



REVIEW

Hot topics in biodiversity and climate change research [version 1; referees: 2 approved]

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Abstract

With scientific and societal interest in biodiversity impacts of climate change growing enormously over the last decade, we analysed directions and biases in the recent most highly cited data papers in this field of research (from 2012 to 2014). The majority of this work relied on leveraging large databases of already collected historical information (but not paleo- or genetic data), and coupled these to new methodologies for making forward projections of shifts in species' geographical ranges, with a focus on temperate and montane plants. A consistent finding was that the pace of climate-driven habitat change, along with increased frequency of extreme events, is outpacing the capacity of species or ecological communities to respond and adapt.



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Introduction

It is now halfway through the second decade of the 21st century, and climate change impact has emerged as a “hot topic” in biodiversity research. In the early decades of the discipline of conservation biology (1970s and 1980s), effort was focused on studying and mitigating the four principal drivers of extinction risk since the turn of the 16th century, colourfully framed by Diamond¹ as the “evil quartet”: habitat destruction, overhunting (or overexploitation of resources), introduced species, and chains of extinctions (including trophic cascades and co-extinctions). Recent work has also emphasised the importance of synergies among drivers of endangerment². But the momentum to understand how other aspects of global change (such as a disrupted climate system and pollution) add to, and reinforce, these threats has built since the Intergovernmental Panel on Climate Change reports³ of 2001 and 2007 and the Millennium Ecosystem Assessment⁴ in 2005.

Scientific studies on the effects of climate change on biodiversity have proliferated in recent decades. A *Web of Science* (webof-science.com) query on the term “biodiversity AND (climate change)”, covering the 14 complete years of the 21st century, shows the peer-reviewed literature matching this search term has grown from just 87 papers in 2001 to 1,377 in 2014. **Figure 1** illustrates that recent scientific interest in climate change-related aspects of biodiversity research has outpaced—in relative terms—the baseline trend of interest in other areas of biodiversity research (i.e., matching the query “biodiversity NOT (climate change)”), with climate-related research rising from 5.5% of biodiversity papers in 2001 to 16.8% in 2014.

Interest in this field of research seems to have been driven by a number of concerns. First, there is an increasing societal and scientific consensus on the need to measure, predict (and, ultimately, mitigate) the impact of anthropogenic climate change⁵, linked to the rise of industrial fossil-fuel combustion and land-use change⁶. Biodiversity loss and ecosystem transformations, in particular, have been highlighted as possibly being amongst the most sensitive of Earth’s systems to global change^{7,8}. Second, there is increasing attention given to quantifying the reinforcing (or occasionally stabilising) feedbacks between climate change and other impacts of human development, such as agricultural activities and land clearing, invasive species, exploitation of natural resources, and biotic interactions^{2,9}. Third, there has been a trend towards increased accessibility of climate change data and predictions at finer spatio-temporal resolutions, making it more feasible to do biodiversity climate research^{10,11}.

What are the major directions being taken by the field of climate change and biodiversity research in recent years? Are there particular focal topics, or methods, that have drawn most attention? Here we summarise major trends in the recent highly cited literature of this field.

Filtering and categorising the publications

To select papers, we used the *Web of Science* indexing service maintained by Thomson Reuters, using the term “biodiversity AND (climate change)” to search within article titles, abstracts, and keywords. This revealed 3,691 matching papers spanning the 3-year period 2012 to 2014. Of these, 116 were categorised by

