



HAL
open science

Biodiversity scenarios neglect future land-use changes

Nicolas Titeux, Klaus Henle, Jean-Baptiste Mihoub, Adrian Regos, Ilse R. Geizendorffer, Wolfgang Cramer, Peter H. Verburg, Lluís Brotons

► **To cite this version:**

Nicolas Titeux, Klaus Henle, Jean-Baptiste Mihoub, Adrian Regos, Ilse R. Geizendorffer, et al.. Biodiversity scenarios neglect future land-use changes. *Global Change Biology*, 2016, 22 (7), pp.2505–2515. 10.1111/gcb.13272 . hal-01444016

HAL Id: hal-01444016

<https://hal.science/hal-01444016>

Submitted on 12 Apr 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Received Date : 20-Nov-2015s

Revised Date : 25-Feb-2016

Accepted Date : 29-Feb-2016

Article type : Opinion

Title

Biodiversity scenarios neglect future land use changes

Running head

Land use changes and biodiversity scenarios

Authors

Nicolas Titeux^{1,2,3*}, Klaus Henle⁴, Jean-Baptiste Mihoub^{4,5}, Adrián Regos^{1,3}, Ilse R. Geijzendorffer⁶, Wolfgang Cramer⁶, Peter H. Verburg⁷ & Lluís Brotons^{1,3,8}

Author affiliations

1. European Bird Census Council (EBCC) and Forest Sciences Centre of Catalonia (CEMFOR-CTFC), InForest Joint Research Unit (CSIC-CTFC-CREAF), Ctra. Sant Llorenç de Morunys km 2, 25280 Solsona, Spain
2. Université catholique de Louvain (UCL), Earth and Life Institute, Croix du Sud 2, 1348 Louvain-la-Neuve, Belgium
3. Centre de Recerca Ecològica i Aplicacions Forestals (CREAF), 08193 Cerdanyola del Vallés, Spain
4. UFZ-Helmholtz Centre for Environmental Research, Department of Conservation Biology, Permoserstr. 15, 04318 Leipzig, Germany
5. Université Pierre et Marie Curie, CESCO, UMR 7204 MNHN-CNRS-UPMC, Paris, France

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/gcb.13272

This article is protected by copyright. All rights reserved.

6. Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale (IMBE), Aix
Marseille Université, CNRS, IRD, Avignon Université, Bâtiment Villemin, Technopôle Arbois-
Méditerranée, BP 80, 13545 Aix-en-Provence cedex 04, France
7. VU University Amsterdam, Department of Earth Sciences, De Boelelaan 1087, 1081 HV
Amsterdam, The Netherlands
8. Consejo Superior de Investigaciones Científicas (CSIC), 08193 Cerdanyola del Vallés, Spain

***Corresponding author**

Nicolas Titeux, Forest Sciences Centre of Catalonia (CEMFOR-CTFC), Ctra. Sant Llorenç de
Morunys, km 2, E-25280 Solsona, Spain. E-mail: nicolas.titeux@ctfc.es, fax: +34 973480431, phone:
+34 973481752

Keywords

Biodiversity projections, climate change, ecological forecasting, land cover change, land system
science, predictive models, species distribution models, storylines

Paper type

Opinion

Abstract

Efficient management of biodiversity requires a forward-looking approach based on scenarios that
explore biodiversity changes under future environmental conditions. A number of ecological models
have been proposed over the last decades to develop these biodiversity scenarios. Novel modelling
approaches with strong theoretical foundation now offer the possibility to integrate key ecological and
evolutionary processes that shape species distribution and community structure. Although biodiversity
is affected by multiple threats, most studies addressing the effects of future environmental changes on
biodiversity focus on a single threat only. We examined the studies published during the last 25 years
that developed scenarios to predict future biodiversity changes based on climate, land use and land

cover change projections. We found that biodiversity scenarios mostly focus on the future impacts of climate change and largely neglect changes in land use and land cover. The emphasis on climate change impacts has increased over time and has now reached a maximum. Yet, the direct destruction and degradation of habitats through land use and land cover changes are among the most significant and immediate threats to biodiversity. We argue that the current state of integration between ecological and land system sciences is leading to biased estimation of actual risks and therefore constrains the implementation of forward-looking policy responses to biodiversity decline. We suggest research directions at the crossroads between ecological and environmental sciences to face the challenge of developing interoperable and plausible projections of future environmental changes and to anticipate the full range of their potential impacts on biodiversity. An intergovernmental platform is needed to stimulate such collaborative research efforts and to emphasize the societal and political relevance of taking up this challenge.

Introduction

Biodiversity plays an important role in the provision of ecosystem functions and services (Mace *et al.*, 2012; Bennett *et al.*, 2015; Oliver *et al.*, 2015a). Yet, it is undergoing important decline worldwide due to human-induced environmental changes (Collen *et al.*, 2009; Pimm *et al.*, 2014). Governance and anticipative management of biodiversity require plausible scenarios of expected changes under future environmental conditions (Sala *et al.*, 2000; Pereira *et al.*, 2010; Larigauderie *et al.*, 2012). A forward-looking approach is essential because drivers of biodiversity decline and their associated impacts change over time. In addition, delayed mitigation efforts are likely more costly and time-consuming than early action and often fail to avoid a significant part of the ecological damage (Cook *et al.*, 2014; Oliver & Roy, 2015). Hence, biodiversity scenarios are on the agenda of international conventions, platforms and programmes for global biodiversity conservation, such as the Convention on Biological Diversity (CBD) and the Intergovernmental Platform for Biodiversity & Ecosystem Services (IPBES) (Leadley *et al.*, 2010, 2014; Secretariat of the Convention on Biological Diversity, 2014; Díaz *et al.*, 2015; Kok *et al.*, 2016).

An increasing number of ecological models have been proposed over the last decades to develop biodiversity scenarios (Evans *et al.*, 2013; Kerr & Dobrowski, 2013; Thuiller *et al.*, 2013). They integrate and predict the effects of the two main factors that will determine the future of biodiversity: (1) the nature, rate and magnitude of expected changes in environmental conditions and (2) the capacity of organisms to deal with these changing conditions through a range of ecological and evolutionary processes (Figure 1). Most modelling approaches rely on strong assumptions about the key processes that shape species distribution, abundance, community structure or ecosystem functioning (Kearney & Porter, 2009; Evans, 2012; Thuiller *et al.*, 2013), with only few studies considering the adaptation potential of the species. Hence, recent work has mainly focused on improving the theoretical foundation of ecological models (Evans *et al.*, 2013; Thuiller *et al.*, 2013; Harfoot *et al.*, 2014a; Zurell *et al.*, 2016).

