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Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise

Rachel Warren · Jeff Price · Andreas Fischlin ·
Santiago de la Nava Santos · Guy Midgley

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Abstract In a meta-analysis we integrate peer-reviewed studies that provide quantified estimates of future projected ecosystem changes related to quantified projected local or global climate changes. In an advance on previous analyses, we reference all studies to a common pre-industrial base-line for temperature, employing up-scaling techniques where necessary, detailing how impacts have been projected on every continent, in the oceans, and for the globe, for a wide range of ecosystem types and taxa. Dramatic and substantive projected increases of climate change impacts upon ecosystems are revealed with increasing annual global mean temperature rise above the pre-industrial mean (ΔT_g). Substantial negative impacts are commonly projected as ΔT_g reaches and exceeds 2°C, especially in biodiversity hotspots. Compliance with the ultimate objective of the United Nations Framework Convention

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R. Warren (✉) · S. de la Nava Santos
Tyndall Centre for Climate Change Research,
School of Environmental Sciences,
University of East Anglia, Norwich, NR4 7TJ, UK
e-mail: R.warren@uea.ac.uk

J. Price
World Wildlife Fund U.S., 1250 24th St. NW,
Washington, DC 20037 USA

J. Price
Department of Geological and Environmental Sciences,
California State University, Chico, CA, USA

A. Fischlin
Systems Ecology, Institute of Integrative Biology: Ecology, Evolution, and Disease,
Department of Environmental Sciences, ETH Zurich,
Universitätstr. 16/CHN E21.1, 8092, Zurich, Switzerland

G. Midgley
Global Change and Biodiversity Program,
South African National Biodiversity Institute,
P/Bag X7, Claremont, 7735, Cape Town, South Africa

on Climate Change (Article 2) requires that greenhouse gas concentrations be stabilized within a time frame "sufficient to allow ecosystems to adapt naturally to climate change". Unless ΔT_g is constrained to below 2°C at most, results here imply that it will be difficult to achieve compliance. This underscores the need to limit greenhouse gas emissions by accelerating mitigation efforts and by protecting existing ecosystems from greenhouse-gas producing land use change processes such as deforestation.

1 Introduction

Effects of climate change are already being observed on a wide range of ecosystems and species in all regions of the world (Rosenzweig et al. 2007), in response to the 0.74°C rise (ΔT_g) in global mean temperature (GMT) that has been experienced since pre-industrial times (Solomon et al. 2007). Such responses include changes in phenology and shifts in species ranges (e.g. Walther et al. 2002; Root et al. 2003), whilst the first extinctions which are likely to be attributable to climate change—acting synergistically with disease—have already occurred in amphibians (Pounds et al. 2006; Bosch et al. 2006). Coral reef bleaching is expected to increase strongly with rising sea surface temperatures (Hughes et al. 2003). At the same time, the ocean has already acidified by 0.1 pH units since pre-industrial times (Solomon et al. 2007) due to the direct effects of increasing atmospheric concentrations of carbon dioxide from the pre-industrial level of 280 ppm to the 2005 level of 379 ppm CO_2 (Solomon et al. 2007).

The literature contains a growing number of studies that project for the future increasingly severe impacts that further anthropogenic climate change would have on ecosystems and species around the world (see the 71 studies referenced in Tables 2, 3, 4 and 5). Such studies typically identify the onset of some positive, but predominantly negative, impacts upon a species or ecosystem as the climate changes. However, these studies have largely been carried out independently from each other and have used a wide range of future climate scenarios. This makes it difficult to compare results and obtain a clear and aggregated picture of how impacts accrue with increasing global mean temperature rise. Such an aggregated picture is important for two reasons: firstly it addresses climate change at the appropriate scale, i.e. as a global phenomenon; and secondly it enables the evaluation of major policy recommendations, such as the much discussed 2°C limit suggested by the EU as both a "safe" and achievable level of global temperature increase. Existing reviews (Houghton et al. 2001; Thomas et al. 2004a; Hare 2006; Warren 2006) have not included the full range of recent literature and have not estimated uncertainties. Similarly to the summary given in Fischlin et al. (2007), this paper integrates the dispersed and fragmented literature on ecosystem impacts of projected climate change, often expressed at a regional level, into a set of tables of projected impacts for different levels of global mean temperature rise with respect to pre-industrial times, ΔT_g, providing an estimate of uncertainty in these levels. The tables report the main findings in terms of: range losses for species, habitats or entire ecosystems; extinction risks; and other biodiversity impacts caused by ecosystem degradations or declines in key populations due to anticipated climate changes.

2 Materials and methods

2.1 Literature search

A literature search was made to assess pertinent impacts of climate change on both terrestrial and marine ecosystems across the globe (Fischlin et al. 2007). Search engines were first used to identify references in the peer reviewed literature, and further references were then derived from information provided within these. Existing reviews (Gitay et al. 2001; Thomas et al. 2004a; Hare 2006; Warren 2006) were particularly useful in identifying additional references. All references were then reviewed for specific information about thresholds in local or global temperature change/sea level rise above which adverse consequences could be expected, and also for quantified projections of ecosystem or species changes associated with quantified local or global climate changes, taking note of the climate scenario and any general circulation model (GCM) used, and the treatment of dispersal and migration. Thus studies that contained insufficient detail about the climate scenario used, or that did not provide quantitative estimates of the resultant ecosystem or species changes, could not be included in the analysis. In particular, studies which reported only the general direction of trends in response to changing temperature or precipitation were deliberately excluded. In cases where more than one study addressed similar species or ecosystems, each study was included separately in the summary table, since it may be projecting different sensitivities due to the use of other climate change scenarios and/or assessing other kinds of impact responses.