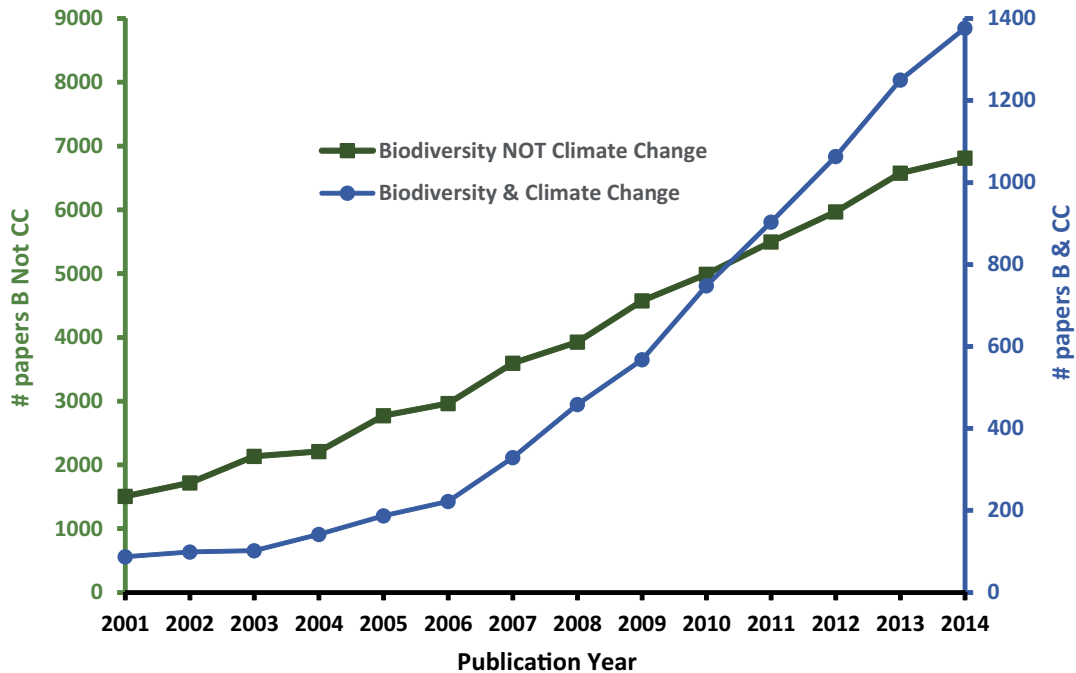


Figure 1. Relative growth of refereed studies on climate change and biodiversity, compared to non-climate-related biodiversity research. Number of refereed papers listed in the *Web of Science* database that were published between 2001 and 2014 on the specific topic “biodiversity AND (climate change)” (blue line, secondary y-axis) compared to the more general search term “biodiversity NOT (climate change)”.

Essential Science Indicators (esi.incites.thomsonreuters.com) as being “Highly Cited Papers” (definition: “As of November/December 2014, this highly cited paper received enough citations to place it in the top 1% of [its] academic field based on a highly cited threshold for the field and publication year”), with five also being classed as “Hot Papers” (definition: “Published in the past two years and received enough citations in November/December 2014 to place it in the top 0.1% of papers in [its] academic field”). The two academic fields most commonly associated with these selected papers were “Plant & Animal Science” and “Environment/Ecology”.

Next we ranked each highly cited paper by year, according to its total accumulated citations through to April 1 2015, and then selected the top ten papers from each year (2012, 2013 and 2014) for detailed assessment. We wished to focus on data-oriented research papers, so only those labelled “Article” (Document Type) were considered, with “Review”, “Editorial”, or other non-research papers being excluded from our final list. Systematic reviews that included a formal meta-analysis were, however, included. We then further vetted each potential paper based on a detailed examination of its content, and rejected those articles for which the topics of biodiversity or climate change constituted only a minor component, or where these were only mentioned in passing (despite appearing in the abstract or key words).

The final list of 30 qualifying highly cited papers is shown in [Table 1](#), ordered by year and first author. The full bibliographic details are given, along with a short description of the key message of the research (a subjective summary, based on our interpretation of the paper). Each paper was categorised by methodological type, the aspect of climate change that was the principal focus, the spatial and biodiversity scale of the study units, the realm, biome and taxa under study, the main ecological focus, and the research type and application (the first row of [Table 1](#) lists possible choices that might be allocated within a given categorisation). Note that our choice of categories for the selected papers was unavoidably idiosyncratic, in this case being dictated largely by the most common topics that appeared in the reviewed papers. Other emphases, such as non-temperature-related drivers of global change, evolutionary responses, and so on, might have been more suitable for other bodies of literature. We also did not attempt to undertake any rigorous quantification of effect sizes in reported responses of biodiversity to climate change; such an approach would have required a systematic review and meta-analysis, which was beyond the scope of this overview of highly cited papers.

Analysis of trends, biases and gaps

Based on the categorisation frequencies in [Table 1](#) (counts are given in the *n* columns adjacent to each category), the “archetypal” highly cited paper in biodiversity and climate change research relies on a database of previously collated information, makes an assessment based on future forecasts of shifts in geographical distributions, is regional in scope, emphasises applied-management outcomes, and uses terrestrial plant species in temperate zones as the study unit.

Many papers also introduced new methodological developments, studied montane communities, took a theoretical-fundamental perspective, and considered physiological, population dynamics, and

migration-dispersal aspects of ecological change. Plants were by far the dominant taxonomic group under investigation. By contrast, relatively few of the highly cited paper studies used experimental manipulations or network analysis; lake, river, island and marine systems were rarely treated; nor did they focus on behavioural or biotic interactions. Crucially, none of the highly cited papers relied on paleoclimate reconstructions or genetic information, despite the potential value of such data for model validation and contextualisation¹². Such data are crucial in providing evidence for species responses to past environmental changes, specifying possible limits of adaptation (rate and extent) and fundamental niches, and testing theories of biogeography and macroecology.