Yet, the credibility of developed biodiversity scenarios remains severely limited by the assumptions used to integrate the expected changes in environmental conditions into the ecological models.

Biodiversity scenarios draw upon narratives (storylines) of environmental change that project plausible socio-economic developments or particularly desirable future pathways under specific policy options and strategies (van Vuuren *et al.*, 2012; O'Neill *et al.*, 2015) (Figure 1). Although biodiversity is affected by multiple interacting driving forces (Millennium Ecosystem Assessment, 2005; Mantyka-Pringle *et al.*, 2012; Settele & Wiemers, 2015), most biodiversity scenarios are based on environmental change projections that represent a single threat only (Bellard *et al.*, 2015). With a literature survey on the biodiversity scenarios published during the last 25 years, we show here a dominant use of climate change projections and a relative neglect of future changes in land use and land cover. The emphasis on the impacts of climate change reflects the urgency to deal with this threat as it emerges from studies, data and reports such as those produced by the Intergovernmental Panel on Climate Change (IPCC) (Tingley *et al.*, 2013; Settele *et al.*, 2014). The direct destruction or degradation of habitats are, however, among the most significant threats to biodiversity to date (Millennium Ecosystem Assessment, 2005; Leadley *et al.*, 2014; Newbold *et al.*, 2015, 2016) and not including them raises concerns for the credibility of biodiversity scenarios. Habitat destruction and

degradation result from both changes in the type of vegetation or human infrastructures that cover the land surface (i.e. land cover) and changes in the manner in which humans exploit and manage the land cover (i.e. land use) (Verburg *et al.*, 2012; van Asselen & Verburg, 2013). The lack of coherent and interoperable environmental change projections that integrate climate, land use and land cover across scales constitutes a major research gap that impedes the development of credible biodiversity scenarios and the implementation of efficient forward-looking policy responses to biodiversity decline. We identify key research challenges at the crossroads between ecological and environmental sciences, and we provide recommendations to overcome this gap.

Climate and land use/cover changes are important drivers of biodiversity decline

Biodiversity decline results from a number of human-induced drivers of change, including land use/cover change, climate change, pollution, overexploitation and invasive species (Pereira *et al.*, 2012; Leadley *et al.*, 2014). Ostberg *et al.* (2015) have recently estimated that climate and land use/cover changes have now reached a similar level of pressure on the biogeochemical and vegetation-structural properties of terrestrial ecosystems across the globe, but during the last three centuries land use/cover change has exposed 1.5 times as many areas to significant modifications as climate change. The relative impacts of these driving forces on biodiversity have also been assessed at the global scale. In its volume on state and trends, the Millennium Ecosystem Assessment (2005) reported that land use/cover change in terrestrial ecosystems has been the most important direct driver of changes in biodiversity and ecosystem services in the past 50 years. Habitat destruction or degradation due to land use/cover change constitute an on-going threat in 44.8% of the vertebrate populations included in the Living Planet Index (WWF, 2014) for which threats have been identified, whereas climate change is a threat in only 7.1% of them. A query performed on the website of the IUCN Red List of Threatened species (assessment during the period 2000-2015) indicates that more than 85% of the vulnerable or (critically) endangered mammal, bird and amphibian species in terrestrial ecosystems are affected by habitat destruction or degradation (i.e. residential and commercial development, agriculture and aquaculture, energy production and mining, transportation and service corridors, and natural system modification) and less than 20% are affected by climate

change and severe weather conditions (see also Pereira *et al.*, 2012). Interactions between multiple driving forces, such as climate, land use and land cover changes, may further push ecological systems beyond tipping points (Mantyka-Pringle *et al.*, 2012; Oliver & Morecroft, 2014) and are key to understanding biodiversity dynamics under changing environmental conditions (Travis, 2003; Forister *et al.*, 2010; Staudt *et al.*, 2013; Mantyka-Pringle *et al.*, 2015).

Emphasis on climate change impacts in biodiversity scenarios

Available projections of climate and land use/cover changes (van Vuuren *et al.*, 2012; O'Neill *et al.*, 2015) are used to inform on future environmental conditions for biodiversity across a variety of spatial and temporal scales (de Chazal & Rounsevell, 2009) (Figure 1). Many studies have predicted the consequences of expected climate change on biodiversity (Bellard *et al.*, 2012; Staudinger *et al.*, 2013; Pacifici *et al.*, 2015). For instance, future climate change is predicted to induce latitudinal or altitudinal shifts in species ranges with important effects on ecological communities (Maes *et al.*, 2010; Barbet-Massin & Jetz, 2015), to increase the risks of species extinction (Thomas *et al.*, 2004; Urban, 2015) or to reduce the effectiveness of conservation areas (Araújo *et al.*, 2011). Projections of land use/cover change have been used to predict future changes in suitable habitats for a number of species (Martinuzzi *et al.*, 2015; Newbold *et al.*, 2015), to predict future plant invasions (Chytrý *et al.*, 2012), to estimate potential future extinctions in biodiversity hotspots (Jantz *et al.*, 2015) or to highlight the restricted potential for future expansion of protected areas worldwide (Pouzols *et al.*, 2014). Visconti *et al.* (2015) estimated the coverage of suitable habitats for terrestrial mammals under future land use/cover change and based on global protected areas expansion plans. They showed that such plans might not constitute the most optimal conservation action for a large proportion of the studied species and that alternative strategies focusing on the most threatened species will be more efficient.

Climate and land use/cover change projections have also been combined in the same modelling framework to address how climate change will interplay with land use/cover change in driving the future of biodiversity (Jetz *et al.*, 2007; Martin *et al.*, 2013; Ay *et al.*, 2014; Saltré *et al.*, 2015; Visconti *et al.*, 2016). For instance, future refuge areas for orang-utans have been identified in Borneo

under projected climate change, deforestation and suitability for oil-palm agriculture (Struebig *et al.*, 2015). Alkemade *et al.* (2009) used land use/cover change, climate change and projections of other driving forces to predict the future impacts of different global-scale policy options on the composition of ecological communities. Recently, it has been shown that the persistence of drought-sensitive butterfly populations under future climate change may be significantly improved if semi-natural habitats are restored to reduce fragmentation (Oliver *et al.*, 2015b).

