search: ('ecosystem service*' OR 'ecosystem good*') AND (climat* NEAR chang*). The key word search was constrained to general terms in order to produce a representative sample of the literature (rather than a comprehensive list). Using 'ecosystem service' OR 'ecosystem good' omitted studies that assessed an ecosystem service, but did not identify it as such (e.g., food production, biofuels, health benefits). Studies that did not use the term 'ecosystem service' would be unlikely to follow an ecosystem service framework, so comparing them to our conceptual framework (Fig. 1) would have potentially exaggerated research gaps (such as incorporating drivers other than climate change and decision making). Additionally, including more specific terms such as 'crops' or 'fisheries' would bias the results toward these services and return an impractical number of papers, so specific key words such as these were excluded. We applied a similar approach to climate change phenomena (e.g., we did not include additional terms like 'sea level rise' or 'global warming') for the same reasons. These general search terms returned 1567 papers (Fig. 2).

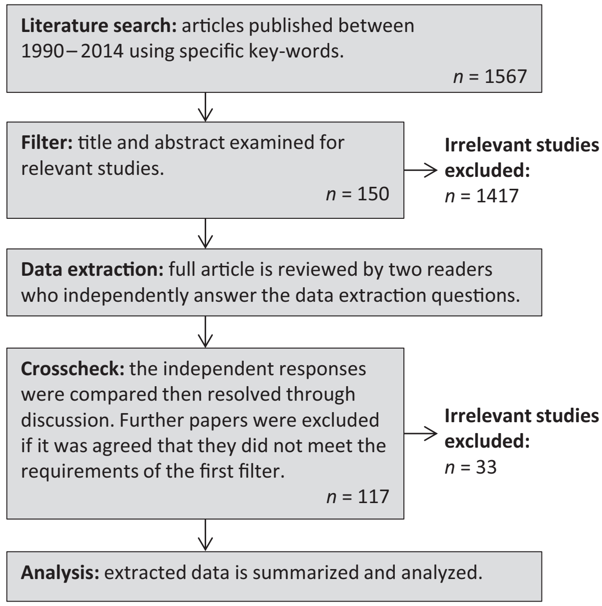

Fig. 2 Flowchart demonstrating the methods used in the systematic quantitative review. Articles published in 2014 only include those that appeared on Web of Science before November 2014.

We read the abstracts of these 1567 papers to determine whether they met the requirement for inclusion in this study (the filter, Fig. 2). These criteria had three components. First, our criteria required papers to be an assessment of provisioning, regulating, or cultural ecosystem services [in accordance with the TEEB (2010) framework]. This excluded reviews or conceptual papers and articles that focused on biodiversity or supporting/habitat services, as these are better defined as ecosystem functions (de Groot *et al.*, 2002, 2010; Wallace, 2007), and the impact of climate change on species and biodiversity has been reviewed elsewhere (Tylianakis *et al.*, 2008; Bellard *et al.*, 2012; Mantyka-Pringle *et al.*, 2012; Chapman *et al.*, 2014; Pacifici *et al.*, 2015). Second, we excluded studies that did not incorporate climate change impacts (e.g., studies focusing on carbon sequestration in the absence of climate change impacts but refer to its importance for mitigating climate change). Last, global-scale assessments of climate change impacts on ecosystem service provision were excluded because regional variations in climate drivers create unique challenges at subglobal scales [such downscaling global climate scenarios (van Vuuren *et al.*, 2007)], and adaptation to the impacts of climate change usually occurs at subglobal scales (Ford *et al.*, 2011).

The 150 papers that passed these criteria were read in detail to extract data using specific questions (Fig. 2). These questions had fixed answer categories, along with an open-ended comment box to clarify responses and ensure consistency in data extraction (see Table 1 for a summary, and Table S4 for details). To minimize errors and biases, each paper was read by two readers (co-authors of this review paper), who independently answered the data extraction questions. The two

Table 1 The structured questions used to extract data from the journal articles

Category	No.	Aim	Question
Filter	1	–	Is the paper an assessment of ecosystem services?
	2	–	Does the paper incorporate the impacts of climate change?
(i) Study area	3	(a)	Spatial scale of assessment?
	4	(a)	Location of assessment?
	5	(a)	Type of ecosystem(s)?
(ii) Ecosystem services	6	(a)	Which ecosystem service(s) were considered? State the indicator used.
	7	(a)	What aspect of each ecosystem service is considered?
	8	(c)	If monetary value was considered, what valuation method was used?
(iii) Drivers: climate	9	(b)	What aspect(s) of climate change are considered?
	10	(b)	Were these attributes of climate change assessed cumulatively, in isolation from each other, or both?
	11	(b)	What was the impact of climate change on the ecosystem services studied?
	12	(b)	Are interactions between services considered (i.e., trade−offs)?
	13	(c)	What method was used to incorporate climate change and ecosystem services?
	14	(c)	Was the method static, or did it consider changes over time?
(iv) Drivers: other	15	(b)	Are other drivers considered?
	16	(b)	If other (non-climate) drivers were incorporated, list the drivers.
	17	(b)	What was the impact of the non-climate driver on the ecosystem service studied?
	18	(c)	How was the impact of the driver(s) assessed?
	19	(b)	How did each driver interact with climate change?
(v) Decision making	20	(e)	Is decision making considered (i.e., actions, policies, or other interventions)?
	21	(e)	How many objectives are considered (list all)?
	22	(e)	What method is used to model or assess the action, policy, or interventions?
	23	(e)	What category do these actions, policies or other interventions fall into?
(vi) Uncertainty	24	(d)	Was uncertainty considered?
	25	(d)	What was the source of the uncertainty, and what methods were used to incorporate it in the assessment?
	26	(d)(e)	If decision making is considered, are the decisions robust to uncertainty?

The roman numerals indicate which component of the conceptual framework (Fig. 1) the section relates to. Each question helps to address one of the aims: (a) identify gaps in the literature relating to the context of the assessments, (b) quantify the impacts of climate change and other drivers on ecosystem services, (c) determine how these impacts were measured or modeled, (d) determine how uncertainty was incorporated in these assessments, and (e) determine the extent to which decision making (actions, policies, or other interventions) was considered. The categories used to answer these questions are given in Table S4.

responses for each paper were then compared, and any discrepancies were noted qualitatively (the nature of the discrepancy) and quantitatively [0 for complete disagreement, and 0.5 for partial agreement (1 was given if there was no discrepancy)]. These quantitative scores revealed a mean agreement of 22.3 (86%) answers [σ = 2.6 (10%)] of a maximum possible 26. Recording the differences qualitatively allowed any discrepancies to be resolved through a discussion between the readers, with a third opinion sought from an additional reader if needed. These final (i.e., resolved) responses were used for the subsequent analyses and form the basis of the results reported here. This process revealed that of the 150 studies that were not initially excluded (from reading the abstract), 33 studies did not fit the criteria described above, so they were excluded from further analysis leaving a total of 117 studies.