At the time of writing, 5 of the 30 highly cited papers listed in [Table 1](#) (16%) also received article recommendations from *Faculty of 1000* experts (f1000.com/prime/recommendations)^{9,13–16} with none of the most recent (2014) highly cited papers having yet received an F1000 Prime endorsement.

Key findings of the highly cited paper collection for 2012–2014

A broad conclusion of the highly cited papers for 2012–2014 (drawn from the “main message” summaries described in [Table 1](#)) is that the pace of climate change-forced habitat change, coupled with the increased frequency of extreme events^{15,17} and synergisms that arise with other threat drivers^{9,18} and physical barriers¹⁹, is typically outpacing or constraining the capacity of species, communities, and ecosystems to respond and adapt^{20,21}. The combination of these factors leads to accumulated physiological stresses^{13,15,22}, might have already induced an “extinction debt” in many apparently viable resident populations^{14,23–25}, and is leading to changing community compositions as thermophilic species displace their more climate-sensitive competitors^{13,26}. In addition to atmospheric problems caused by anthropogenic greenhouse-gas emissions, there is mounting interest in the resilience of marine organisms to ocean acidification^{27,28} and altered nutrient flows¹⁶.

Although models used to underpin the forecasts of climate-driven changes to biotic populations and communities have seen major advances in recent years, as a whole the field still draws from a limited suite of methods, such as ecological niche models, matrix population projections and simple measures of change in metrics of ecological diversity^{7,12,29}. However, new work is pushing the field in innovative directions, including a focus on advancements in dynamic habitat-vegetation models^{30–32}, improved frameworks for projecting shifts in species distributions^{29,33,34} and how this might be influenced by competition or predation^{35,36}, and analyses that seek to identify ecological traits that can better predict the relative vulnerability of different taxa to climate change^{37,38}.

In terms of application of the research to conservation and policy, some offer local or region-specific advice on ecosystem management and its integration with other human activities (e.g., agriculture, fisheries) under a changing climate^{18,24,35,39}. However, the majority of the highly cited papers used some form of forecasting to predict the consequences of different climate-mitigation scenarios (or business-as-usual) on biodiversity responses and extinctions^{20–22,33,40}, so as to illustrate the potentially dire consequences of inaction.

Table 1. Summary information on the 30 most highly cited papers related to climate change effects on biodiversity, for the period 2012–2014. Summary of the ten most highly cited research papers based on the search term: "biodiversity AND (climate change)", for each of 2012^{9,13,14,22,26,32,34,36-40,45}, 2013^{15-17,21,27,30,31,33,37,39} and 2014^{18-20,22,24,25,28,29,35,38}, as determined in the ISI Web of Science database. Filters: Reviews, commentaries, and opinion pieces were excluded, as were papers for which climate change was not among the focal topics of the research. The first row of the Table is a key that shows the possible categorisations that were open to selection (more than one description might be selected for a given paper), *n* is the number of times a category term was allocated.