We searched published literature from 1990 to 2014 to estimate the yearly number of studies that developed biodiversity scenarios based on climate change projections, land use/cover change projections or the combination of both types of projections. A list of 2,313 articles was extracted from the search procedure described in Table 1. We expected a number of articles within this list would only weakly focus on the development of biodiversity scenarios based on climate and/or land use/cover change projections and therefore, we randomly sampled articles within this list (sample size: N=300). We then carefully checked their titles and abstracts to allocate each of them to one of the following categories:

1. Article reporting on the development of biodiversity scenarios based only on climate change projections
2. Article reporting on the development of biodiversity scenarios based only on land use/cover change projections
3. Article reporting on the development of biodiversity scenarios based on the use of climate and land use/cover change projections
4. Article reporting on the development of biodiversity scenarios based on other types of environmental change projections
5. Article not reporting on the actual development of biodiversity scenarios

We considered that articles reported on the development of biodiversity scenarios when they produced predictions of the response of biodiversity to future changes in environmental conditions.

We calculated for each year between 1990 and 2014 the proportions of studies allocated to each of the five categories among the random sample of articles. We used a window size of 5 years and we calculated two-sided moving averages of the yearly proportions along the 25-year long time series. With this approach, we smoothed out short-term fluctuations due to the limited sample size and we highlighted the long-term trend in the proportions of articles allocated to the different categories.

We used these smoothed proportions estimated from the sample of articles and the total number of 2,313 articles extracted from the search procedure to estimate the yearly numbers of articles during 1990-2014 that reported on the development of biodiversity scenarios and that used climate change projections (category 1), land use/cover change projections (category 2) and both types of environmental change projections (category 3).

Our survey revealed that the number of studies that have included the expected impacts of future land use/cover change on biodiversity falls behind in comparison with the number of studies that have focused on the effects of future climate change (Figure 2). Among the studies published during the period 1990-2014 and that drew upon at least one of these two driving forces to develop biodiversity scenarios, we estimated that 85.2% made use of climate change projections alone and that 4.1% used only projections of land use/cover change. Climate and land use/cover change projections were combined in 10.7% of the studies. A sensitivity analysis was carried out and indicates that the number of articles for which we checked the titles and abstracts was sufficient to reflect those proportions in a reliable way (Appendix S1 and Figure S1). The imbalance between the use of climate and land use/cover change projections has increased over time in the last 25 years and has now reached a maximum (Figure 2).

Where biodiversity scenarios lack credibility

Disregarding future changes in land use or land cover when developing biodiversity scenarios assumes that their effects on biodiversity will be negligible compared to the impacts of climate change. Two main reasons are frequently brought forward when omitting to include the effects of land use/cover change in biodiversity scenarios: (1) the available representations of future land use/cover

change are considered unreliable or irrelevant for addressing the future of biodiversity (e.g. Stanton *et al.*, 2012) and (2) climate change could outpace land use and land cover as the greatest threat to biodiversity in the next decades (e.g. Bellard *et al.*, 2012). Here, we build on these two lines of arguments to discuss the lack of credibility of assuming unchanged land use/cover in biodiversity scenarios and to stress the need for further development of land use/cover change projections.

Available large-scale land use/cover change projections are typically associated with a relatively coarse spatial resolution and a simplified thematic representation of the land surface (Verburg *et al.*, 2012). This is largely due to the fact that most of these projections have been derived from integrated assessment models which simulate expected changes in the main land cover types and their impacts on climate through emission of greenhouse gases (de Chazal & Rounsevell, 2009; Verburg *et al.*, 2012; Harfoot *et al.*, 2014b). A strong simplification of the representation of land use and land cover is inevitable due to the spatial extent and computational complexity of these models. Some studies have implemented downscaling methods based on spatial allocation rules to improve the representation of landscape composition in large-scale projections (Verburg *et al.*, 2006). Because their primary objective is to respond to the pressing need to assess future changes in climatic conditions and to explore climate change mitigation options, such downscaled projections use, however, only a small number of land cover types and are, consequently, of limited relevance for addressing the full impact of landscape structure and habitat fragmentation on biodiversity (de Chazal & Rounsevell, 2009; Verburg *et al.*, 2012; Harfoot *et al.*, 2014b).

In addition, much of land system science has focused on conversions between land cover types (e.g. from forest to open land through deforestation), but little attention has been paid to capture some of the most important dimensions of change for biodiversity that result from changes in land use within – and not only between – certain types of land cover (de Chazal & Rounsevell, 2009; van Asselen & Verburg, 2013; Stürck *et al.*, 2015). Changes in land management regimes (e.g. whether grasslands are mown or grazed) and intensity of use (e.g. through wood harvesting or the use of fertilizers, pesticides and irrigation in cultivated areas) are known to strongly impact biodiversity (Pe'er *et al.*, 2014) and are expected to cause unprecedented habitat modifications in the next decades (Laurance,

2001; Tilman, 2001). For instance, management intensification of currently cultivated areas (Meehan *et al.*, 2011) rather than agricultural surface expansion will likely provide the largest contribution to the future increases in agricultural production (van Asselen & Verburg, 2013). These aspects of land use change remain poorly captured and integrated into currently available projections (Rounsevell *et al.*, 2012; Verburg *et al.*, 2012; Stürck *et al.*, 2015). Furthermore, the frequency and sequence of changes in land use and land cover, or the lifespan of certain types of land cover, interact with key ecological processes and determine the response of biodiversity to such changes (Kleyer *et al.*, 2007; Watson *et al.*, 2014). Although methods have become available to represent the dynamics and the expected trajectories of the land system (Rounsevell *et al.*, 2012), these temporal dimensions of change are still rarely incorporated in land use/cover change projections (de Chazal & Rounsevell, 2009; Harfoot *et al.*, 2014b).

This lack of integration between ecological and land system sciences limits the ability to make credible evaluations of the future response of biodiversity to land use and land cover changes in interaction with climate change (de Chazal & Rounsevell, 2009; Harfoot *et al.*, 2014b). In turn, this makes it hazardous to speculate that the expected rate and magnitude of climate change will downplay the effects of land use/cover change on biodiversity in the future. There is no consensus on how the strength of future climate change impact should be compared to that of other threats such as changes in land use and land cover (Tingley *et al.*, 2013). Some of the few studies that included the combined effect of both types of drivers in biodiversity scenarios have stressed that, although climate change will severely affect biodiversity at some point in the future, land use/cover change may lead to more immediate and even greater biodiversity decline in some terrestrial ecosystems (Jetz *et al.*, 2007; Pereira *et al.*, 2010; Visconti *et al.*, 2016). For example, considerable habitat loss is predicted in some regions during the next few decades due to increasing pressures to convert natural habitats into agricultural areas (Lambin & Meyfroidt, 2011). The rapid conversion of tropical forests and natural grasslands for agriculture, timber production and other land uses (Laurance & Edwards, 2014) is expected to have more significant impacts on biodiversity than climate in the near future (Jetz *et al.*, 2007; Laurance *et al.*, 2012). Again, most of these studies focused on changes