We designed the data extraction questions to apply to our aims and conceptual framework (presented in Fig. 1). The data extraction questions were organized by each component of the conceptual framework, and each question relates to one of our aims (Table 1): (a) to identify gaps in the literature relating to the context of the assessments, (b) to quantify the impacts of climate change and other drivers on ecosystem services, (c) to determine how these impacts were measured or modeled, (d) to determine how uncertainty was incorporated in these assessments, and (e) to determine the extent to which decision making (actions, policies, or other interventions) was considered. To identify any gaps in the contexts of the assessments (a), we extracted data relating to the study's spatial (Q3), geographical (Q4), and ecological (Q5) setting, along with which ecosystem services (Q6), and which aspects of each service (Q7) were assessed. We adopted the ecosystem service typology for provisioning, regulating, and cultural services from TEEB (2010), and the definitions of ecosystem service supply and delivery based on Tallis *et al.* (2012) (Table S4). Not every study fitted neatly into these categories, which caused of some of the aforementioned discrepancies, although these were resolved through a discussion of the semantics of the TEEB ecosystem service definitions.

A range of questions were used to quantify the impacts of climate change and other drivers on ecosystem services (b) and the methods used to assess them (c). We collected information on which aspects of climate change (Q9) and which non-climate drivers of change (if any) (Q15, Q16) were considered. Options for which climate change attributes were included were adapted from IPCC (2014). The response categories for which non-climate drivers were assessed (Q15) were not predefined, so any driver could be included. To quantify the (directional) impact of drivers on ecosystem services, the impact of climate change (Q11) and non-climate drivers (Q17) was recorded as positive, negative, neutral, or mixed. We did not specify quantitative measures of the magnitude of change, as this would be problematic to compare across different services using different methods (particularly qualitative methods), baselines, and indicators. We also recorded if any interactions between services were assessed (Q12), and if the attributes of climate change were assessed cumulatively, in isolation from each other, or using both of these approaches (Q10). If the study considered both the cumulative and individual impacts of climate change and other drivers (Q18), we allowed an option to record the interaction between climate and non-climate drivers, specifically, whether their impacts are synergistic, antagonistic, additive, or unclear (Q19) [based on definitions in Brown *et al*. (2013)]. The methods used to assess the impact of climate change could be identified as empirical (i.e., a laboratory or field-based study), a statistical or process-based model (with or without the use of local field-based data), expert elicitation, or other methods (Q13). These methods were further classified as static (assessing only one future or past time point in addition to the baseline) or dynamic (assessing more than one future or past time points), and the interval between time points was also recorded (Q14). If monetary valuation was undertaken, the valuation method was specified (e.g., market value, avoidance cost, contingent valuation) (Q8), based on definitions from Christie *et al*. (2012).

To determine how uncertainty was incorporated in these assessments (d), we first recorded whether uncertainty was mentioned, explicitly incorporated in the assessment, or ignored (Q24). We then identified the methods used to incorporate uncertainty (i.e., scenario analysis, sensitivity analysis, multiple models, probabilistic approaches, or other methods), which were adapted from Polasky *et al*. (2011), Yousefpour *et al*. (2012), and Refsgaard *et al*. (2007) (Q25). For each method, we also identified which source(s) of uncertainty it addressed (e.g., the magnitude of climate change, or how ecosystem services are supplied) (Q25). This information was also used to identify gaps in the sources of uncertainty that were accounted for.

To get an understanding of the extent to which decision making was incorporated (e), we recorded if solutions were explicitly measured or modeled, just mentioned, or ignored (Q20). Where decision making was included, we identified the methods used (e.g., cost/benefit analysis, adaptive management) (Q21, Q22), the solutions proposed (Q23), and if these solutions were robust to the uncertainties included (Q26). Here we focused on decision making that occurred at a similar scale to the study area (Fig. 1). Of course, decision making can also occur at much larger scales (e.g., global policies), but these decisions were usually bundled with other external drivers (and were treated as such in this review). A full list of questions and response categories are given in Table S4.

We then conducted a meta-analysis to determine whether there was statistically significant variation in climate change impacts on ecosystem services across service categories, climate change attributes, methods used, biomes, and spatial scales. Given the categorical nature of our data, we used cumulative logit models with the ordinal categorical impacts of climate change on ecosystem services as the response variable, and the spatial scale of the study, type of ecosystem (i.e., terrestrial, freshwater or marine), climate change attributes (e.g., temperature increase, CO_2 fertilization or sea level rise), ecosystem service categories, and methods used (i.e., empirical, expert elicitation, process-based, or statistical modeling) as predictor variables. Broad ecosystem service categories (i.e., provisioning, regulating, and cultural) were used instead of the 15 individual TEEB ecosystem service types to ensure a sufficiently large number of records in each category (see Appendix S1 for details).

Results

Contextual information

Our review revealed clear patterns in the contextual information of the reviewed papers and the characteristics of the ecosystem services studied (Fig. 3). All studies that passed the first filter were published since 2003, with 78% of these published since 2011 (Fig. 3c). This trend suggests a growing interest in climate change impacts on ecosystem services. We found that the studies considered a diversity of spatial scales (Fig. 3d), but there was a clear dominance of terrestrial ecosystems (91 studies) over freshwater (40 studies) and marine (17 studies) ecosystems (Fig. 3e). Although a large number of countries were covered by at least one study (131 countries), there was a focus on the USA and Europe, with 30 studies (26%) in the USA and 49 studies (42%) in Europe (Fig. 3g).

There were also biases in the characteristics of the ecosystem services studied. Provisioning services (particularly food, raw materials, and freshwater) and carbon sequestration dominated the literature, with cultural services receiving the least attention (Fig. 3f). Whilst the focus of most studies was on the supply side of ecosystem service provision, the link to beneficiaries (demand) was also included in almost 40% of cases (Fig. 3f). Finally, nearly half of the studies focused on a single ecosystem service (48%, Fig. 3a), which provided the opportunity for in-depth analysis but meant that interactions between services (e.g., trade-offs) in the context of climate change were rarely considered (only 17% of studies).