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | Biome | n | Taxon | Use | n | Ecological Focus | n |
|--|----------------------|---|--|--------------------------------------|---|---|----------------------------------|--|---|---|--------------------------------|--|--|--|---|--|---|---|
| Author 1 Author 2 Author 3 ...then <i>et al.</i> | 2012 2013 2014 | Article title | Publication details Journal, volume Page range | Digital Object Identifier | Key findings of the paper | Methods development Meta-analysis New model Experiment New field data Database Statistical | 9 3 7 5 6 14 8 | Observed Retrospective validation Reconstruction Future forecast Experimental | Local Regional Global Multiscale | Population Species Community Ecosystem | Terrestrial Marine Other | Montane Polar Boreal Temperate Subtropical Tropical Desert Island Riverine Lacustrine Pelagic Benthic Abyssal Global Any | 9 3 4 11 6 4 2 0 1 0 3 5 1 4 2 | Plant Invertebrate Amphibian Reptile Fish Bird Mammal All | Theoretical- Fundamental Applied- Management Strategic- Policy | 13 4 17 4 7 2 3 5 | Trait Population dynamics Biogeography Physiology Behaviour Distribution Genetic Migration- dispersal Networks Threatened species Community dynamics Biotic Interactions Global change | 5 7 3 10 1 16 0 8 1 3 4 2 3 |
| Dullinger, S., Gattringer, A., Thuiller, W., <i>et al.</i> | 2012 | Extinction debt of high- mountain plants under twenty-first- century climate change | Nature Climate Change/ 2619-622 | 10.1038/nclimate1514 | European Alps plants will suffer average 21stC range contractions of 50% but population dynamics will lag, causing extinction debt | New model, Database | | Future forecast | Regional | Community, Species | Terrestrial | Montane | Plant | Strategic-Policy | | | Population dynamics, Distribution | |
| Eimendorff, S.C., Henry, G.H.R., Hollister, R.D., <i>et al.</i> | 2012 | Global assessment of experimental climate warming on tundra vegetation: heterogeneity over space and time | Ecology Letters/ 15164-175 | 10.1111/j.1461- 0248.2011.01716.x | Response of tundra plants to experimental warming was linear/ cumulative, with no obvious saturation or threshold impacts (including lack of feedbacks) but strong regional heterogeneity | Meta-analysis Database | | Experimental | Multiscale | Community, Ecosystem | Terrestrial | Polar, Boreal | Plant | Theoretical- Fundamental | | | Population dynamics, Community dynamics | |
| Fordham, D.A., Akçaya, H.R., Araujo, M.B., <i>et al.</i> | 2012 | Plant extinction risk under climate change: are forecast range shifts alone a good indicator of species vulnerability to global warming? | Global Change Biology/ 181357-1371 | 10.1111/j.1365- 2486.2011.02614.x | It is important to consider direct measures of extinction risk, as well as measures of change in habitat area, when assessing climate change impacts on biodiversity | Methods development, Database | | Future forecast | Regional | Species | Terrestrial | Temperate | Plant | Applied- Management | | | Population dynamics, Distribution, Trait | |
| Gottfried, M., Pauli, H., Futschik, A., <i>et al.</i> | 2012 | Continent- wide response of mountain vegetation to climate change | Nature Climate Change/ 2111-115 | 10.1038/nclimate1329 | Based on 60 mountain peaks in Europe plant communities are being transformed by gradual warming, with thermophilic species displacing competitors at a geographically variable pace | Database | | Observed | Regional | Community | Terrestrial | Montane | Plant | Theoretical- Fundamental | | | Trait, Physiology, Community dynamics | |

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| Hickler, T., Vohland, K., Feehan, J., <i>et al.</i> | 2012 | Projecting the future distribution of European potential natural vegetation zones with a generalised, tree species-based dynamic vegetation model | Global Ecology and Biogeography/ 21/50-63 | 10.1111/j.1466-8238.2010.00613.x | A new dynamic vegetation model shows that climate change is likely to cause significant shifts in vegetation types in Europe | New model | | Future forecast | Regional | Community | Terrestrial | | Montane, Boreal, Temperate | | Plant | Theoretical-Fundamental, Applied-Management | | Biogeography, Distribution | |
| Manyika-Pringle, C.S., Mar, T.G., Rhodes, J.R. | 2012 | Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis | Global Change Biology/ 18/1239-1252 | 10.1111/j.1365-2486.2011.02593.x | In synergy with other threats, maximum temperature was most closely associated with habitat loss, followed by mean precipitation decrease | Meta-analysis, Database | | Observed | Global | Population, Community | Terrestrial | | Global | | All | Strategic-Policy | | Global change, Distribution | |
| Schloss C.A., Nunez, T.A., Lawler, J.J. | 2012 | Dispersal will limit ability of mammals to track climate change in the Western Hemisphere | Proceedings of the National Academy of Sciences of the United States of America/ 109/8606-8611 | 10.1073/pnas.1116791109 | Many mammals in the Western Hemisphere will be unable to migrate fast enough to keep pace with climate change | Database, Statistical | | Future forecast | Regional - Western Hemisphere | Species | Terrestrial | | Montane, Polar, Boreal, Temperate, Subtropical, Tropical, Desert | | Mammal | Applied-Management | | Distribution, Migration-dispersal | |
| Sunday, J.M., Bates, A.E., DuVoy, N.K. | 2012 | Thermal tolerance and the global redistribution of animals | Nature Climate Change/ 2/686-690 | 10.1038/nclimate1539 | Thermal tolerance determines the ranges of marine, but not terrestrial, ectotherms | Database, Statistical | | Observed | Global | Species | Terrestrial, Marine | | Global | | Invertebrate, Amphibian, Reptile, Fish | Theoretical-Fundamental, Applied-Management | | Biogeography, Physiology, Distribution | |
| Urban, M.C., Tewisburry, J.J., Sheldon, K.S. | 2012 | On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change | Proceedings of the Royal Society B-Biological Sciences/ 279/2072-2080 | | Interspecific competition and dispersal differences between species will elevate future climate-driven extinctions | Methods development | | Future forecast | Local | Community | Terrestrial | | Montane | | All | Theoretical-Fundamental | | Community dynamics, Biotic interactions, Migration-dispersal | |