that will emerge from conversions between different types of land cover and only few of them addressed the future impacts of land use change within certain types of land cover. For instance, the distribution changes of broad habitat types were predicted under future climate, land use and CO₂ change projections in Europe and it was shown that land use change is expected to have the greatest effects in the next few decades (Lehsten *et al.*, 2015). In this region, effects of land use change might lead to both a loss and a gain of habitats benefitting different aspects of biodiversity. This will likely happen through parallel processes of intensification and abandonment of agriculture that offer potential for recovering wilderness areas (Henle *et al.*, 2008; Queiroz *et al.*, 2014). These immediate effects of land use/cover changes on biodiversity deserve further attention with regard to the ecological forecast horizon, i.e. how far into the future useful predictions can be made (Petchey *et al.*, 2015). Immediate changes in land use/cover may significantly alter the ability of ecological systems to deal with the impacts of climate change that are expected to be increasingly severe in the future (Tingley *et al.*, 2013). Hence, ecological predictions that neglect the immediate effects of land use/cover changes and only focus on the effects of climate change in a distant future may be largely uncertain. It is therefore needed to identify appropriate time horizons for biodiversity scenarios, with increased reliance on those associated with greater predictability and higher policy relevance (Petchey *et al.*, 2015).

Climate change will exert severe impacts on the land system, but the way humans are managing the land will also influence climatic conditions, so that both processes interact with each other. For instance, deforestation and forest management constitute a major source of carbon loss with direct impacts on the carbon cycle and indirect effects on climate (Pütz *et al.*, 2014; Naudts *et al.*, 2016).

Climate change mitigation strategies include important modifications of the land surface such as the increased prevalence of biofuel crops. This mitigation action may pose some conflicts between important areas for biodiversity conservation and bioenergy production (Alkemade *et al.*, 2009; Fletcher *et al.*, 2011; Meller *et al.*, 2015). In integrated assessment models or other global land use models, such interactions are often restricted to impacts of climate change on crop productivity and shifts in potential production areas. These models neglect a wide range of human adaptive responses

to climate change in the land system (Rounsevell *et al.*, 2014), such as spatial displacement of activities (Lambin & Meyfroidt, 2011) that may pose a significant threat to biodiversity (Estes *et al.*, 2014). Increased attention to the feedback effects between climate and land use/cover changes is therefore needed to help assessing the full range of consequences of the combined impacts of these driving forces on biodiversity in the future.

Both climate and land use/cover changes are constrained or driven by large-scale forces linked to economic globalization, but the actual changes in land use/cover are largely determined by local factors (Lambin *et al.*, 2001; Lambin & Meyfroidt, 2011; Rounsevell *et al.*, 2012). Modifications in the land system are highly location-dependent and a reflection of the local biophysical and socio-economic constraints and opportunities (Rounsevell *et al.*, 2014). In Europe, observed changes in agricultural practices in response to increased market demands and globalization of commodity markets include the intensification of agriculture, the abandonment of marginally productive areas, and the changing scale of agricultural operations. These processes occur at the same time but at different locations across the continent (Henle *et al.*, 2008; Stürck *et al.*, 2015; van Vliet *et al.*, 2015). Hence, land use/cover change and its impacts on biodiversity are highly scale-sensitive processes: they show strongly marked contrasts from one location to the other (Tzanopoulos *et al.*, 2013). Many subtle changes that are locally or regionally significant for biodiversity may be seriously underestimated in the available land use/cover change projections because they are occurring below the most frequently used spatial, temporal and thematic resolution of analysis in large-scale land use models (de Chazal & Rounsevell, 2009). Most statistical downscaling approaches based on spatial allocation rules neglect such scale-sensitivity issues and therefore fail to represent landscape composition and structure to appropriately address the local or regional impacts of land use/cover changes on biodiversity (Verburg *et al.*, 2012).

A multi-scale, integrated approach is therefore required to unravel the relative and interacting roles of climate, land use and land cover in determining the future of biodiversity across a range of temporal and spatial scales. A good example of this need is the prediction of the impacts of changes in

disturbance regimes, such as fire, for which idiosyncratic changes may be expected in particular combinations of future climate and land use/cover changes (Brotons *et al.*, 2013; Regos *et al.*, 2016).

A way forward for biodiversity scenarios

Most large-scale land cover change projections are derived from integrated assessment models. They are coherent to some extent with climate change projections because they are based on the same socio-economic storylines. This coherence is useful for studying the interplay between different driving forces. Integrated assessment models capture human energy use, industrial development, agriculture and main land cover changes within a single modelling framework. However, their original, primary objective is to provide future predictions of greenhouse gas emissions. It is therefore important to recognise that these models are not designed to describe the most relevant aspects of land use and land cover changes for (changes in) biodiversity (de Chazal & Rounsevell, 2009; Harfoot *et al.*, 2014b). Here, we provide two recommendations to increase the ecological relevance of land use/cover change projections: (1) reconciling local and global land use/cover modelling approaches and (2) incorporating important ecological processes in land use/cover models.

Novel and flexible downscaling and upscaling methods to reconcile global-, regional- and local-scale land use modelling approaches are critically required and constitute one of the most burning issues in land system science (Letourneau *et al.*, 2012; Rounsevell *et al.*, 2012; Verburg *et al.*, 2012). An important part of the land use modelling community focuses on the development of modelling and simulation approaches at local to regional scales where human decision-making and land use/cover change processes are incorporated explicitly (Rounsevell *et al.*, 2014). These models offer potential to include a more detailed representation of land use/cover trajectories than integrated assessment models. Beyond the classification of dominant land cover types, they inform on land use, intensity of use, management regimes, and other dimensions of land use/cover changes (van Asselen & Verburg, 2013). An integration of scales will provide the opportunity to better represent the interactions between local trajectories and global dynamics (Kok *et al.*, 2016) and to deal more explicitly with scale-sensitive factors such as land use/cover changes (Tzanopoulos *et al.*, 2013). To achieve this integration, a strengthened connection between ecological and land use modelling communities is

needed as it would ensure that the spatial, temporal and thematic representation of changes in land use models matches with the operational scale at which biodiversity respond to these changes. Harfoot *et al.* (2014b) recently suggested development needs for integrated assessment models and recommended the general adoption of a user-centred approach that would identify why ecologists need land use/cover change projections and how they intend to use them to build biodiversity scenarios. Although we believe such an approach will also be needed to ensure the ecological relevance of integrating the different scales of analysis in land use models, this will only be successful if ecologists increase their use of already available land use/cover change projections and suggest concrete modifications to improve their ecological relevance (de Chazal & Rounsevell, 2009; Martin *et al.*, 2013). To address the scale-sensitivity issue thoroughly, we should also move beyond the current emphasis on large and coarse scale of analysis in global change impact research and increase our recognition for studies examining the local and regional effects of climate and land use/cover changes on biodiversity.