2.2 Converting to a pre-industrial reference point for global mean temperature change

Information on the climate change scenario simulated by each original study was converted to a common pre-industrial reference point for temperature. Studies often refer to baselines of pre-industrial (<1850), 1960–1990 mean, 1990, or "present day" (e.g. 1980–1999). In this study the temperature rise between pre-industrial and the 1960–1990 mean is taken as 0.3°C and the temperature rise between pre-industrial and 1990 is taken as 0.6°C (Houghton et al. 2001); whilst that from the mid 1970s to 1990 is taken as 0.2°C (Houghton et al. 2001). Where studies report impacts as caused by a particular GCM simulation using the HadCM3 model, Table 7 of Arnell et al. (2004) was used to convert the temperatures to a common pre-industrial baseline.

While some of the literature relates impacts directly to global mean temperature increases, many studies refer only to local temperature rise, and hence upscaling from a local to a global scale is required. Upscaling was carried out as detailed below for the different classes of studies identified (Table 1) and also provided an opportunity to estimate the uncertainties arising from the use of different GCMs in climate projection. Whenever possible it was also considered whether the impact had been estimated based only on temperature change, or also on associated precipitation change.

When studies gave minimal detail about GCM scenarios, such as referring to them only as "CO_2 doubling scenarios", the original literature publishing that scenario was traced, and/or the model authors were contacted, in order to verify the global mean

Table 1 Detail of the upscaling methodology used to derive global mean temperature (GMT) change (ΔT_g) for the eight study classes a–h

Class	Description of study	Derivation of central estimate of GMT change ΔT_g	Derivation of range of GMT change
a	Relates global impacts directly to ΔT_g	ΔT_g by definition already provided: harmonised if necessary to pre-industrial	Not derived unless provided in original study
b	Relates local impact (e.g. x% species at risk of extinction) to regional temperature change without using GCM output	ΔT_g is the mean of values derived via upscaling procedure, using the cited regional temperature change	Range of values derived via upscaling procedure using the cited regional temperature change
c	Relates a local impact (e.g. y% species at risk of extinction) to regional temperature change while using the output of specific GCM(s)[2]	As not all studies provide the regional temperature change this may need to be derived by first downscaling for the appropriate timeslice (e.g. Gyalistras and Fischlin 1999). ΔT_g is then the mean of values derived via a subsequent upscaling of the downscaled regional temperature change	Range of values derived via upscaling procedure, using the downscaled regional temperature change
d	As b but regional precipitation change also used	As b	As b
e	As c but study uses also GCM simulated precipitation as well as temperature	Upscaling is not applicable, as procedure is based on temperature only. ΔT_g is derived from published values simulated by the used GCM(s)	Not derivable
f	Cases where upscaling is not possible because regional temperature changes are out of range of the GCM patterns available	Estimated from maps in Meehl et al. (2007) relating local and global temperature change	Not derivable
g	As c or e but GCM output comes from 3 or more different GCM models	Mean of values as simulated by the used GCM(s)	Range derived from published values simulated by the used GCM(s)
h	Cases where the key variable is sea surface temperature	Estimated from maps in Meehl et al. (2007) relating local surface air temperature over the sea to ΔT_g, since maps of SST were not readily available, and increases in surface air temperature over the ocean were assumed to approximate increases in SST	Not derivable

temperature increase corresponding to CO_2 doubling, taking into account the control CO_2 concentration as necessary.

2.3 Dynamics

Many reviewed studies do not consider a temporal dimension. There are two issues here (1) whether the climate scenario a study considers relates to transient or equilibrium climate change and (2) whether the projected ecological response is considered a steady state. Studies in class b project impacts without distinguishing between transient and equilibrium temperature change. However, most studies use models, which project the future long-term ecological response to a changed climate (i.e. a new steady state) while the climate scenario is a transient one: studies in classes c and e are typically based on transient climate change scenarios produced by GCMs, although there are a few which also include equilibrium temperature change scenarios. Hence, the ecological projections are *not* mere snapshots of a transient climate change and its concomitant response, rather do these studies artificially hold the transient climate constant and assume the ecosystem response to equilibrate, regardless of the time the system may need to actually reach such an equilibrium. Thus an important question is the time lag between the forcing temperature change, be it transient or equilibrium, and the ecosystem response (see Section 4). The upscaling procedure described below is based on transient GCM scenario outputs throughout.

2.4 Upscaling procedure

The upscaling procedure involved the use of 0.5 × 0.5° resolution outputs produced from original 5 × 5° resolution outputs of five GCM models HadCM3, ECHAM4, CSIRO2, PCM, and CGCM2, by using pattern scaling and downscaling methods (Christensen et al. 2007). These climate projections based on transient GCM outputs were available for the entire global land area at a resolution of 0.5 × 0.5°. They were produced from up to four IPCC SRES emission scenarios (Nakicenovic et al. 2000) providing 13 different GCM patterns on which to base the upscaling (available at http://ipcc-ddc.cru.uea.ac.uk). In each 0.5 × 0.5° grid cell, 13 alternative twenty-first century time series of regional annual (or if required seasonal) temperature were thus available, each one expressed as the running 30-year mean temperature increase since 1961–1990 mean climate, to smooth inter-annual variability.