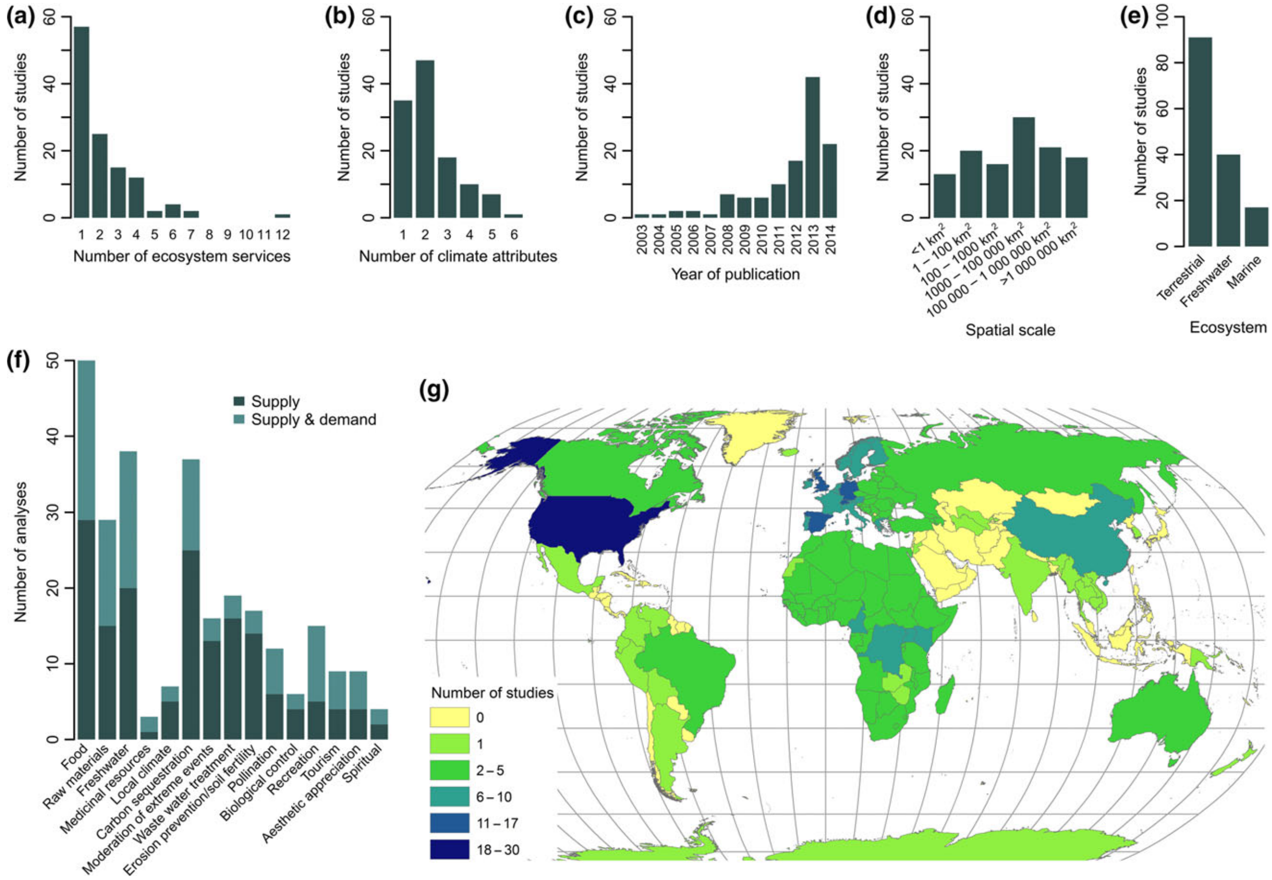

Fig. 3 Key attributes of the 117 ecosystem service assessments: (a) the number of ecosystem services included in each paper with a unique indicator (i.e., if the same indicator was used for multiple services, it was only counted once), (b) the number of attributes of climate change included in each paper, (c) the frequency of each year of publication (2014 only includes papers that appeared on Web of Science before November 2014), (d) the frequency of each spatial scale, (e) the frequency of each type of ecosystem, (f) the frequency of each ecosystem service and whether supply and/or demand was considered, and (g) the number of studies by nation. In panel (f), the ecosystem services are ordered in accordance with the TEEB (2010) framework, so that they are grouped by provisioning (i.e., food, raw materials, freshwater, and medicinal resources), regulating (from local climate to biological control) and cultural (i.e., recreation, tourism, esthetic appreciation, and spiritual benefits) services. Panels (e)–(g) sum to more than the total number of papers, as each paper could span more than one nation, and could cover more than one ecosystem and service.

The impact of climate change and other drivers

We found that a diversity of climate change attributes were included, with most studies considering more than one attribute (70%, Fig. 3b). The most common attributes were temperature (81% of papers), often coupled with precipitation change (an increase, decrease, or increasing variability; 63%), but other combinations of climate change attributes were also explored. Of those studies that considered two or more climate change attributes, 77% assessed these impacts cumulatively (all together), 9.8% assessed the attributes individually, and 13% assessed the impacts both individually and cumulatively. We found that the impact of climate change on ecosystem services was predominantly negative (59% of analyses were negative, 24% mixed, 13% positive, 4% neutral); however, this pattern was not consistent across services or attributes of climate change (Fig. 4a). The category of ecosystem service (i.e., provisioning, regulating, or cultural) influenced the results, with regulating and cultural services being impacted more negatively by climate change than provisioning services [regression coefficients are −0.38 (regulating) and −1.9 (cultural), relative to provisioning services, Table S2]. However, this effect was only significant for cultural services ($p = 0.00155$, Table S2).

Based on the four impact categories, carbon sequestration had the most variable response to climate change (41% of analyses were mixed, 35% negative, 20.5% positive, 3.5% neutral), but other services had a more negative response (e.g., 92% of analyses of the

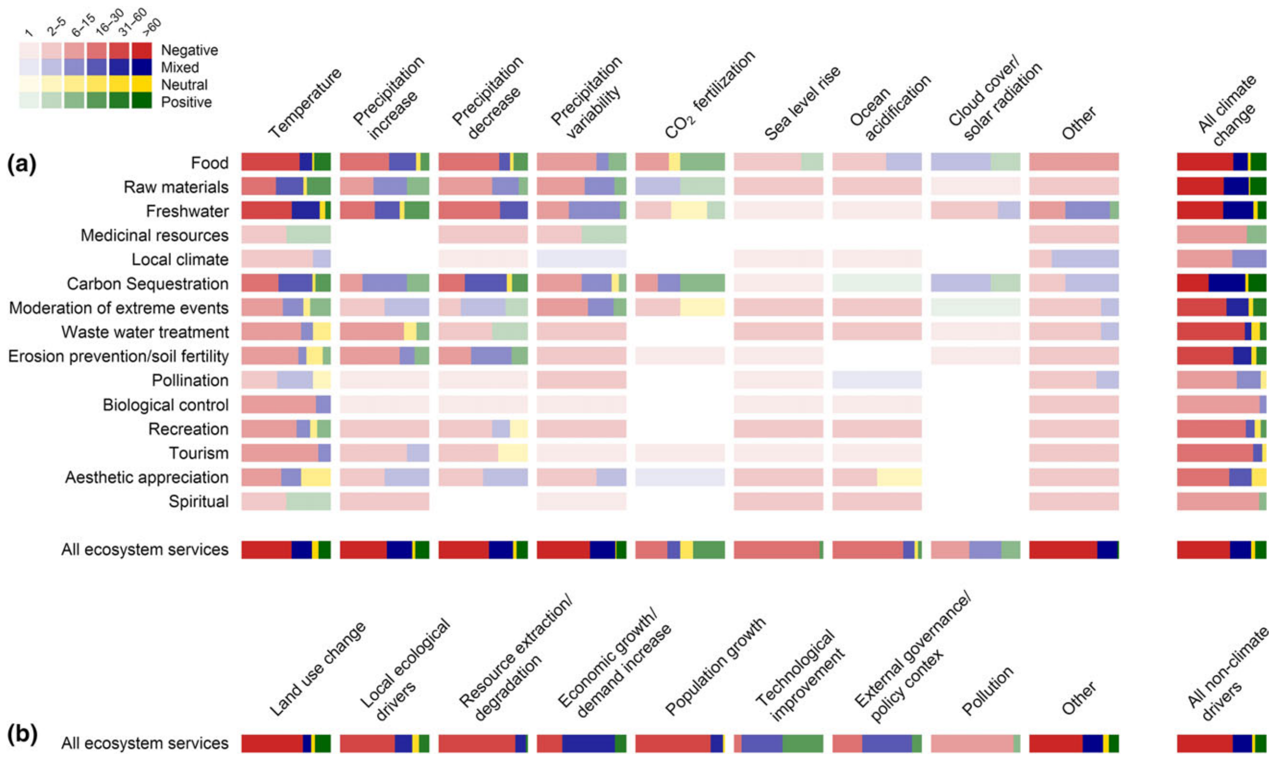

Fig. 4 The impact of climate change and other drivers on ecosystem services. Panel (a) shows the impact of individual attributes of climate change on individual ecosystem services. The bottom row of this panel shows the impact of each climate change attribute across all services, and the far right column shows the total climate change impact for each service. The bottom right bar of this panel gives the total impact for all services and attributes of climate change. Panel (b) shows the individual and total impact of other drivers on all ecosystem services. For both panels, the bar indicates the *proportion* of analyses giving a negative, mixed, neutral, or positive response for each ecosystem service and driver combination (i.e., this does not take into account effect sizes). The strength of the color represents the *total* number of analyses for that driver and ecosystem service (i.e., solid colors indicate many analyses, whereas faded colors indicate few analyses, and blank space indicates zero studies). The number of analyses for each level of color strength is shown in the legend.

impact on biological control were negative, with only 8% mixed) (Fig. 4a). Similarly, CO_2 fertilization had the most positive impact on services (i.e., 36% of analyses were positive, 36% negative, 14% mixed, and 14% neutral), whereas other climate change attributes produced a stronger negative response (e.g., 96% of studies on the impact of sea level rise were negative) (Fig. 4a).