Ecological processes in marine, freshwater or terrestrial ecosystems remain poorly incorporated in existing integrated assessment models and other land use models (Harfoot *et al.*, 2014b). Ecological processes in natural and anthropogenic ecosystems provide essential functions, such as pollination, disease or pest control, nutrient or water cycling and soil stability, that exert a strong influence on land systems through complex mechanisms (Sekercioglu *et al.*, 2004; Klein *et al.*, 2007).

Incorporating these processes at appropriate spatial and temporal scales in land use models constitutes an important challenge, but it would considerably increase the ecological realism of these models and, in turn, their ability to predict emergent behaviour of the future ecosystems and the related biodiversity patterns (Harfoot *et al.*, 2014b). Therefore, we urge the need for strengthened interactions between different scientific communities to identify (1) which ecological processes are relevant in driving land use/cover dynamics and (2) how and at which scales these processes could be incorporated in land use models to predict the trajectories of socio-ecological systems.

A successful implementation of our two recommendations does not solely depend on collaborative scientific efforts, but it also requires societal agreement and acceptance. The dialogue with and engagement of stakeholders, such as policy advisers and NGOs, within a participatory modelling framework (Voinov & Bousquet, 2010) will be key to agreeing on a set of biodiversity-oriented storylines and desirable pathways at relevant spatial and temporal scales for decision-making processes in biodiversity conservation and management. An improved integration of the expertise and knowledge from social science into the development and interpretation of the models may allow a better understanding of likely trajectories of land use/cover changes. Moreover, such an integration would provide a better theoretical understanding and practical use of social-ecological feedback loops in form of policy and management responses to changes in biodiversity and ecosystem services, which in turn will impact future land use decisions and trajectories.

The priority given to investigating future climate change impacts on biodiversity most likely reflects how the climate change community has attracted attention during the last decades. The availability of long-term time series of climatic observations in most parts of the world and the increasing amount of science-based, spatially explicit climatic projections derived from global and regional circulation models have clearly stimulated the development of studies focusing on the impacts of climate change (Tingley *et al.*, 2013; Harfoot *et al.*, 2014b). Under the World Climate Research Programme (WCRP), the working group on coupled modelling has established the basis for climate model diagnosis, validation, inter-comparison, documentation and accessibility (Overpeck *et al.*, 2011). The requirements for climate policy, mediated through the IPCC, have further mobilized the use of a common reference in climate observations and simulations by the scientific community. The set of common future emission scenarios (SRES) released in 2000 (Nakicenovic *et al.*, 2000), the more recent representative concentration pathways (RCPs) (van Vuuren *et al.*, 2011), and the fact that these can be shared easily have played a major role in mobilizing the scientific community to use climate change projections in biodiversity scenarios. Work is underway to facilitate open access to land use/cover change time series and projections, but clear and transparent documentation of land use

model representations, uncertainties and differences is also needed and should be understandable and interpretable by a broad interdisciplinary audience (Harfoot *et al.*, 2014b).

The IPCC has also clearly demonstrated that an independent intergovernmental body is an appropriate platform for attracting the attention of the non-scientific community. Many actors now perceive climate change as an important threat to ecosystem functions and services. This emphasis can be heard in the media and among policy makers, such as during the United Nations conferences on climate change. As a response to the increasing societal and political relevance of climate change, research efforts have been mostly directed towards climate change impact assessments (Herrick *et al.*, 2013). From this observed success of the IPCC and the climate change community, it becomes evident that an independent body is needed for mobilizing the scientific and non-scientific communities to face the significant challenge of developing biodiversity-oriented references for land use and land cover change projections. With its focus on multi-scale, multi-disciplinary approaches, the working programme of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (Inouye, 2014; Díaz *et al.*, 2015; Lundquist *et al.*, 2015) is offering a suitable context to stimulate collaborative efforts for taking up this challenge. In line with Kok *et al.* (2016), we therefore encourage IPBES to strengthen its investment in the development and use of interoperable and plausible projections of environmental changes that will allow to better explore the future of biodiversity.

Conclusion

Neglecting the future impacts of land use and land cover changes on biodiversity and focusing on climate change impacts only is not a credible approach. We are concerned that such an overemphasis on climate change reduces the efficiency of identifying forward-looking policy and management responses to biodiversity decline. However, the current state of integration between ecological and land system sciences impedes the development of a comprehensive and well-balanced research agenda addressing the combined impacts of future climate, land use and land cover changes on biodiversity and ecosystem services. We recommend addressing two key areas of developments to increase the ecological relevance of land use/cover change projections: (1) reconciling local and

global land use/cover modelling approaches and (2) incorporating important ecological processes in land use/cover models. A multi-disciplinary framework and continuing collaborative efforts from different research horizons are needed and will have to build on the efforts developed in recent years by the climate community to agree on a common framework in climate observations and simulations. It is now time to extend these efforts across scales in order to produce reference environmental change projections that embrace multiple pressures such as climate, land use and land cover changes. IPBES offers a timely opportunity for taking up this challenge, but this independent body can only do so if adequate research efforts are undertaken.

Acknowledgements

N.T., K.H., J.B.M., I.R.G., W.C. and L.B. acknowledge support from the EU BON project (no. 308454, FP7-ENV-2012, European Commission, Hoffmann *et al.*, 2014). N.T. and L.B. were also funded by the TRUSTEE project (no. 235175, RURAGRI ERA-NET, European Commission). N.T., A.R. and L.B. were also supported by the FORESTCAST project (CGL2014-59742, Spanish Government). I.R.G. and W.C. contribute to the Labex OT-Med (no. ANR-11-LABX-0061) funded by the French Government through the A*MIDEX project (no. ANR-11-IDEX-0001-02). P.H.V. received funding from the GLOLAND project (no. 311819, FP7-IDEAS-ERC, European Commission). We thank Piero Visconti and one anonymous reviewer for useful comments on a previous version of this paper.