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | n | Biome | Taxon | n | Use | n | Ecological Focus | n |
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| Zhu, K., Woodall, C.W., Clark, J.S. | 2012 | Failure to migrate: lack of tree range expansion in response to climate change | Global Change Biology/ 18/1042-1052 | 10.1111/gcb.12100 2486.2011.02571.x | Tree species in the US showed a pattern of climate-related contraction in range, or a northwards shift, with ~5% expanding. No relationship between climate velocity and rate of seedling spread | Database | 9 | Observed | Regional | Population | Terrestrial | 24 | Montane, Temperate, Subtropical | Plant | 9 | Theoretical-Fundamental | 16 | Distribution Migration-dispersal | 3 |
| Anderegg, W.R.L., Plavcova, L., Anderegg, L.D., <i>et al.</i> | 2013 | Drought's legacy: multyear hydraulic deterioration underlies widespread aspen forest die-off and increased future risk | Global Change Biology/ 19/1188-1196 | 10.1111/gcb.12100 | Accumulation of drought-induced hydraulic damage to trees over multiple years leads to increased forest mortality rates and increased vulnerability to extreme events | New field data, Experiment | 9 | Observed, Experimental | Local | Population | Terrestrial | 24 | Temperate | Plant | 9 | Theoretical-Fundamental | 16 | Physiology, Population dynamics | 3 |
| Boetius, A., Albrecht, S., Bakker, K., <i>et al.</i> | 2013 | Export of algal biomass from the melting Arctic sea ice | Science/339/1430-1432 | 10.1126/science.1231346 | Anomalous melting of summer Arctic sea-ice enhanced the export of algal biomass to the deep-sea, leading to increased sequestering of carbon to oceanic sediments | New field data | 9 | Observed | Regional | Ecosystem | Marine | 24 | Polar, Pelagic, Benthic | Plant | 9 | Theoretical-Fundamental | 16 | Global change | 3 |
| Foden, W.B., Butchart, S.H.M., Stuart, S.N., <i>et al.</i> | 2013 | Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait-Based Assessment of all Birds, Amphibians and Corals | PLoS ONE/8/e65427 | 10.1371/journal.pone.0065427 | Species' traits associated with heightened sensitivity and low adaptive capacity to climate change can be used to identify the most vulnerable species and regions | Database, Methods development | 9 | Future forecast | Global | Species | Terrestrial/Marine | 24 | Any | Amphibian, Invertebrate, Bird | 9 | Applied-Management, Strategic-Policy | 16 | Threatened species, Distribution, Trait | 3 |