We found that more than half of the papers in our review (56%) incorporated drivers other than climate change, and 31% either mentioned in passing or discussed these drivers in depth (without incorporating them). Whilst the impact of all non-climate drivers varied, they had a predominantly negative impact (62% of analyses were negative, 33% neutral, 22% mixed, 13% positive), with the exception of technological improvement, which had a largely positive impact (46% of analyses were positive, 46% mixed, 8% negative) (Fig. 4b). Land use (or land use management) change was the non-climate driver that was most often included (28% of analyses that included non-climate drivers), with largely negative impacts (69% of analyses were negative, 18% positive, 9% mixed, 4% neutral). Of studies that considered non-climate drivers, 61% assessed the cumulative impact with climate change, 5.8% assessed other drivers and climate change separately, and 33% considered both cumulative and individual impacts.

Methods used to assess impacts

A variety of methods were employed to determine the impact of climate change on ecosystem services. Process-based modeling (e.g., hydrological models, deterministic ecosystem service models) was the most frequently used method (51% of analyses), and most of these process-based analyses were parameterized with some local field data (85%). However, empirical field-based or laboratory studies were less frequently used (10% of analyses) (Fig. 5a, c). Almost half of studies (48%) conducted a dynamic assessment (i.e., considered

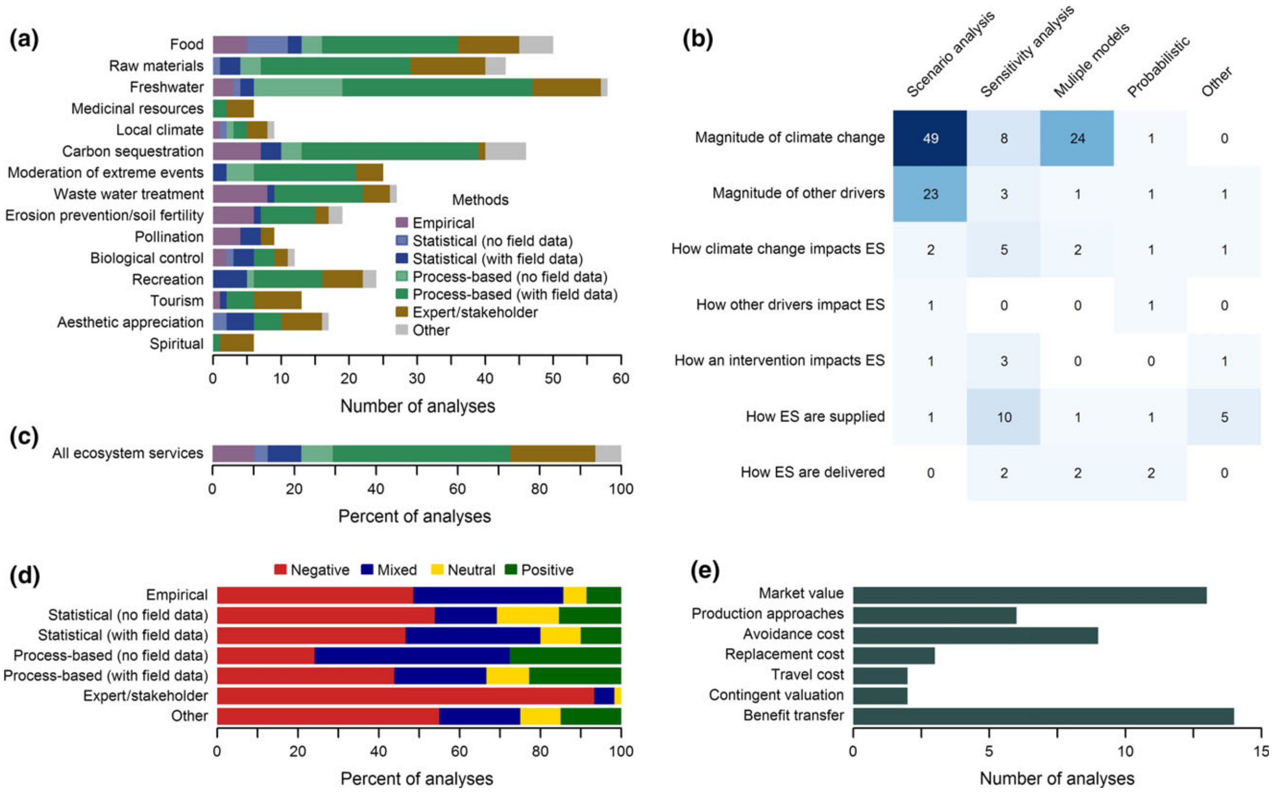

Fig. 5 Methods used to assess the impact of climate change on ecosystem services. Panel (a) shows the frequency each method was used to assess the impact of climate change on each ecosystem service. Panel (b) shows the frequency of methods used to incorporate uncertainty into the ecosystem service (ES) assessments by the frequency of the type of uncertainty that was addressed. Panel (c) shows the percent of analyses that used each method to assess the impact of climate change across all services, and panel (d) shows the proportion of analyses that had a negative, mixed, neutral, or positive impact of climate change on ecosystem services by each of these methods. Panel (e) illustrates the frequency of different methods used when monetary valuation was included in the assessment. Each paper potentially assessed more than one ecosystem service and potentially used more than one method, so the number of analyses can sum to more than the total number of papers, and differ from those in Fig. 3.

more than one future time point), and of these studies, the time interval between future time points varied between 0.2 days (for some hydrological models) and 100 years. Similarly, of the 19 papers (16%) that included monetary valuation of ecosystem services, a variety of valuation methods were used (including market methods, production approaches and avoidance cost), but benefit transfer was relied upon the most often (in 29% of analyses) (Fig. 5e).

We also found that the method used may impact the outcome of the assessment. Specifically, relying on expert opinion to determine the impact of climate change (in 21% of analyses, Fig 5c) gave primarily negative results (94% of these analyses were negative), which was in contrast to other (empirical, quantitative modeling) methods that showed more variation in the impacts of climate change (where 47% of analyses were negative) (Fig. 5d). The more frequently negative impacts of expert elicitation were reflected in a relatively large regression coefficient (−5.2, relative to process-based models) which was found to be statistically significant (p = 0.003) (Table S2).