References

- Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M, ten Brink B (2009) GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss. *Ecosystems*, **12**, 374–390.
- Araújo MB, Alagador D, Cabeza M, Nogués-Bravo D, Thuiller W (2011) Climate change threatens European conservation areas. *Ecology Letters*, **14**, 484–492.
- van Asselen S, Verburg PH (2013) Land cover change or land-use intensification: simulating land system change with a global-scale land change model. *Global Change Biology*, **19**, 3648–3667.
- Ay J-S, Chakir R, Doyen L, Jiguet F, Leadley PW (2014) Integrated models, scenarios and dynamics of climate, land use and common birds. *Climatic Change*, **126**, 13–30.
- Barbet-Massin M, Jetz W (2015) The effect of range changes on the functional turnover, structure and diversity of bird assemblages under future climate scenarios. *Global Change Biology*, **21**, 2917–

2928.

- Bellard C, Bertelsmeier C, Leadley PW, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters*, **15**, 365–377.
- Bellard C, Leclerc C, Courchamp F (2015) Combined impacts of global changes on biodiversity across the USA. *Scientific Reports*, **5**, 11828.
- Bennett EM, Cramer W, Begossi A et al. (2015) Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. *Current Opinion in Environmental Sustainability*, **14**, 76–85.
- Brotons L, Aquilué N, de Cáceres M, Fortin M-J, Fall A (2013) How fire history, fire suppression practices and climate change affect wildfire regimes in Mediterranean landscapes. *PLoS ONE*, **8**, e62392.
- de Chazal J, Rounsevell MDA (2009) Land-use and climate change within assessments of biodiversity change: a review. *Global Environmental Change*, **19**, 306–315.
- Chytrý M, Wild J, Pyšek P et al. (2012) Projecting trends in plant invasions in Europe under different scenarios of future land-use change. *Global Ecology and Biogeography*, **21**, 75–87.
- Collen B, Loh J, Whitmee S, McRae L, Amin R, Baillie JEM (2009) Monitoring change in vertebrate abundance: the living planet index. *Conservation Biology*, **23**, 317–327.
- Cook CN, Wintle BC, Aldrich SC, Wintle BA (2014) Using strategic foresight to assess conservation opportunity. *Conservation Biology*, **28**, 1474–1483.
- Díaz S, Demissew S, Carabias J et al. (2015) The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in Environmental Sustainability*, **14**, 1–16.
- Estes LD, Paroz L-L, Bradley BA et al. (2014) Using changes in agricultural utility to quantify future climate-induced risk to conservation. *Conservation Biology*, **28**, 427–437.
- Evans MR (2012) Modelling ecological systems in a changing world. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, **367**, 181–190.
- Evans MR, Bithell M, Cornell SJ et al. (2013) Predictive systems ecology. *Proceedings of the Royal Society of London Series B-Biological Sciences*, **280**, 20131452.
- Fletcher RJ, Robertson BA, Evans J, Doran PJ, Alavalapati JR, Schemske DW (2011) Biodiversity conservation in the era of biofuels: risks and opportunities. *Frontiers in Ecology and the Environment*, **9**, 161–168.
- Forister ML, McCall AC, Sanders NJ et al. (2010) Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. *Proceedings of the National Academy of Sciences of the United States of America*, **107**, 2088–2092.
- Harfoot MJB, Newbold T, Tittensor DP et al. (2014a) Emergent global patterns of ecosystem structure and function from a mechanistic general ecosystem model. *PLoS biology*, **12**, e1001841.
- Harfoot MJB, Tittensor DP, Newbold T, McInerney G, Smith MJ, Scharlemann JPW (2014b) Integrated assessment models for ecologists: the present and the future. *Global Ecology and Biogeography*, **23**, 124–143.

- Henle K, Alard D, Clitherow J et al. (2008) Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe – A review. *Agriculture, Ecosystems & Environment*, **124**, 60–71.
- Herrick JE, Sala OE, Karl JW (2013) Land degradation and climate change: a sin of omission? *Frontiers in Ecology and the Environment*, **11**, 283.
- Hoffmann A, Penner J, Vohland K et al. (2014) Improved access to integrated biodiversity data for science, practice, and policy - the European Biodiversity Observation Network (EU BON). *Nature Conservation*, **6**, 49–65.
- Inouye DW (2014) IPBES: global collaboration on biodiversity and ecosystem services. *Frontiers in Ecology and the Environment*, **12**, 371.
- Jantz SM, Barker B, Brooks TM et al. (2015) Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology*, **29**, 1122–1131.
- Jetz W, Wilcove DS, Dobson AP (2007) Projected impacts of climate and land-use change on the global diversity of birds. *PLoS biology*, **5**, e157.
- Kearney MR, Porter W (2009) Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecology Letters*, **12**, 334–350.
- Kerr JT, Dobrowski SZ (2013) Predicting the impacts of global change on species, communities and ecosystems: it takes time. *Global Ecology and Biogeography*, **22**, 261–263.
- Klein A-M, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society of London Series B-Biological Sciences*, **274**, 303–313.
- Kleyer M, Biedermann R, Henle K et al. (2007) Mosaic cycles in agricultural landscapes of Northwest Europe. *Basic and Applied Ecology*, **8**, 295–309.
- Kok MTJ, Kok K, Peterson GD, Hill R, Agard J, Carpenter SR (2016) Biodiversity and ecosystem services require IPBES to take novel approach to scenarios. *Sustainability Science*, **in press**, doi: 10.1007/s11625-016-0354-8.
- Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 3465–3472.
- Lambin EF, Turner BL, Geist HJ et al. (2001) The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change*, **11**, 261–269.
- Larigauderie A, Prieur-Richard A-H, Mace GM et al. (2012) Biodiversity and ecosystem services science for a sustainable planet: the DIVERSITAS vision for 2012-20. *Current opinion in environmental sustainability*, **4**, 101–105.
- Laurance WF (2001) Future shock: forecasting a grim fate for the Earth. *Trends in Ecology & Evolution*, **16**, 531–533.
- Laurance WF, Edwards D (2014) Saving logged tropical forests. *Frontiers in Ecology and the Environment*, **12**, 147.
- Laurance WF, Useche DC, Rendeiro J et al. (2012) Averting biodiversity collapse in tropical forest

protected areas. *Nature*, **489**, 290–294.

Leadley PW, Pereira HM, Alkemade R, Fernandez-Manjarrés JF, Proença V, Scharlemann JPW, Walpole M (2010) *Biodiversity scenarios: projections of 21st century change in biodiversity and associated ecosystem services*. Secretariat of the Convention on Biological Diversity, Montreal, Canada.

Leadley PW, Krug CB, Alkemade R et al. (2014) *Progress towards the Aichi Biodiversity Targets: An Assessment of Biodiversity Trends, Policy Scenarios and Key Actions*. Secretariat of the Convention on Biological Diversity, Montreal, Canada.

Lehsten V, Sykes MT, Scott AV et al. (2015) Disentangling the effects of land-use change, climate and CO₂ on projected future European habitat types. *Global Ecology and Biogeography*, **24**, 653–663.