For each study in Table 1 of type b or c, the location was then related to a grid cell or to grid cells depending on how large an area the study covered. For each grid cell, all 13 upscaling calculations were carried out, to encompass the full range of inter-GCM and inter-scenario pattern variability as an uncertainty surrogate. The upscaling calculation was simply performed by examining any one of the 13 time series for a grid cell. A computer program calculated the date at which the regional temperature reached the temperature threshold which is referred to in the study of type b or c and therein associated with some particular impact on an ecological system. The program then used this derived date to identify the associated global temperature rise ΔT_g in the transient GCM runs, matching this same date, using if available the global temperature time series from the exact same GCM scenario as

Table 2 Projected impacts of climate change on various ecological systems and species as reported in the literature for different levels of global mean annual temperature rise ΔT_g, relative to pre-industrial climate (mean and range), showing also regional temperature change ΔT_{reg} relative to 1990 if provided by the literature: range losses for species, habitats or whole ecosystems

No.	ΔT_g above pre-ind °C	ΔT_g (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
1	1.3	1.1–1.6	1	8% loss freshwater fish habitat, 15% loss in Rocky Mountains, 9% loss of salmon	N America	Fish	13
2	1.6			Bioclimatic envelopes eventually exceeded leading to 10% transformation of global ecosystems; loss of 47% wooded tundra, 23% cool conifer forest, 21% scrubland, 15% grassland/steppe, 14% savannah, 13% tundra and 12% temperate deciduous forest. Ecosystems variously lose 2–47% areal extent	Globe		6
3	1.6	1.1–2.1	1	Suitable climates for 25% of eucalypts exceeded	Australia	Plants	12
4	1.7	1.3–2.4	2	16% freshwater fish habitat loss, 28% loss in Rocky Mountains, 18% loss of salmon	N America	Fish	13
5	1.8			Mean latitude of range of *Aloe dichotoma* shifts S by 1.1° of latitude causing range loss	Namibia	Plants	68
6	<1.9	<1.6–2.4	<1	Range loss begins for Golden Bowerbird	Australia	Birds	4
7	1.9	1.6–2.4	1	Range loss of 40–60% for Golden Bowerbird	Australia	Birds	4
8	2.1			Without dispersal 17 common European deciduous trees variously lose 1–100% of their range (2 sp. lose 100%); whilst full dispersal could reduce this to 11 losing between 1–99% (2 sp. lose 99%) and 6 increasing their range by 42–303%	Europe	Plants	67
9	2.3	1.6–3.2	3	24% loss freshwater fish habitat, 40% loss in Rocky Mountains, 27% loss of salmon	N America	Fish	13
10	2.4			63 of 165 rivers studied lose >10% of their fish species	Globe	Fish	19
11	2.5	1.9–4.3		42% of UK land area with bioclimate unlike any currently found there; in Hampshire, declines in climate suitability space for curlew and hawfinch and gain for yellow-necked mouse; loss of montane habitat in Scotland; potential bracken invasion of Snowdonia montane areas	UK, Europe	Birds, mammals, plants	57
12	2.5			20–70% loss (mean 44%) of coastal bird habitat at 4 sites	USA	Birds	29

13	2.5	1.9–3.5		20% loss of coastal migratory bird habitat	Delaware, USA	Birds	36
14	2.7			32–70% of 111 European mammals studied lose >30% of current distribution whilst 24–35% undergo range expansions	Europe	Mammals	71
15	2.7			Bioclimatic envelopes exceeded leading to eventual transformation of 16% of global ecosystems: loss of 58% wooded tundra, 31% cool conifer forest, 25% scrubland, 20% grassland/steppe, 21% tundra, 21% temperate deciduous forest, 19% savanna. Ecosystems variously lose 5–66% of their areal extent	Globe		6
16	2.8	2.3–4.6	2.1–2.5	Cloud forest regions lose hundreds of metres of elevational extent, potential extinctions ΔT_{reg} 2.1°C for C America and ΔT_{reg} 2.5°C for Africa	C. America, Tropical Africa, Indonesia		17
17	2.8	2.1–3.1	3	Eventual loss of 9–62% of the mammal species from Great Basin montane areas	USA	Mammals	32
18	2.8			Most European bird distributions are reduced in area by 81% and displaced from 38–53% of their present location; 25% have ranges reduced by > = 90%. Avian species richness reduced by 9–60% depending on dispersal assumptions	Europe	Birds	65
19	2.8	1.9–3.8	3	38–54% loss of waterfowl habitat in prairie pothole region	USA	Birds	37, 38
20	2.9		3.2–6.6	50% loss existing tundra offset by only 5% eventual gain; millions of Arctic nesting shorebirds species variously lose up to 5–57% of breeding area; high Arctic species most at risk; geese species variously lose 5–56% of breeding area	Arctic	Birds	14
21	2.9			Lat. of N forest limits shifts N by 0.5° latitude in W Europe, 1.5° in Alaska, 2.5° in Chukotka and 4° in Greenland	Arctic	Plants	40
22	2.9			Substantial loss of boreal forest	China	Plants	15
23	3.0			66 of 165 rivers studied lose >10% of their fish species	Globe	Fish	19

Table 2 (continued)