Uncertainty

We found that there were gaps in the sources of uncertainties considered in the analyses, along with the methods used to incorporate them (Fig. 5b and Table S4 for definitions of methods). At least one source of uncertainty was explicitly incorporated in 71% of studies and was mentioned or discussed by another 17%. Uncertainty in the magnitude of climate change was the main uncertainty addressed (Fig. 5b), and the dominant method for addressing this, as for most sources of uncertainty, was scenario analysis, followed using multiple models (Fig. 5b). This was usually achieved through the use of multiple IPCC emissions scenarios to inform multiple global circulation models, which formed the basis of the analyses (e.g., Matthews *et al.*, 2013; Müller *et al.*, 2014).

Decision making

Whilst various types of decision making were often mentioned (83% of papers), decision making was less frequently included in analyses (29% of papers). A number of different solutions were proposed, and these were assessed using a variety of methods across the studies that incorporated decision making (Fig. S1). Only five studies included decision making outcomes (i.e., policies or management strategies) that assessed robustness to at least one type of uncertainty, and three of these focused on a single ecosystem service (i.e., a single objective). These decision making strategies included: planting a climate-resilient species mix for silviculture (Seidl *et al.*, 2011; Steenberg *et al.*, 2011), protecting wetlands (Grossmann & Dietrich, 2012), setting maximum stocking rates for livestock (Schaldach *et al.*, 2013), and managing a buffer stock of timber (Raulier *et al.*, 2014).

Discussion

Our review revealed that the majority of studies found a negative impact of climate change on ecosystem services, yet the effects varied across services, climate change attributes, and assessment methods, and in some cases were positive. There is strong evidence that climate change is having a negative (but variable) impact on biodiversity (Bellard *et al.*, 2012; Pacifici *et al.*, 2015) so it is unsurprising that the services that flow from species and ecosystems are similarly impacted. Our finding of predominantly negative impacts is also in line with qualitative syntheses of climate change impacts on ecosystem services (Mooney *et al.*, 2009; Scholes, 2016), which highlight the need for climate change adaptation strategies to ameliorate these impacts. The complex temporal and spatial patterns across multiple climate change attributes (Dobrowski *et al.*, 2013; IPCC, 2013) suggest that the variability seen in our results is an accurate representation of climate change impacts.

We found that carbon sequestration had the most variable response to climate change (Fig. 4a), and the context of each study appeared to affect the direction of climate change impacts. For instance, a freshwater mesocosm experiment showed that temperature increases reduced carbon sequestration by 13 percent by shifting the metabolic balance of the ecosystem (Yvon-Durocher *et al.*, 2010). In contrast, climate change had a positive impact on carbon sequestration in the Swiss Alps, as increasing temperatures enabled forest expansion into higher altitudes (Grêt-Regamey *et al.*, 2013). This variability is supported by other meta-analyses on the response of carbon sequestration to temperature increases or elevated atmospheric carbon dioxide. Luo *et al.* (2006) found that elevated atmospheric carbon dioxide increased total carbon accumulation in terrestrial ecosystems, but these results were highly variable across studies and carbon pools. Similarly, the analyses by Lu *et al.* (2013) revealed that carbon sequestration response to temperature increase varied by ecosystem type (i.e., forest, grassland, shrubland, tundra, and wetlands).

Although the impacts on other ecosystem services were more consistently negative (Fig. 4a), contextual factors (e.g., climatic zone and type of ecosystem) still appeared to influence the results. For example, the impact of drought on the persistence and production of perennial grasses used for forage varied between temperate and Mediterranean climate types in France (Poirier *et al.*, 2012). This variability in food provision is supported by a global meta-analysis, which showed that whilst increases in temperature generally decreased crop yield, there was significant yield variability across crop types and temperate/tropical regions (Challinor *et al.*, 2014). Similar variability in food provision in response to temperature increases can be seen in the marine environment, with maximum fisheries catch potential increasing in offshore regions but decreasing in the coastal zone (Cheung *et al.*, 2010). The lack of generalities and statistical significance across services and climate change attributes indicates the importance of local and regional assessments of ecosystem services, by service type, rather than relying on averages, aggregates, or trends seen at broader spatial scales.

Our systematic review also revealed gaps in the context and characteristics of the ecosystem services studies. The literature was dominated by studies from the USA and Europe (Fig. 3g), indicating a need for further studies beyond these regions. This is particularly important as the impacts of climate change on ecosystem services are likely to disproportionately affect developing countries, who also have a lower capacity to adapt to these impacts (Srinivasan, 2011). Another major gap was the study of cultural services (Fig. 3f), which is unsurprising given they are often omitted from assessments of ecosystem services due to the difficulties in characterizing these services (Chan *et al.*, 2012). Similarly, most studies focused on the biophysical supply (or 'supply side') of ecosystem services, which is consistent with the findings of other ecosystem services reviews (e.g., Martinez-Harms *et al.*, 2015). However, this focus on supply misses an opportunity to provide a complete assessment of ecosystem services by demonstrating benefit to people ('demand side') (Tallis *et al.*, 2012). This link is particularly important, as there is often a spatial mismatch between the supply and demand of ecosystem services (Bagstad *et al.*, 2012). It may be the case that only part of the area supplying the service may be necessary to meet demand, or, conversely, a greater area of supply may be required (Bagstad *et al.*, 2012). In addition, clearly demonstrating the benefits to humans is essential for meaningful integration with planning and policy decisions (Daily *et al.*, 2009).

Assessing both the relative and cumulative impacts of multiple attributes of climate change was often overlooked. We found that most studies considered the cumulative impacts of climate change, which is promising as this has previously been highlighted as an important area for future research (Tylianakis *et al.*, 2008; Staudt *et al.*, 2013). On the other hand, studies that isolate the impacts of individual attributes of climate change are still vital for determining the relative impact of each attribute. We found that the relatively few studies that considered both the cumulative and individual impacts of climate change allowed for further insights that would not have been possible with other study designs. This was illustrated by Lindeskog *et al.* (2013), who revealed that CO_2 fertilization would only partially offset the negative impacts of other climate change attributes (including temperature increase, precipitation change, and solar radiation) on carbon sequestration. Although these types of studies are often time and resource intensive, they are vital for determining the relative importance of each driver. Knowing which drivers are the most important may be valuable for future assessments where the inclusion of all climate change attributes (and other key drivers) is not possible due to resource constraints.

Integrating other global or local drivers with climate change is critical for understanding the complexities of the impacts on ecosystem services (Carpenter *et al.*, 2009; Bryan, 2013). We found that land use change was the driver that was most often included, which is likely due to the well-established importance of this driver, the existence of land use change models, and the largely negative impacts of land use change (Foley *et al.*, 2005). For example, the conversion of forest to agriculture in the Brazilian Amazon not only reduces carbon stocks but could also reduce agricultural output in the long run, as deforestation exacerbates the negative impacts of climate change through regional land–climate feedbacks (Oliveira *et al.*, 2013). Where both cumulative and individual impacts of climate change and other drivers were considered, the interactions between these drivers were often ambiguous (i.e., it was unclear whether their interaction was antagonistic, synergistic, or additive), which was largely because the nature of the interactions were not the focus of these studies. Additionally, the dominance of scenario analyses meant that in many cases, it would be problematic to completely isolate all the scenario components without violating the assumption of internal consistency (Amer *et al.*, 2013). Consequently, the impact on ecosystem services that results from interactions between climate change and other drivers remains an important area for future research.