Letourneau A, Verburg PH, Stehfest E (2012) A land-use systems approach to represent land-use dynamics at continental and global scales. *Environmental Modelling & Software*, **33**, 61–79.

Lundquist CJ, Báldi A, Dieterich M et al. (2015) Engaging the conservation community in the IPBES process. *Conservation Biology*, **29**, 1493–1495.

Mace GM, Norris K, Fitter AH (2012) Biodiversity and ecosystem services: a multilayered relationship. *Trends in Ecology & Evolution*, **27**, 19–26.

Maes D, Titeux N, Hortal J et al. (2010) Predicted insect diversity declines under climate change in an already impoverished region. *Journal of Insect Conservation*, **14**, 485–498.

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.

Mantyka-Pringle CS, Visconti P, Di Marco M, Martin TG, Rondinini C, Rhodes JR (2015) Climate change modifies risk of global biodiversity loss due to land-cover change. *Biological Conservation*, **187**, 103–111.

Martin Y, Van Dyck H, Dendoncker N, Titeux N (2013) Testing instead of assuming the importance of land use change scenarios to model species distributions under climate change. *Global Ecology and Biogeography*, **22**, 1204–1216.

Martinuzzi S, Withey JC, Pidgeon AM et al. (2015) Future land-use scenarios and the loss of wildlife habitats in the southeastern United States. *Ecological Applications*, **25**, 160–171.

Meehan TD, Werling BP, Landis DA, Gratton C (2011) Agricultural landscape simplification and insecticide use in the Midwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 11500–11505.

Meller L, Thuiller W, Pironon S, Barbet-Massin M, Hof A, Cabeza M (2015) Balance between climate change mitigation benefits and land use impacts of bioenergy: conservation implications for European birds. *GCB Bioenergy*, **7**, 741–751.

Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being*. Island Press, Washington, DC.

Nakicenovic N, Alcamo J, Davis G et al. (2000) *Special Report on Emission Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change* (eds

Nakicenovic N, Swart R). Cambridge University Press, Cambridge, UK.

Naudts K, Chen Y, McGrath MJ, Ryder J, Valade A, Otto J, Luysaert S (2016) Europe's forest management did not mitigate climate warming. *Science*, **351**, 597–600.

Newbold T, Hudson LN, Hill SLL et al. (2015) Global effects of land use on local terrestrial biodiversity. *Nature*, **520**, 45–50.

Newbold T, Hudson LN, Hill SLL et al. (2016) Global patterns of terrestrial assemblage turnover within and among land uses. *Ecography*, **accepted**, doi: 10.1111/ecog.01932.

O'Neill BC, Kriegler E, Ebi KL et al. (2015) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **in press**, doi:10.1016/j.gloenvcha.2015.01.004.

Oliver TH, Morecroft MD (2014) Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, **5**, 317–335.

Oliver TH, Roy DB (2015) The pitfalls of ecological forecasting. *Biological Journal of the Linnean Society*, **115**, 767–778.

Oliver TH, Heard MS, Isaac NJB et al. (2015a) Biodiversity and Resilience of Ecosystem Functions. *Trends in Ecology & Evolution*, **30**, 673–684.

Oliver TH, Marshall HH, Morecroft MD, Brereton T, Prudhomme C, Huntingford C (2015b) Interacting effects of climate change and habitat fragmentation on drought-sensitive butterflies. *Nature Climate Change*, **5**, 941–945.

Ostberg S, Schaphoff S, Lucht W, Gerten D (2015) Three centuries of dual pressure from land use and climate change on the biosphere. *Environmental Research Letters*, **10**, 044011.

Overpeck JT, G.A. M, Bony S, Easterling DR (2011) Climate Data Challenges in the 21st Century. *Science*, **331**, 700–702.

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

Pe'er G, Dicks L V, Visconti P et al. (2014) EU agricultural reform fails on biodiversity. *Science*, **344**, 1090–1092.

Pereira HM, Leadley PW, Proença V et al. (2010) Scenarios for global biodiversity in the 21st century. *Science*, **330**, 1496–1501.

Pereira HM, Navarro LM, Martins IS (2012) Global biodiversity change: the bad, the good, and the unknown. *Annual Review of Environment and Resources*, **37**, 25–50.

Petchey OL, Pontarp M, Massie TM et al. (2015) The ecological forecast horizon, and examples of its uses and determinants. *Ecology Letters*, **18**, 597–611.

Pimm SL, Jenkins CN, Abell R et al. (2014) The biodiversity of species and their rates of extinction, distribution, and protection. *Science*, **344**, 1246752.

Pouzols FM, Toivonen T, Di Minin E et al. (2014) Global protected area expansion is compromised by projected land-use and parochialism. *Nature*, **516**, 383–386.

Pütz S, Groeneveld J, Henle K et al. (2014) Long-term carbon loss in fragmented Neotropical forests.

Nature Communications, **5**, 5037.

- Queiroz C, Beilin R, Folke C, Lindborg R (2014) Farmland abandonment: threat or opportunity for biodiversity conservation? A global review. *Frontiers in Ecology and the Environment*, **12**, 288–296.
- Regos A, D’Amen M, Titeux N, Herrando S, Guisan A, Brotons L (2016) Predicting the future effectiveness of protected areas for bird conservation in Mediterranean ecosystems under climate change and novel fire regime scenarios. *Diversity and Distributions*, **22**, 83–96.
- Rounsevell MDA, Pedrolí B, Erb K-H et al. (2012) Challenges for land system science. *Land Use Policy*, **29**, 899–910.
- Rounsevell MDA, Arneth A, Alexander P et al. (2014) Towards decision-based global land use models for improved understanding of the Earth system. *Earth System Dynamics*, **5**, 117–137.
- Sala OE, Chapin III FS, Armesto JJ et al. (2000) Global Biodiversity Scenarios for the Year 2100. *Science*, **287**, 1770–1774.
- Saltré F, Duputié A, Gaucherel C, Chuine I (2015) How climate, migration ability and habitat fragmentation affect the projected future distribution of European beech. *Global Change Biology*, **21**, 897–910.
- Secretariat of the Convention on Biological Diversity (2014) *Global Biodiversity Outlook 4*. Montréal, Canada.
- Sekercioglu CH, Daily GC, Ehrlich PR (2004) Ecosystem consequences of bird declines. *Proceedings of the National Academy of Sciences of the United States of America*, **101**, 18042–18047.
- Settele J, Wiemers M (2015) Biodiversity: Interacting global change drivers. *Nature Climate Change*, **5**, 913–914.
- Settele J, Scholes R, Betts R et al. (2014) Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL), pp. 271–359. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Stanton JC, Pearson RG, Horning N, Ersts P, Reşit Akçakaya H (2012) Combining static and dynamic variables in species distribution models under climate change. *Methods in Ecology and Evolution*, **3**, 349–357.
- Staudinger MD, Carter SL, Cross MS et al. (2013) Biodiversity in a changing climate: a synthesis of current and projected trends in the US. *Frontiers in Ecology and the Environment*, **11**, 465–473.
- 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.
- Struebig MJ, Fischer M, Gaveau DLA et al. (2015) Anticipated climate and land-cover changes reveal refuge areas for Borneo’s orang-utans. *Global Change Biology*, **21**, 2891–2904.
- Stürck J, Levers C, van der Zanden EH et al. (2015) Simulating and delineating future land change

trajectories across Europe. *Regional Environmental Change*, **in press**, doi: 10.1007/s10113-015-0876-0.