No.	ΔT_g above pre-ind °C	ΔT_g (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
24	2.4–4.0			431 bird species lose on average 76–89% of their present range, with new potential ranges overlapping original ones by 31–47% so that species richness declines locally by a mean of 9–56% depending on dispersal assumptions	Europe	Birds	73
25	3.3	2.3–3.9	2.6–2.9	Substantial loss of alpine zone, and its assoc. flora and fauna (e.g., alpine sky lily, and mountain pygmy possum)	Australia	Plants, marsupials	45
26	3.4			6–22% loss of coastal wetlands; large loss migratory bird habitat particularly in USA, Baltic and Mediterranean	Globe	Birds	35, 36
27	3.5	2.3–4.1	2.5–3.5	Loss of temperate forest wintering habitat of Monarch butterfly	Mexico	Insects	28
28	3.6	2.6–4.3	3	Bioclimatic limits of 50% of eucalypts exceeded	Australia	Plants	12
29	3.6	3.0–3.9		Parts of the USA lose 30–57% neotropical migratory bird species richness	USA	Birds	43
30	3.7			Bioclimatic envelopes exceeded leading to eventual transformation of 22% of global ecosystems; loss of 68% wooded tundra, 44% cool conifer forest, 34% scrubland, 28% grassland/steppe, 27% savannah, 38% tundra and 26% temperate deciduous forest. Ecosystems variously lose 7–74% areal extent	Globe		6
31	3.7	2.6–4.8	3	Up to 60% loss in upland stream macro-invertebrate abundance; local extinction of 4 taxa; 25% of mean species richness at risk of local extinction	UK	Invertebrates	62

32	4.0	3.3	47–78% of 111 European mammals studied lose >30% of current distribution whilst 13–33% undergo range expansions	Europe	Mammals	71
33	>>4.0	5	Bioclimatic limits of 73% of eucalypts exceeded	Australia	Plants	12
34	4.9		Without dispersal 17 common European deciduous tree species variously lose 15–100% of their range; full instantaneous dispersal could reduce this to 11 losing between 13% and 100% and 6 increasing their range by 3–320%	Europe	Plants	67
35	5.0		92–97% of 100 *Banksia* species studied experience range contraction, 9% expand	W Australia	Plants	74
36	5.2		62–100% loss of bird habitat at 4 major coastal sites	USA	Birds	29

A novel climate is a climate which is significantly different from the present climate whilst a disappearing climate is a climate that disappears from a given area, for example on a mountaintop or a coastline where geography prevents a species from tracking the changing climate. For further details see Williams et al. (2007)

Sources: 1—Thomas et al. (2004a), 2—Hoegh-Guldberg (1999), 4—Hilbert et al. (2004), 5—Rutherford et al. (2000), 6—Leemans and Eickhout (2004), 7—Williams et al. (2003), 8—Theurillat and Guisan (2001), 9—Sheppard (2003), 10—Eliot et al. (1999), 11—Symon et al. (2005), 12—Hughes et al. (1996), 13—Preston (2006), 14—Zöckler and Lysenko (2000), 15—Ni (2001), 16—Bakkenes et al. (2002), 17—Still et al. (1999), 18—Benning et al. (2002), 19—Xenopoulos et al. (2005), 20—European Climate Forum (2004), 21—Cox et al. (2004), 22—Thuiller et al. (2005), 23—Thuiller et al. (2006), 24—Midgley et al. (2002), 25—Hannah et al. (2002), 26—Peterson et al. (2002), 27—Erasmus et al. (2002), 28—Villers-Ruiz and Trejo-Vazquez (1998), 29—Galbraith et al. (2002), 30—Beaumont and Hughes (2002), 31—Kerr and Packer (1998), 32—McDonald and Brown (1992), 33—Halloy and Mark (2003), 34—Moriondo et al. (2006), 35—Nicholls et al. (1999), 36—Najjar (2000), 37—Sorenson et al. (1998), 38—Johnson et al. (2005), 39—Broennimann et al. (2006), 40—Kaplan et al. (2003), 41—Theurillat et al. (1998), 42—Forcada et al. (2006), 43—Price and Root (2005), 44—Siqueira and Peterson (2003), 45—Pickering et al. (2004), 46—Scholze et al. (2006), 47—Raven et al. (2005), 48—Cox et al. (2000), 49—Orr et al. (2005), 50—Malcolm et al. (2006), 51—Peck et al. (2004), 52—Pounds et al. (2006), 53—Arzel et al. (2006), 54—Bosch et al. (2006), 57—Berry et al. (2005), 58—Lucht et al. (2006), 59—Schaphoff et al. (2006), 60—McClean et al. (2005), 61—Williams et al. (2007), 62—Durance and Ormerod (2007), 63—Hawkes et al. (2007), 64—van Vuuren et al. (2006), 65—Huntley et al. (2006), 66—Lensing and Wise (2007), 67—Ohlemüller et al. (2006), 68—Foden et al. (2007), 69—Cramer et al. (2001), 70—Sekercioglu et al. (2008), 71—Levinsky et al. (2007), 72—Memmott et al. (2007), 73—Huntley et al. (2008), 74—Fitzpatrick et al. (2008)

Table 3 Projected impacts of climate change on various ecological systems and species as reported in the literature for different levels of global mean annual temperature rise ΔT_g, relative to pre-industrial climate (mean and range), showing also regional temperature change ΔT_{reg} relative to 1990 if provided by the literature: extinction risks