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | n | Biome | n | Taxon | n | Use | n | Ecological Focus | n |
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| Author 1 Author 2 Author 3 ...then <i>et al.</i> | 2012 2013 2014 | Article title | Publication details Journal, volume Page range | Digital Object Identifier | Key findings of the paper | Methods development Meta-analysis New model Experiment New field data Database Statistical | 9 3 7 5 6 14 8 | Observed validation Retrospective reconstruction Future forecast Experimental | Local Regional Global Multiscale | Population Species Community Ecosystem | Terrestrial Marine Other | 24 8 1 | Montane Polar Boreal Temperate Subtropical Tropical Desert Island Riverine Lacustrine Pelagic Benthic Abyssal Global Any | 9 3 4 11 6 4 2 0 1 0 3 5 1 4 2 | Plant Invertebrate Amphibian Reptile Fish Bird Mammal All | 16 4 4 4 2 3 5 | Theoretical-Fundamental Applied-Management Strategic-Policy | 13 7 17 7 16 0 8 1 3 3 4 2 3 | Trait Population dynamics Biogeography Physiology Behaviour Distribution Genetic Migration-dispersal Networks Threatened species Community dynamics Biotic interactions Global change | |
| Franklin, J., David, F.W., Ikeami, M., <i>et al.</i> | 2013 | Modeling plant species distributions under future climates: how do climate projections need to be? | Global Change Biology/ 19/473-483 | 10.1111/gcb.12051 | The spatial resolution of models influences the location and amount of forecast suitable habitat under climate change | Methods development, Database, Statistical | | Future forecast | Regional | Species | Terrestrial | | Temperate, Montane | | Plant | | Applied-Management | | Distribution | |
| Hannah, L., Reinhardt, P. Ikemami, M., <i>et al.</i> | 2013 | Climate change, wine, and conservation | Proceedings of the National Academy of Sciences of the United States of America/ 110/6907-6912 | 10.1073/pnas.1210127110 | Climate change will have a substantial impact on suitable habitat for viticulture, potentially causing conservation conflicts | Statistical, Database | | Future forecast | Global | Species | Terrestrial | | Temperate | | Plant | | Applied-Management | | Distribution | |
| Harvey B.P., Gwynn-Jones, D., Moore, P.J. | 2013 | Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming | Ecology and Evolution/ 3/1016-1030 | 10.1002/ece3.516 | Biological responses of marine organisms are affected by synergisms between ocean acidification and warming | Meta-analysis, Experiment | | Future forecast | Multiscale | Population | Marine | | Pelagic, Benthic, Abyssal | | Plant, Invertebrate, Fish | | Theoretical-Fundamental, Applied-Management | | Physiology, Population dynamics | |
| Hazen, E.L., Jorgensen, S., Rybczakowski, R., <i>et al.</i> | 2013 | Predicted habitat shifts of Pacific top predators in a changing climate | Nature Climate Change/ 3/234-238 | 10.1038/nclimate1666 | For a forecast rise of 1-6C in sea-surface temperature, predicts up to a +/-35% change in core habitat of top marine predators | New model, New field data | | Future forecast | Regional | Ecosystem | Marine | | Temperate, Pelagic | | Bird, Fish, Mammal, Reptile | | Theoretical-Fundamental, Strategic-Policy | | Distribution, Migration-dispersal | |
| Scheiter, S., Langan, L., Higgins, S.I. | 2013 | Next-generation dynamic global vegetation models: learning from community ecology | New Phytologist/ 198/957-969 | 10.1111/nph.12210 | Describes features of next-generation dynamic global vegetation models, illustrates how current limits could be addressed by integrating community assembly rules | New model, Methods development | | Retrospective validation, Future forecast | Global | Population, Ecosystem | Terrestrial | | Boreal, Temperate, Subtropical, Tropical | | Plant | | Theoretical-Fundamental, Applied-Management | | Trait, Physiology, Biogeography | |

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | n | Biome | n | Taxon | n | Use | n | Ecological Focus |
|--|----------------------|--|--|----------------------------|---|--|---------------------------------------|--|---|--|-----------------------|--------------|--|--|--|---------------------------------------|---|--|---|
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| Smale, D.A., Wernberg, T. | 2013 | Extreme climatic event drives range contraction of a habitat-forming species | Proceedings of the Royal Society B-Biological Sciences/280/20122829 | 10.1098/rspb.2012.2829 | Extreme warming events can cause population extirpation leading to distribution shifts | New field data, Experiment | | Observed | Regional | Species | Marine | | Benthic | | Plant | | Applied-Management | | Distribution, Physiology |
| Warren, R., VanDerWal, J., Price, J., <i>et al.</i> | 2013 | Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss | Nature Climate Change/3/678-682 | 10.1038/nclimate1887 | Analysis of a range of future climate change scenarios shows that over 1/2 plant species and 1/3 mammals likely to lose >50% of range by 2080s; mitigation substantially curbs this | Database, Statistical | | Future forecast | Global | Species | Terrestrial | | Global | All | | Strategic-Policy | | Distribution | |
| Bates, A.E., Barrett, N.S., Swarf-Smith, R.D., <i>et al.</i> | 2014 | Resilience and signatures of tropicalisation in protected reef fish communities | Nature Climate Change/4/62-67 | 10.1038/nclimate2062 | Protection from fishing buffers fluctuations in reef fish diversity and provides resistance to climate change | New field data, Statistical | | Observed | Local | Community | Marine | | Benthic | | Fish | | Applied-Management | | Global change |
| Burrows M.T., Schoeman, D.S., Richardson, A.J., <i>et al.</i> | 2014 | Geographical limits to species-range shifts are suggested by climate velocity | Nature/507/492-495 | 10.1038/nature12976 | Global and regional maps of future climate velocity can be used to infer shifts in species distributions | Methods development | | Reconstruction, Future forecast | Global | Species | Terrestrial | | Global | All | | Applied-Management, Strategic-Policy | | Migration-dispersal, Distribution | |
| Hennige S.J., Wicks, L.C., Kamenos, N.A., <i>et al.</i> | 2014 | Short-term metabolic and growth responses of the cold-water coral <i>Lophelia pertusa</i> to ocean acidification | Deep-Sea Research Part II: Tropical Studies in Oceanography/99/27-35 | 10.1016/j.dsr2.2013.07.005 | Increased levels of atmospheric carbon dioxide will negatively influence the respiration rates, but not calcification rates, of cold-water corals | Experiment | | Future forecast | Local | Population | Marine | | Benthic | | Invertebrate | | Theoretical-Fundamental | | Physiology |