- Thomas CD, Cameron A, Green RE et al. (2004) Extinction risk from climate change. *Nature*, **427**, 145–148.
- Thuiller W, Münkemüller T, Lavergne S, Mouillot D, Mouquet N, Schiffrers K, Gravel D (2013) A road map for integrating eco-evolutionary processes into biodiversity models. *Ecology Letters*, **16**, 94–105.
- Tilman D (2001) Forecasting Agriculturally Driven Global Environmental Change. *Science*, **292**, 281–284.
- Tingley MW, Estes LD, Wilcove DS (2013) Climate change must not blow conservation off course. *Nature*, **500**, 271–272.
- Travis JMJ (2003) Climate change and habitat destruction: a deadly anthropogenic cocktail. *Proceedings of the Royal Society of London Series B-Biological Sciences*, **270**, 467–473.
- Tzanopoulos J, Mouttet R, Letourneau A et al. (2013) Scale sensitivity of drivers of environmental change across Europe. *Global Environmental Change*, **23**, 167–178.
- Urban MC (2015) Accelerating extinction risk from climate change. *Science*, **348**, 571–573.
- Verburg PH, Schulp CJE, Witte N, Veldkamp A (2006) Downscaling of land use change scenarios to assess the dynamics of European landscapes. *Agriculture, Ecosystems and Environment*, **114**, 39–56.
- Verburg PH, van Asselen S, van der Zanden EH, Stehfest E (2012) The representation of landscapes in global scale assessments of environmental change. *Landscape Ecology*, **28**, 1067–1080.
- Visconti P, Bakkenes M, Smith RJ, Joppa L, Sykes RE (2015) Socio-economic and ecological impacts of global protected area expansion plans. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, **370**, 20140284.
- Visconti P, Bakkenes M, Baisero D et al. (2016) Projecting Global Biodiversity Indicators under Future Development Scenarios. *Conservation Letters*, **9**, 5–13.
- van Vliet J, de Groot HLF, Rietveld P, Verburg PH (2015) Manifestations and underlying drivers of agricultural land use change in Europe. *Landscape and Urban Planning*, **133**, 24–36.
- Voinov A, Bousquet F (2010) Modelling with stakeholders. *Environmental Modelling & Software*, **25**, 1268–1281.
- van Vuuren DP, Edmonds J, Kainuma M et al. (2011) The representative concentration pathways: an overview. *Climatic Change*, **109**, 5–31.
- van Vuuren DP, Kok MTJ, Girod B, Lucas PL, de Vries B (2012) Scenarios in global environmental assessments: key characteristics and lessons for future use. *Global Environmental Change*, **22**, 884–895.
- Watson SJ, Luck GW, Spooner PG, Watson DM (2014) Land-use change: incorporating the frequency, sequence, time span, and magnitude of changes into ecological research. *Frontiers in Ecology and the Environment*, **12**, 241–249.
- WWF (2014) *Living Planet Report 2014: Species and Spaces, People and Places* (eds McLellan R,

Iyengar L, Jeffries B, Oerlemans N). WWF International, Gland, Switzerland.

Zurell D, Thuiller W, Pagel J et al. (2016) Benchmarking novel approaches for modelling species range dynamics. *Global Change Biology*, **accepted**, doi: 10.1111/gcb.13251.

Supporting Information captions

Appendix S1. Sensitivity analysis to examine the effect of sample size in the literature survey.

Figure S1. Effect of sample size in the literature survey.

Tables

Table 1. Search procedure implemented in the literature survey carried out on the 1st of July 2015 in Web of Science Core Collection (SCI expanded).

Query	Field	Parameters	Motivation
#1	Year	(1990-2014)	Restricts the
			time period of the results to the last 25 years
#2	Topic	(scenari* OR projecti* OR predicti* OR simulati* OR forecast* OR foresight* OR storyline*) AND future*	Captures
			studies addressing predictions in the future
#3	Topic	("climat* chang*" OR "chang* climat*") OR ("land use chang*" OR "land cover chang*" OR "land* chang*")	Identifies
			studies focusing on climate or land use/cover changes

We used Boolean operators “AND” to combine the different queries and we refined the obtained results using “Articles” as *Document Type* and using “Ecology” or “Biodiversity conservation” as *Web of Science Categories*. We also tested if the parameters that we used in the query #3 might potentially underestimate the number of studies focusing on land use/cover change. To do so, we tried to capture land use/cover change in a broader sense and we included additional parameters in the query #3 as follows: ("climat* chang*" OR "chang* climat*") OR ("land use chang*" OR "land cover chang*" OR "land* system* chang*" OR "land* chang*" OR "habitat loss*" OR "habitat degradation*" OR "habitat chang*" OR "habitat modification*"). We refined the results as described above and we obtained a list of 2,388 articles, that is, only 75 additional articles compared to the search procedure with the initial query #3 (see main text). Hence, the well-balanced design of the search procedure as described in the table does not underestimate the use of land use/cover change projections compared to climate change projections in biodiversity scenarios studies.

Figure captions

Figure 1. Biodiversity scenarios: a predictive tool to inform policy-makers on expected biodiversity responses (after Bellard *et al.*, 2012 with minor modifications) to future human-induced environmental changes. A great variety of ecological models integrate the nature, rate and magnitude of expected changes in environmental conditions and the capacity of organisms to deal with these changing conditions to generate biodiversity scenarios (Thuiller *et al.*, 2013).

Figure 2. Relative neglect of future land use and land cover change in biodiversity scenarios. Temporal trend in the estimated yearly number of studies that reported on the development of biodiversity scenarios during 1990-2014 and that drew upon climate change projections alone, land use/cover change projections alone or the combination of both climate and land use/cover change projections.