No.	ΔT_g above pre-ind °C	ΔT_g above pre-ind °C (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
37	0.6			Amphibian extinctions/extinction risks on mountains due to climate-change induced disease outbreaks	Costa Rica, Spain, Australia	Amphibians	52, 54
38	1.6	1.2–2.0	0.7–1.5	9–31% (mean 18%) of species committed to extinction	Globe (20% terrestrial surface)	Plants, vertebrates and insects	1
39[a]	1.6			23–25% of bird species at risk of extinction, and 1–2% projected extinct	Western Hemisphere	Birds	70
40	1.7	1.2–2.6		38–45% of the plants in the Cerrado committed to extinction	Brazil	Plants	1, 44
41	1.7	1.3–3		2–18% of the mammals, 2–8% of the birds and 1–11% of the butterflies committed to extinction	Mexico	Mammals, birds, insects	1, 26
42	1.75	1.5–2.0		2–4% loss of global vascular plant diversity	Globe	Plants	64
43	1.9	1.6–2.4	1	7–14% of reptiles, 8–18% of frogs, 7–10% of birds, and 10–15% of mammals committed to extinction as 47% of appropriate habitat in Queensland lost	Australia	Reptiles, amphibians, birds, mammals	1, 7
44	2.1			41–51% loss in plant endemic species richness	S Africa, Namibia	Plants	39
45	2.1		1.4–2.6	13–23% of butterflies committed to extinction	Australia	Insects	1, 30
46	2.1	1.4–2.6		Bioclimatic envelopes of 2–10% plants exceeded leading to endangerment or extinction; mean species turnover of 48% (spatial range 17–75%); mean species loss of 27% (spatial range 1–68%)	Europe	Plants	22

47	2.2			3–16% of plants committed to extinction	Europe	Plants	1
48	2.2	2.1–2.3	1.6–1.8	15–37% (mean 24%) of species committed to extinction	Globe (20% terrestrial surface)	Plants, vertebrates and insects	1
49	2.2	1.7–3.2		8–12% of 277 medium/large mammals in 141 national parks critically endangered or extinct; 22–25% endangered	Africa	Mammals	23
50	2.3	1.5–2.7	2°C SST	Loss of Antarctic bivalves and limpets	Southern Ocean	Molluscs	51
51	2.3	1.5–2.7	2.5–3.0	Extinctions (100% potential range loss) of 10% endemics; 51–65% loss of Fynbos; including 21–40% of *Proteaceae* committed to extinction; Succulent Karoo area reduced by 80%, threatening 2800 plant species with extinction; 5 parks lose >40% of plant species	S Africa	Plants	1, 5, 24, 25
52	2.3	2.3–4.0	2.5–3.0	24–59% of mammals, 28–40% of birds, 13–70% of butterflies, 18–80% of other invertebrates, 21–45% of reptiles committed to extinction; 66% of animal species potentially lost from Kruger National Park	S Africa	Mammals, birds, reptiles, insects, other invertebrates	1, 27
53	2.3	2.2–4.0		2–20% of mammals, 3–8% of birds and 3–15% of butterflies committed to extinction	Mexico	Mammals, birds, insects	1, 26
54	2.3	1.6–3.2		48–57% of Cerrado plants committed to extinction	Brazil	Plants	1
55[a]	2.3			27–28% of bird species at risk of extinction, and 2–3% projected extinct	Western Hemisphere	Birds	70
56	2.3			Changes in ecosystem composition, 32% of plants move from 44% of area with potential extinction of endemics	Europe		16

Table 3 (continued)

No.	ΔT_g above pre-ind °C	ΔT_g above pre-ind °C (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
57	2.4			Bioclimatic range of 25–57% (full dispersal) or 34–76% (no dispersal) of 5,197 plant species exceeded leading to extinction risks	Subsaharan Africa		60
58	2.5		2°C SST	Functional extinction of coral reef ecosystems (overgrown by algae)	Indian Ocean	Corals, fish	9
59	2.6			4–21% of plants committed to extinction	Europe	Plants	1
60	2.7			1–6 rodent species (1–5% of 111 mammals studied) committed to extinction	Europe	Mammals	71
61	2.8	2.5–3.0		Multimodel mean 62% (range 40–100%) loss Arctic summer ice extent, high risk of extinction of polar bears, walrus, seals; Arctic ecosystem stressed	Arctic	Mammals	11, 53
62	2.8			65 species at increased risk of extinction with high risk for endemic Scottish Crossbill, Imperial Eagle and Marmora's warbler	Europe	Birds	65
63	2.9		2.1–3.9	21–36% of butterflies committed to extinction; >50% range loss for 83% of 24 lat. restricted species	Australia	Insects	1, 30
64	2.9	2.6–3.3	2.1–2.8	21–52% (mean 35%) of species committed to extinction	Globe (20% terrestrial surface)	Plants, vertebrates and insects	1
65	3.1	2.3–3.7	2°C SST	Functional extinction of remaining coral reef ecosystems (overgrown by algae)	Globe	Corals, fish	2
66	3.1	2.5–4.0	2	High risk of extinction of Golden Bowerbird as habitat reduced by 90%	Australia	Birds	4