Whilst some studies employed sophisticated dynamic models or conducted well-designed empirical research to determine the impact of climate change on ecosystem services, other studies utilized simpler methods, which may be prone to errors and biases. For example, when assessing the monetary value of ecosystem services, there was a reliance on benefit transfer (i.e., applying values quantified in other studies, conducted elsewhere) for many value estimates (Fig. 5e). This method is considered to be unreliable as it is prone to errors resulting from a lack of transferability between locations (although these errors can be reduced if the two sites are very similar) (Plummer, 2009; Eigenbrod *et al.*, 2010a). A variety of other methods for monetary valuation exist [e.g., market price, avoidance cost, damage reduction (Christie *et al.*, 2012)], which should ideally be utilized instead of a value transfer where possible.

We also found that relying solely on expert elicitation to determine the impact of climate change on ecosystem services may overestimate the negative impacts of climate change. Studies that used expert elicitation gave more frequent negative results than studies employing empirical or quantitative modeling methods, and this effect was statistically significant. This difference could be due to motivational or accessibility bias among experts (Martin *et al.*, 2012). Specifically, the knowledge that the impacts of climate change are generally negative may exert a disproportionate influence on the experts' judgment, even in cases where the actual impact of climate change may be positive or mixed. A variety of methods exist to minimize bias and verify the accuracy of elicited information [such as eliciting information from a high number and wide variety of experts, eliciting uncertainties alongside best estimates, and providing feedback to experts (Martin *et al.*, 2012)], but it was not clear if these methods were followed in the studies included in this review. Whilst involving stakeholders is important to facilitate implementation (Reed, 2008), when assessing the impact of climate change, expert elicitation should follow formal procedures and ideally be accompanied by other methods where available.

In some assessments, a biological indicator (such as the presence, abundance, biomass, or percentage cover of a particular species or ecosystem) was used as a proxy to measure provision of an ecosystem service, and in some cases, the same indicator was used for multiple services. This can be seen in Saulnier-Talbot *et al.* (2014), where the same set of indicators of lake health were used to measure tourism, freshwater, and food provision. This is particularly concerning, as the way an ecosystem service is measured has been shown to have a substantial bearing on the outcome of the assessment (Eigenbrod *et al.*, 2010b; Liss *et al.*, 2013). The importance of this is highlighted by Doherty *et al.* (2014) who found that biomass (a commonly used indicator) was negatively correlated with four regulating services (flow attenuation, stormwater retention, erosion resistance, and water quality) in some contexts. Consequently, future studies should avoid the use of proxies and measure or model service provision directly where possible.

Incorporating the uncertainty associated with climate change is vital given the current range of climate projections (IPCC, 2014), and we found that the magnitude of climate change was the main source of uncertainty addressed. However, other potential uncertainties within the analyses received relatively little attention. For example, uncertainties relating to *how* climate change impacts ecosystem services were rarely incorporated (Fig. 5b), as this can involve varying which model is used, or the model structure, which requires further time and expertise. Despite these challenges, Jung *et al.* (2013) included multiple uncertainties in their modeling of freshwater yield in South Korea using two emissions scenarios, 13 global circulation models, and three different hydrological models. Other methods exist for incorporating multiple sources of uncertainty throughout the modeling process, such as Monte Carlo simulation or uncertainty matrices (Refsgaard *et al.*, 2007; P. Hamel & B. Bryant, in review), but these were usually overlooked. Therefore, building on climate change scenarios to incorporate multiple sources of uncertainty into ecosystem service assessments remains an important area for future research.

Making decisions in the context of climate change and other drivers is difficult due to the long time frames and uncertainties involved. The main objective of most of the reviewed studies was to investigate the impact of climate change, rather than determine the outcomes of decisions (i.e., policy and management). As assessing the impact of climate change on ecosystem services is a substantial undertaking in itself, it is understandable that these papers also did not address decision making in any great detail. Studies that included decision making usually employed a limited assessment (i.e., only one ecosystem service or attribute of climate change) or had methods and results spanning multiple papers. This is illustrated by Bateman *et al.* (2013), who explored policy options for multiple ecosystem services in the context of multiple drivers, had a team of 15 authors, and some aspects of the study were published in separate papers [specifically Abson *et al.* (2014) and Fezzi *et al.* (2014)]. Similarly, Bryan *et al.* (2016) explored policy options to preserve carbon and biodiversity services under a range of global change drivers using a complex, integrated environmental-economic model, which was developed over several papers [specifically Bryan *et al.* (2014) and Connor *et al.* (2015)]. Therefore, it is unlikely to be feasible to include multiple drivers and decisions in every analysis, especially for empirical studies that seek to isolate climate impacts. However, the results of these ecosystem services assessments could be useful for future studies that aim to develop or apply decision making methods under climate change, provided that the data underpinning the results of these ecosystem service assessments are shared by the authors.

A major gap exists in developing and applying decision making methods for ecosystem services under climate change that are robust to uncertainty. In our review, only one study (Raulier *et al.*, 2014) explicitly incorporated robustness to uncertainty into their decision making objectives. Many methods exist for making good decisions under uncertainty (Polasky *et al.*, 2011) and have been applied in other fields. For example, Lempert *et al.* (2012) combined a stochastic cost-benefit analysis with robust optimization to advise the Port of Los Angeles on which facilities (if any) it should upgrade to protect against extreme, but unlikely, sea level rise. Similarly, Bertsimas & Pachamanova (2008) applied robust optimization approaches to multiperiod portfolio selection to develop an optimal, time-dynamic financial investment strategy under uncertainty in future returns. Alternatively, Regan *et al.* (2005) used information-gap theory to determine the optimal management strategies to minimize the extinction risk of the Sumatran rhino (*Dicerorhinus sumatrensis*) under severe uncertainty relating to population models, causes of decline, and the effectiveness of management strategies. Applying methods such as these to managing ecosystem services under global change will bring unique challenges that may require substantial methodological innovation, which should be the focus of further research.

We recommend incorporating complexity into ecosystem service assessments and decisions under climate change, which can involve using sophisticated methods and including multiple services, drivers of change, and sources of uncertainty. Yet acquiring the data (and expertise) to accurately assess and incorporate these complexities is likely to be costly and/or time-consuming. However, this investment could lead to substantial improvement in outcomes (or cost savings) in cases where the inclusion of this additional information substantially changes the management strategy or policy (e.g., Runting *et al.*, 2013). Alternatively, unnecessary time and resources may be spent on incorporating multiple drivers, quantifying uncertainty, and improving data quality for outputs that ultimately do not change the decision (e.g., Pannell, 2006; Grantham *et al.*, 2008). Consequently, an important area for future research is quantifying the value of including multiple drivers and sources of uncertainty into complex models for ecosystem service assessments and decisions. Similarly, assessing the individual *and* cumulative impacts of multiple uncertain drivers of change could be useful in revealing which drivers (or combination of drivers) have the greatest bearing on results and should therefore be prioritized for inclusion in future ecosystem service assessments.

Conclusions

Our systematic review revealed multiple gaps in the body of literature assessing the impacts of climate change on ecosystem services. Cultural services were under-represented, and studies on the USA and Europe dominated the literature. Overall, climate change and other drivers negatively impacted ecosystem services, but this varied across drivers, the services assessed, the context of the study, and the method used. This highlights the importance of conducting local and regional ecosystem service assessments, rather than relying on averages or aggregates from other contexts. Although uncertainty was usually incorporated, there were substantial gaps in the sources of uncertainty included, along with the methods used to incorporate them. We found that relatively few studies integrated decision making, and even fewer studies aimed to identify solutions that were robust to uncertainty.