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | n | Bionne | n | Taxon | Use | n | Ecological Focus |
|--|----------------------|--|--|---------------------------|---|--|---------------------------------------|---|---|------------------------|--------------------------------|--------------|--|--|--|---|---------------------------------------|---|
| Author 1 Author 2 Author 3 ...then <i>et al.</i> | 2012 2013 2014 | Article title | Publication details Journal, volume Page range | Digital Object Identifier | Key findings of the paper | Methods development Meta-analysis New model Experiment New field data Database Statistical | 9 3 3 5 5 6 14 8 | Observed Retrospective validation Reconstruction Future forecast Experimental | Local Regional Global Multiscale | 7 14 7 2 6 | Terrestrial Marine Other | 24 8 1 | Montane Polar Boreal Temperate Subtropical Tropical Island Riverine Pelagic Benthic Abyssal Global Aty | 9 3 4 11 6 4 2 0 1 3 3 5 1 4 2 | Plant Invertebrate Amphibian Reptile Fish Bird Mammal All | Theoretical-Fundamental Applied-Management Strategic-Policy | 16 4 4 4 4 2 3 5 | Trait Population dynamics Biogeography Physiology Behaviour Distribution Genetic Migration-dispersal Networks Threatened species Community dynamics Biotic interactions Global change |
| Jantz, P., Goetz, S., Laporte, N. | 2014 | Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics | Nature Climate Change/ 4/138-142 | 10.1038/nclimate2105 | If corridors were established to strategically connect tropical forest reserves, dual benefit of facilitating dispersal and capturing 15% of currently unprecipitated carbon stocks | Statistical | | Future forecast | Regional | Ecosystem | Terrestrial | | Tropical | | Plant | Applied-Management | | Networks, Migration-dispersal |
| Pearson, R.G., Stanton, J.C., Shoemaker, K., <i>et al.</i> | 2014 | Life history and spatial traits predict extinction risk due to climate change | Nature Climate Change/ 4/217-221 | 10.1038/nclimate2113 | Extinction risk from climate change can be predicted using spatial and demographic variables already used in species conservation assessments | Methods development, Database | | Future forecast | Regional | Population, Species | Terrestrial | | Montane, Temperate, Subtropical, Desert, Riverine | | Amphibian, Reptile | Applied-Management | | Trait, Population dynamics, Distribution, Migration-dispersal, Threatened species |
| Redossavijic, A., Anderson, R.P. | 2014 | Making better MAXENT models of species distributions: complexity, overfitting and evaluation | Journal of Biogeography/ 4/1629-643 | 10.1111/jbi.12227 | Application of MAXENT to a threatened mouse species to illustrate how species-specific tuning can improve model fit and retrospective validation scores | Statistical, Methods development | | Retrospective validation | Regional | Species | Terrestrial | | Tropical | | Mammal | Theoretical-Fundamental | | Distribution, Threatened species |
| Scheffers, B.R., Edwards, D.P., Diesmos, A., <i>et al.</i> | 2014 | Microhabitats reduce animals exposure to climate extremes | Global Change Biology/ 20/495-503 | 10.1111/gcb.12439 | Microhabitats decrease the vulnerability of species and communities to climate change | New field data, Experiment | | Future forecast | Local | Species | Terrestrial | | Montane | | Amphibian, Reptile | Applied-Management | | Physiology |