67	3.1	1.8–4.2	3–4	Risk of extinction of Alpine species	Europe	Plants	41
68	2.4–4.0			Of 40 endemic/near endemic species studied, 5–8 are threatened with extinction losing 90–100% of their original range	Europe	Birds	73
69	3.3	2.8–3.8	2	Risk of extinction of Hawaiian honeycreepers as suitable habitat reduced by 62–89%	Hawaii	Birds	18
70	3.3		3.7	4–38% of birds committed to extinction	Europe	Birds	1
71[a]	3.3			32–34% of bird species at risk of extinction, and 6–8% projected extinct	Western Hemisphere	Birds	70
72	3.5	2.0–5.5		Projected extinction of 15–40% endemic species in global biodiversity hotspots (narrow specificity)	Globe		50
73	3.6	2.6–3.7		30–40% of 277 mammals in 141 parks critically endangered/extinct; 15–20% endangered	Africa	Mammals	23
74	3.9			4–24% plants critically endangered/extinct; mean species turnover of 63% (spatial range 22–90%); mean species loss of 42% (spatial range 2.5–86%)	Europe	Plants	22
75	4.0	3.0–5.1	3	Likely extinctions of 200–300 species (32–63%) of alpine flora	New Zealand	Plants	33
76	4.0			1–10 species (1–9.% of 111 mammals studied) committed to extinction	Europe	Mammals	71
77	>4.0		3.5	38–67% of frogs, 48–80% of mammals, 43–64% of reptiles and 49–72% of birds committed to extinction in Queensland as 85–90% of suitable habitat lost	Australia	Reptiles, amphibians, birds, mammals	1, 7
78[a]	4.5			39–42% of bird species at risk of extinction, and 10–15% projected extinct	Western Hemisphere	Birds	70
79	>>4.0		5	57 endemic frogs/mammals eventually extinct, 8 endangered	Australia	Amphibians, mammals	7

Table 3 (continued)

No.	ΔT_g above pre-ind °C	ΔT_g above pre-ind °C (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
80	>>4.0		7	Eventual total extinction of all endemic species of Queensland rainforest	Australia	Reptiles, amphibians, birds, mammals	7
81	5.0			22–24% of 100 *Banksia* species studied projected extinct	W. Australia	Plants	74
82[a]	6.9			50–57% of bird species at risk of extinction, and 19–30% projected extinct	Western Hemisphere	Birds	70

A novel climate is a climate which is significantly different from the present climate whilst a disappearing climate is a climate that disappears from a given area, for example on a mountaintop or a coastline where geography prevents a species from tracking the changing climate. For further details see Williams et al. (2007)

Sources: 1—Thomas et al. (2004a), 2—Hoegh-Guldberg (1999), 4—Hilbert et al. (2004), 5—Rutherford et al. (2000), 6—Leemans and Eickhout (2004), 7—Williams et al. (2003), 8—Theurillat and Guisan (2001), 9—Sheppard (2003), 10—Eliot et al. (1999), 11—Symon et al. (2005), 12—Hughes et al. (1996), 13—Preston (2006), 14—Zöckler and Lysenko (2000), 15—Ni (2001), 16—Bakkenes et al. (2002), 17—Still et al. (1999), 18—Benning et al. (2002), 19—Xenopoulos et al. (2005), 20—European Climate Forum (2004), 21—Cox et al. (2004), 22—Thuiller et al. (2005), 23—Thuiller et al. (2006), 24—Midgley et al. (2002), 25—Hannah et al. (2002), 26—Peterson et al. (2002), 27—Erasmus et al. (2002), 28—Villers-Ruiz and Trejo-Vazquez (1998), 29—Galbraith et al. (2002), 30—Beaumont and Hughes (2002), 31—Kerr and Packer (1998), 32—McDonald and Brown (1992), 33—Halloy and Mark (2003), 34—Moriondo et al. (2006), 35—Nicholls et al. (1999), 36—Najjar (2000), 37—Sorenson et al. (1998), 38—Johnson et al. (2005), 39—Broennimann et al. (2006), 40—Kaplan et al. (2003), 41—Theurillat et al. (1998), 42—Forcada et al. (2006), 43—Price and Root (2005), 44—Siqueira and Peterson (2003), 45—Pickering et al. (2004), 46—Scholze et al. (2006), 47—Raven et al. (2005), 48—Cox et al. (2000), 49—Orr et al. (2005), 50—Malcolm et al. (2006), 51—Peck et al. (2004), 52—Pounds et al. (2006), 53—Arzel et al. (2006), 54—Bosch et al. (2006), 57—Berry et al. (2005), 58—Lucht et al. (2006), 59—Schaphoff et al. (2006), 60—McClean et al. (2005), 61—Williams et al. (2007), 62—Durance and Ormerod (2007), 63—Hawkes et al. (2007), 64—van Vuuren et al. (2006), 65—Huntley et al. (2006), 66—Lensing and Wise (2007), 67—Ohlemüller et al. (2006), 68—Foden et al. (2007), 69—Cramer et al. (2001), 70—Sekercioglu et al. (2008), 71—Levinsky et al. (2007), 72—Memmott et al. (2007), 73—Huntley et al. (2008), 74—Fitzpatrick et al. (2008)

[a] Uniquely in this table, these five entries originate from a study which considers impacts by 2100 through a combination of climate change and land use change

Table 4 Projected impacts of climate change on various ecological systems and species as reported in the literature for different levels of global mean annual temperature rise ΔT_g, relative to pre-industrial climate (mean and range), showing also regional temperature change ΔT_{reg} relative to 1990 if provided by the literature: large-scale ecosystem collapse