Climate change can have a significant impact on the effectiveness of management decisions targeted at sustaining ecosystem service provision (Poiani *et al.*, 2010). For management and policy to ensure the delivery of ecosystem services, an integrated approach that incorporates multiple drivers of change and accounts for multiple sources of uncertainty is needed. Explicitly incorporating the range of uncertainties into assessment methods is vital for meaningful integration with decision making (Gregr & Chan, 2014). It is concerning that the relatively few studies that incorporated decision making did not assess how well their proposed solutions performed under the range of uncertainties. Making good decisions with limited information and substantial uncertainty will require innovative methods, such as the use of robust optimization (Hallegatte, 2009). Whilst this is undoubtedly a challenging task, ignoring this uncertainty could result in misleading assessments of the impacts of climate change, suboptimal management outcomes, and the inefficient allocation of resources.

Acknowledgements

We would like to thank Maria Martinez-Harms and the University of Queensland Ecosystem Services Group for valuable discussions. RKR is supported by a University of Queensland – Commonwealth Scientific and Industrial Research Organization (CSIRO) Integrated Natural Resource Management Postgraduate Fellowship, FJFM and RKR are funded by an Australian Postgraduate Award, and KAW is supported by an Australian Research Council Future Fellowship. This work was also supported by funding from the Australian Research Council Centre of Excellence for Environmental Decisions.

References

Abson DJ, Termansen M, Pascual U, Aslam U, Fezzi C, Bateman I (2014) Valuing climate change effects upon UK agricultural GHG emissions: spatial analysis of a regulating ecosystem service. *Environmental and Resource Economics*, **57**, 215–231.

Amer M, Daim TU, Jetter A (2013) A review of scenario planning. *Futures*, **46**, 23–40.

Bagstad KJ, Johnson GW, Voigt B, Villa F (2012) Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. *Ecosystem Services*, **4**, 117–125.

Bateman IJ, Harwood AR, Mace GM *et al.* (2013) Bringing ecosystem services into economic decision-making: land use in the United Kingdom. *Science*, **341**, 45–50.

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15**, 365–377.

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. *Ecology Letters*, **12**, 1394–1404.

Bertsimas D, Pachamanova D (2008) Robust multiperiod portfolio management in the presence of transaction costs. *Computers & Operations Research*, **35**, 3–17.

Brown CJ, Saunders MI, Possingham HP, Richardson AJ (2013) Managing for interactions between local and global stressors of ecosystems. *PLoS One*, **8**, e65765.

Bryan BA (2013) Incentives, land use, and ecosystem services: synthesizing complex linkages. *Environmental Science & Policy*, **27**, 124–134.

Bryan BA, Nolan M, Harwood TD *et al.* (2014) Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Global Environmental Change*, **28**, 166–181.

Bryan BA, Runting RK, Capon T *et al.* (2016) Designer policy for carbon and biodiversity co-benefits under global change. *Nature Climate Change*, **6**, 301–305.

Buch A, Dixon AB (2009) South Africa's working for water programme: searching for win–win outcomes for people and the environment. *Sustainable Development*, **17**, 129–141.

Carpenter SR, Mooney HA, Agard J *et al.* (2009) Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 1305–1312.

Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N (2014) A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4**, 287–291.

Chan KMA, Guerry AD, Balvanera P *et al.* (2012) Where are cultural and social in ecosystem services? A framework for constructive engagement. *BioScience*, **62**, 744–756.

Chapman S, Mustin K, Renwick AR, Segan DB, Hole DG, Pearson RG, Watson JEM (2014) Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales (ed Richardson D). *Diversity and Distributions*, **20**, 1221–1228.

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, **16**, 24–35.

Christie M, Fazey I, Cooper R, Hyde T, Kenter JO (2012) An evaluation of monetary and non-monetary techniques for assessing the importance of biodiversity and ecosystem services to people in countries with developing economies. *Ecological Economics*, **83**, 67–78.

Connor JD, Bryan BA, Nolan M *et al*. (2015) Modelling Australian land use competition and ecosystem services with food price feedbacks at high spatial resolution. *Environmental Modelling & Software*, **69**, 141–154.

Daily GC, Polasky S, Goldstein J *et al*. (2009) Ecosystem services in decision making: time to deliver. *Frontiers in Ecology and the Environment*, **7**, 21–28.

Dobrowski SZ, Abatzoglou J, Swanson AK, Greenberg JA, Mynsberge AR, Holden ZA, Schwartz MK (2013) The climate velocity of the contiguous United States during the 20th century. *Global Change Biology*, **19**, 241–251.

Doherty JM, Miller JF, Prellwitz SG, Thompson AM, Loheide SP, Zedler JB (2014) Hydrologic regimes revealed bundles and tradeoffs among six wetland services. *Ecosystems*, **17**, 1026–1039.

Eigenbrod F, Armsworth PR, Anderson BJ *et al*. (2010a) Error propagation associated with benefits transfer-based mapping of ecosystem services. *Biological Conservation*, **143**, 2487–2493.

Eigenbrod F, Armsworth PR, Anderson BJ *et al*. (2010b) The impact of proxy-based methods on mapping the distribution of ecosystem services. *Journal of Applied Ecology*, **47**, 377–385.

Fezzi C, Bateman I, Askew T, Munday P, Pascual U, Sen A, Harwood A (2014) Valuing provisioning ecosystem services in agriculture: the impact of climate change on food production in the United Kingdom. *Environmental and Resource Economics*, **57**, 197–214.

Foley JA, Defries R, Asner GP *et al*. (2005) Global consequences of land use. *Science*, **309**, 570–574.

Ford JD, Berrang-Ford L, Paterson J (2011) A systematic review of observed climate change adaptation in developed nations. *Climatic Change*, **106**, 327–336.

Grantham HS, Moilanen A, Wilson KA, Pressey RL, Rebelo TG, Possingham HP (2008) Diminishing return on investment for biodiversity data in conservation planning. *Conservation Letters*, **1**, 190–198.

Gregr EJ, Chan KMA (2014) Leaps of faith: how implicit assumptions compromise the utility of ecosystem models for decision-making. *BioScience*, **65**, 43–54.

Grêt-Regamey A, Brunner S, Altwegg J, Christen M, Bebi P (2013) Integrating expert knowledge into mapping ecosystem services trade-offs for sustainable forest management. *Ecology and Society*, **18**, 34.

de Groot RS, Wilson MA, Boumans RMJ (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, **41**, 393–408.

de Groot RS, Alkemade R, Braat L, Hein L, Willemen L (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, **7**, 260–272.

Grossmann M, Dietrich O (2012) Integrated economic-hydrologic assessment of water management options for regulated wetlands under conditions of climate change: a case study from the Spreewald (Germany). *Water Resources Management*, **26**, 2081–2108.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change*, **19**, 240–247.

IPCC (2013) Climate change 2013: the physical science basis. In: *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM), Cambridge University Press, Cambridge, UK and New York, NY.

IPCC (2014) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. In: *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Field CB, Barros V., Dokken DJ, Mach K., Mastrandrea M., Bilir T., Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White L). Cambridge University Press, Cambridge, UK and New York, NY.

Jung IW, Bae DH, Lee BJ (2013) Possible change in Korean streamflow seasonality based on multi-model climate projections. *Hydrological Processes*, **27**, 1033–1045.

Lempert RJ, Sriver RL, Keller K (2012) Characterizing uncertain sea level rise projections to support investment decisions, California Energy Commission, Santa Monica.