| Authors | Year | Title | Journal/Vol/Pg | DOI | Main Message | Type | n | Climate Change | Spatial Scale | Biodiversity Scale | Realm | Biome | Taxon | n | Use | Ecological Focus | n |
|---|----------------------|--|--|---|---|--|---------------------------------------|---|---|---|--------------------------------|--|--|---------------------------------------|---|---|---|
| Author 1 Author 2 Author 3 ...then <i>et al.</i> | 2012 2013 2014 | Article title | Publication details Journal, volume Page range | Digital Object Identifier | Key findings of the paper | Methods development Meta-analysis New model Experiment New field data Database Statistical | 9 3 2 1 5 6 14 8 | Observed Retrospective validation Reconstruction Future forecast Experimental | Local Regional Global Multiscale | Population Species Community Ecosystem | Terrestrial Marine Other | Montane Polar Boreal Temperate Subtropical Tropical Desert Island Riverine Lacustrine Pelagic Benthic Abyssal Global Any | Plant Invertebrate Amphibian Reptile Fish Bird Mammal All | 16 4 4 4 4 2 3 5 | Theoretical-Fundamental Applied-Management Strategic-Policy | Trait Population dynamics Biogeography Physiology Behaviour Distribution Genetic Migration-dispersal Networks Threatened species Community dynamics Biotic interactions Global change | 5 7 3 10 16 0 8 1 3 3 4 2 3 |
| Schmitz O.J., Barton, B.T. | 2014 | Climate change effects on behavioral and physiological ecology of predator-prey interactions: Implications for conservation biological control | Biological Control/ 75:87-96 | 10.1016/j.biocontrol.2013.10.001 | Develops a "habitat domain" framework to help to forecast how climate change will affect predator-prey interactions and biological control | Methods development | | Future forecast | Local | Community | Terrestrial | Any | All | Applied-Management | Behaviour, Physiology, Biotic interactions | | |
| Shoo, L.P., O'Mara, J., Perhans, K., <i>et al.</i> | 2014 | Moving beyond the conceptual specificity in regional climate change adaptation actions for biodiversity in South East Queensland, Australia | Regional Environmental Change/14:435-447 | 10.1007/s10113-012-0385-3 | Uses case studies from SE Queensland biomes to illustrate the value of context-specific approaches to conservation planning under climate change | Database | | Future forecast | Local | Ecosystem | Terrestrial, Other | Subtropical | Plant | Applied-Management | Community dynamics, Physiology | | |
| Zhu, K., Woodall, C.W., Ghosh, S., <i>et al.</i> | 2014 | Dual impacts of climate change: forest migration and turnover through life history | Global Change Biology/ 20:251-264 | 10.1111/gcb.12392 | Tree species in eastern US are not migrating sufficiently to track climate change, and are instead responding with faster turnover rates in warm and wet climates | Database, New model | | Observed | Regional | Species | Terrestrial | Temperate, Subtropical | Plant | Strategic-Policy | Migration-dispersal, Population dynamics | | |

Future directions

The current emphasis on leveraging large databases for evidence of species responses to observed (recent) climate change is likely to wane as existing datasets are scrutinised repeatedly. This suggests to us that future research will be forced to move increasingly towards the logistically more challenging experimental manipulations (laboratory, mesocosm, and field-based). The likelihood of this shift in emphasis is reinforced by the recent trend towards mechanistic models in preference to correlative approaches⁴¹. Such approaches arguably offer the greatest potential to yield highly novel insights, especially for predicting and managing the outcomes of future climate-ecosystem interactions that have no contemporary or historical analogue. Along with this work would come an increasing need for systematic reviews and associated meta-analysis, to summarise these individual studies quantitatively and use the body of experiments to test hypotheses.

Technological advances will also drive this field forward. This includes the development of open-source software and function libraries that facilitate and standardise routine tasks like validation and sensitivity analysis of projection or statistical models^{42,43}, as well as improved access to data layers from large spatio-temporal datasets like ensemble climate forecasts¹⁰ and palaeoclimatic hindcasts⁴⁴. An increasing emphasis on cloud-based storage and use of off-site high-performance parallel computing infrastructure will make it realistic for researchers to undertake computationally intensive tasks³¹ from their desktop.

These approaches are beginning to emerge, and a few papers on these topics already appear in the highly cited paper list (Table 1). This includes the innovative exposure of coral populations to varying carbon dioxide concentrations, and the meta-analyses of tundra plant response to experimental warming⁴⁵ and marine organisms to ocean chemistry²⁷. Such work must also be underpinned by improved models of the underlying mechanisms and dynamic processes, ideally using multi-species frameworks that make use of ensemble forecasting methods for improved incorporation of scenario and climate model uncertainty¹⁰. Such an approach can account better for biotic interactions⁴¹ *via* individual-based and physiologically explicit “bottom-up” models of adaptive responses³¹. Lastly, there must be a greater emphasis on using genetic information to integrate eco-evolutionary processes into biodiversity models⁴⁶, and on improving methods for making the best use of retrospective knowledge from palaeoecological data¹².

Competing interests

The authors declare that they have no disclosures or conflicts of interest.

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I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

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