No.	ΔT_g above pre-ind °C	ΔT_g above pre-ind °C (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
83	2.5		2°C SST	Functional extinction of coral reef ecosystems (overgrown by algae)	Indian Ocean	Corals, fish	9
84	2.5	2.0–3.0		Major loss of Amazon rainforest with large losses of biodiversity	S America, Globe		21, 46
85	>2.5			Sink service of terrestrial biosphere saturates and begins turning into a net carbon source	Globe	Land ecosystems	58, 59
86	3.1	2.3–3.7	2°C SST	Functional extinction of remaining coral reef ecosystems (overgrown by algae)	Globe	Corals, fish	2
87	3.7			Few ecosystems can adapt	Globe		6
88	3.7			50% of nature reserves cannot fulfil conservation objectives	Globe		6

A novel climate is a climate which is significantly different from the present climate whilst a disappearing climate is a climate that disappears from a given area, for example on a mountaintop or a coastline where geography prevents a species from tracking the changing climate. For further details see Williams et al. (2007)

Sources: 1—Thomas et al. (2004a), 2—Hoegh-Guldberg (1999), 4—Hilbert et al. (2004), 5—Rutherford et al. (2000), 6—Leemans and Eickhout (2004), 7—Williams et al. (2003), 8—Theurillat and Guisan (2001), 9—Sheppard (2003), 10—Eliot et al. (1999), 11—Symon et al. (2005), 12—Hughes et al. (1996), 13—Preston (2006), 14—Zöckler and Lysenko (2000), 15—Ni (2001), 16—Bakkenes et al. (2002), 17—Still et al. (1999), 18—Benning et al. (2002), 19—Xenopoulos et al. (2005), 20—European Climate Forum (2004), 21—Cox et al. (2004), 22—Thuiller et al. (2005), 23—Thuiller et al. (2006), 24—Midgley et al. (2002), 25—Hannah et al. (2002), 26—Peterson et al. (2002), 27—Erasmus et al. (2002), 28—Villers-Ruiz and Trejo-Vazquez (1998), 29—Galbraith et al. (2002), 30—Beaumont and Hughes (2002), 31—Kerr and Packer (1998), 32—McDonald and Brown (1992), 33—Halloy and Mark (2003), 34—Moriondo et al. (2006), 35—Nicholls et al. (1999), 36—Najjar (2000), 37—Sorenson et al. (1998), 38—Johnson et al. (2005), 39—Broennimann et al. (2006), 40—Kaplan et al. (2003), 41—Theurillat et al. (1998), 42—Forcada et al. (2006), 43—Price and Root (2005), 44—Siqueira and Peterson (2003), 45—Pickering et al. (2004), 46—Scholze et al. (2006), 47—Raven et al. (2005), 48—Cox et al. (2000), 49—Orr et al. (2005), 50—Malcolm et al. (2006), 51—Peck et al. (2004), 52—Pounds et al. (2006), 53—Arzel et al. (2006), 54—Bosch et al. (2006), 57—Berry et al. (2005), 58—Lucht et al. (2006), 59—Schaphoff et al. (2006), 60—McClean et al. (2005), 61—Williams et al. (2007), 62—Durance and Ormerod (2007), 63—Hawkes et al. (2007), 64—van Vuuren et al. (2006), 65—Huntley et al. (2006), 66—Lensing and Wise (2007), 67—Ohlemüller et al. (2006), 68—Foden et al. (2007), 69—Cramer et al. (2001), 70—Sekercioglu et al. (2008), 71—Levinsky et al. (2007), 72—Memmott et al. (2007), 73—Huntley et al. (2008), 74—Fitzpatrick et al. (2008)

Table 5 Projected impacts of climate change on various ecological systems and species as reported in the literature for different levels of global mean annual temperature rise ΔT_g, relative to pre-industrial climate (mean and range), showing also regional temperature change ΔT_{reg} relative to 1990 if provided by the literature: miscellaneous impacts

No.	ΔT_g above pre-ind °C	ΔT_g above pre-ind °C (range)	ΔT_{reg} above 1990 °C (range)	Impacts to unique or widespread ecosystems or population systems	Region	Taxa	Source
89	0.6			Increased coral bleaching	Caribbean, Indian Ocean, Great Barrier Reef	Corals	2
90	<1			Marine ecosystems affected by continued reductions in krill possibly impacting Adelie and chinstrap penguin populations; Arctic ecosystems increasingly damaged	Antarctica, Arctic	Crustaceans	42, 11, 14
91	1.7	1–2.3	1°C SST	All coral reefs bleached	Great Barrier Reef, SE Asia, Caribbean	Corals	2
92	1.9	1.0–2.8		Most areas experience 8–20% increase in number ≥7 day periods with Forest Fire Weather Index > 45: increased fire frequency converts forest and Macquis to scrub, leads to more pest outbreaks	Mediterranean		34
93	2.0	1.3–2.3	1	21% decline in spring macro-invertebrate abundance in upland streams	UK	Invertebrates	62
94	2.1	1.0–3.2	1–2	Alpine systems in Alps can tolerate local temperature rise of 1–2°C, tolerance likely negated by land use change	Europe		8
95	2.2	–		Net primary production rises from 45–60 (pre-industrial) to 60–75 Pg C/year; net ecosystem production from zero (pre-industrial) to 2.5–7.5 Pg C/year	Globe		69
96	2.3	2.0–2.5		Fish populations decline, wetland ecosystems dry and disappear	Malawi (Africa), Great Lakes	Fish	20
97	2.4	2.0–3.5		4–20% of the earth's terrestrial surface experiences novel climate; 4–20% experiences disappearing climate	Globe		61
98	2.4	1.8–3.2	3	Extreme levels of mortality in loggerhead sea turtle	Southern US	Reptiles	63
99	2.6	1.6–3.5		Most areas experience 20–34% increase in number ≥7 day periods with Forest Fire Weather Index > 45: increased fire frequency converts forest and Macquis to scrub, causes more pest outbreaks	Mediterranean		34