Lindeskog M, Arneth A, Bondeau A, Waha K, Seaquist J, Olin S, Smith B (2013) Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. *Earth System Dynamics*, **4**, 385–407.

Liss KN, Mitchell MG, MacDonald GK *et al*. (2013) Variability in ecosystem service measurement: a pollination service case study. *Frontiers in Ecology and the Environment*, **11**, 414–422.

Lu M, Zhou X, Yang Q *et al*. (2013) Responses of ecosystem carbon cycle to experimental warming: a meta-analysis. *Ecology*, **94**, 726–738.

Luo Y, Hui D, Zhang D (2006) Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis. *Ecology*, **87**, 53–63.

Mantyka-Pringle CS, Martin TG, Rhodes JR (2012) Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Global Change Biology*, **18**, 1239–1252.

Martin TG, Burgman MA, Fidler F, Kuhnert PM, Low-Choy S, McBride M, Mengersen K (2012) Eliciting expert knowledge in conservation science. *Conservation Biology*, **26**, 29–38.

Martinez-Harms MJ, Bryan BA, Balvanera P, Law EA, Rhodes JR, Possingham HP, Wilson KA (2015) Making decisions for managing ecosystem services. *Biological Conservation*, **184**, 229–238.

Matthews SN, Iverson LR, Peters MP, Prasad AM, Subburayalu S (2013) Assessing and comparing risk to climate changes among forested locations: implications for ecosystem services. *Landscape Ecology*, **29**, 213–228.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: A Framework for Assessment*. Island Press, Washington, DC.

Mooney H, Larigauderie A, Cesario M *et al*. (2009) Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, **1**, 46–54.

Müller C, Waha K, Bondeau A, Heinke J (2014) Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. *Global Change Biology*, **20**, 2505–2517.

Oliveira LJC, Costa MH, Soares-Filho BS, Coe MT (2013) Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environmental Research Letters*, **8**, 024021.

Pacifici M, Foden WB, Visconti P *et al*. (2015) Assessing species vulnerability to climate change. *Nature Climate Change*, **5**, 215–224.

Pannell DJ (2006) Flat earth economics: the far-reaching consequences of flat payoff functions in economic decision making. *Review of Agricultural Economics*, **28**, 553–566.

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. *Trends in Ecology & Evolution*, **24**, 497–504.

Plummer ML (2009) Assessing benefit transfer for the valuation of ecosystem services. *Frontiers in Ecology and the Environment*, **7**, 38–45.

Poiani KA, Goldman RL, Hobson J, Hoekstra JM, Nelson KS (2010) Redesigning biodiversity conservation projects for climate change: examples from the field. *Biodiversity and Conservation*, **20**, 185–201.

Poirier M, Durand J-L, Volaire F (2012) Persistence and production of perennial grasses under water deficits and extreme temperatures: importance of intraspecific vs. interspecific variability. *Global Change Biology*, **18**, 3632–3646.

Polasky S, Carpenter SR, Folke C, Keeler B (2011) Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology & Evolution*, **26**, 398–404.

Raulier F, Dhital N, Racine P, Tittler R, Fall A (2014) Increasing resilience of timber supply: how a variable buffer stock of timber can efficiently reduce exposure to shortfalls caused by wildfires. *Forest Policy and Economics*, **46**, 47–55.

Reed MS (2008) Stakeholder participation for environmental management: a literature review. *Biological Conservation*, **141**, 2417–2431.

Refsgaard JC, van der Sluijs JP, Højberg AL, Vanrolleghem PA (2007) Uncertainty in the environmental modelling process – a framework and guidance. *Environmental Modelling & Software*, **22**, 1543–1556.

Regan HM, Ben-Haim Y, Langford B, Wilson WG, Lundberg P, Andelman SJ, Burgman MA (2005) Robust decision-making under severe uncertainty for conservation management. *Ecological Applications*, **15**, 1471–1477.

Rosenzweig C, Elliott J, Deryng D *et al*. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 3268–3273.

Runting RK, Wilson KA, Rhodes JR (2013) Does more mean less? The value of information for conservation planning under sea level rise. *Global Change Biology*, **19**, 352–363.

Runting RK, Lovelock CE, Beyer HL, Rhodes JR (2016) Costs and opportunities for preserving coastal wetlands under sea level rise. *Conservation Letters*.

Saulnier-Talbot É, Gregory-Eaves I, Simpson KG, Efitre J, Nowlan TE, Taranu ZE, Chapman LJ (2014) Small changes in climate can profoundly alter the dynamics and ecosystem services of tropical crater lakes. *PLoS One*, **9**, e86561.

Schaldach R, Wimmer F, Koch J, Volland J, Geissler K, Köchy M (2013) Model-based analysis of the environmental impacts of grazing management on Eastern Mediterranean ecosystems in Jordan. *Journal of Environmental Management*, **127**, S84–S95.

Scholes RJ (2016) Climate change and ecosystem services. *Wiley Interdisciplinary Reviews: Climate Change*, **7**, 537–550 Early view.

Seidl R, Rammer W, Lexer MJ (2011) Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps. *Canadian Journal of Forest Research*, **41**, 694–706.

Shackleton S, Shanley P, Ndoye O (2007) Invisible but viable: recognising local markets for non-timber forest products. *International Forestry Review*, **9**, 697–712.

Srinivasan UT (2011) Economics of climate change: risk and responsibility by world region. *Climate Policy*, **10**, 298–316.

Staudt A, Leidner AK, Howard J *et al*. (2013) The added complications of climate change: understanding and managing biodiversity and ecosystems. *Frontiers in Ecology and the Environment*, **11**, 494–501.

Steenberg JWN, Duinker PN, Bush PG (2011) Exploring adaptation to climate change in the forests of central Nova Scotia, Canada. *Forest Ecology and Management*, **262**, 2316–2327.

Tallis H, Mooney H, Andelman S *et al*. (2012) A global system for monitoring ecosystem service change. *BioScience*, **62**, 977–986.

TEEB (2010) *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. Progress Press, Malta.

Tylianakis JM, Didham RK, Bascompte J, Wardle DA (2008) Global change and species interactions in terrestrial ecosystems. *Ecology Letters*, **11**, 1351–1363.

van Vuuren DP, Lucas PL, Hilderink H (2007) Downscaling drivers of global environmental change: enabling use of global SRES scenarios at the national and grid levels. *Global Environmental Change*, **17**, 114–130.

Wallace KJ (2007) Classification of ecosystem services: problems and solutions. *Biological Conservation*, **139**, 235–246.

Yousefpour R, Jacobsen JB, Thorsen BJ, Meilby H, Hanewinkel M, Oehler K (2012) A review of decision-making approaches to handle uncertainty and risk in adaptive forest management under climate change. *Annals of Forest Science*, **69**, 1–15.

Yvon-Durocher G, Jones JI, Trimmer M, Woodward G, Montoya JM (2010) Warming alters the metabolic balance of ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **365**, 2117–2126.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Methods.
Table S1. Correlations (Cramer's V) among categorical explanatory variables used in the cumulative logit mixed model.
Table S2. Regression coefficients and *P*-values from the cumulative logit mixed model with only the ecosystem service category and methods used as the explanatory variables.
Table S3. Regression coefficients and *P*-values from the saturated cumulative logit mixed model.
Table S4. The structured questions used to extract data from the journal articles, with answer categories.
Figure S1. Decision making for ecosystem services under climate change.