100	2.8	1.2–4.5	1–3	Extensive loss/conversion of habitat in Kakadu wetland due to sea level rise and saltwater intrusion	Australia		10
101	2.8	2.5–3.0		Multimodel mean 62% (range 40–100%) loss Arctic summer ice extent, high risk of extinction of polar bears, walrus, seals; Arctic ecosystem stressed	Arctic	Mammals	11, 53
102	2.9	1.6–4.1		Threat of marine ecosystem disruption through loss of aragonitic pteropods	S Ocean	Crustaceans	49
103	2.9	1.6–4.1		70% reduction in deep-sea cold-water aragonitic corals	Ocean Basins	Corals	48
104	3.0			In a study of 1420 pollinator species feeding on 429 plant species, 17–50% experience disruption in food supply	Illinois, USA	Plants, insects	72
105	3.1	1.9–4.1	3–4	Alpine systems in Alps degraded	Europe		8
106	3.2	–		Net primary production rises from 45–60 (pre-industrial) to 72–93 Pg C/year; net ecosystem production from zero (pre-industrial) to 0–7 Pg C/year	Globe		69
107	3.3	2.0–4.5		Reduced growth in warm water aragonitic corals by 20–60%; 5% decrease in global phytoplankton productivity	Globe	Corals	2, 47, 48
108	4.0	2.5–4.5		12–39% earth's surface experiencing novel climate; 10–48% disappearing climate	Globe		61

A novel climate is a climate which is significantly different from the present climate whilst a disappearing climate is a climate that disappears from a given area, for example on a mountaintop or a coastline where geography prevents a species from tracking the changing climate. For further details see Williams et al. (2007)

Sources: 1—Thomas et al. (2004a), 2—Hoegh-Guldberg (1999), 4—Hilbert et al. (2004), 5—Rutherford et al. (2000), 6—Leemans and Eickhout (2004), 7—Williams et al. (2003), 8—Theurillat and Guisan (2001), 9—Sheppard (2003), 10—Eliot et al. (1999), 11—Symon et al. (2005), 12—Hughes et al. (1996), 13—Preston (2006), 14—Zöckler and Lysenko (2000), 15—Ni (2001), 16—Bakkenes et al. (2002), 17—Still et al. (1999), 18—Benning et al. (2002), 19—Xenopoulos et al. (2005), 20—European Climate Forum (2004), 21—Cox et al. (2004), 22—Thuiller et al. (2005), 23—Thuiller et al. (2006), 24—Midgley et al. (2002), 25—Hannah et al. (2002), 26—Peterson et al. (2002), 27—Erasmus et al. (2002), 28—Villers-Ruiz and Trejo-Vazquez (1998), 29—Galbraith et al. (2002), 30—Beaumont and Hughes (2002), 31—Kerr and Packer (1998), 32—McDonald and Brown (1992), 33—Halloy and Mark (2003), 34—Moriondo et al. (2006), 35—Nicholls et al. (1999), 36—Najjar (2000), 37—Sorenson et al. (1998), 38—Johnson et al. (2005), 39—Broennimann et al. (2006), 40—Kaplan et al. (2003), 41—Theurillat et al. (1998), 42—Forcada et al. (2006), 43—Price and Root (2005), 44—Siqueira and Peterson (2003), 45—Pickering et al. (2004), 46—Scholze et al. (2006), 47—Raven et al. (2005), 48—Cox et al. (2000), 49—Orr et al. (2005), 50—Malcolm et al. (2006), 51—Peck et al. (2004), 52—Pounds et al. (2006), 53—Arzel et al. (2006), 54—Bosch et al. (2006), 57—Berry et al. (2005), 58—Lucht et al. (2006), 59—Schaphoff et al. (2006), 60—McClean et al. (2005), 61—Williams et al. (2007), 62—Durance and Ormerod (2007), 63—Hawkes et al. (2007), 64—van Vuuren et al. (2006), 65—Huntley et al. (2006), 66—Lensing and Wise (2007), 67—Ohlemüller et al. (2006), 68—Foden et al. (2007), 69—Cramer et al. (2001), 70—Sekercioglu et al. (2008), 71—Levinsky et al. (2007), 72—Memmott et al. (2007), 73—Huntley et al. (2008), 74—Fitzpatrick et al. (2008)

used originally by the study to assess the impact. The process was repeated (1) for the other 12 GCM/emission scenarios and (2) for eight surrounding adjacent grid cells to test the sensitivity of the results in terms of spatial coherence when using a group of grid cells versus a single grid cell. For each GCM scenario, the average ΔT for the nine (central plus eight adjacent) grid cells was computed. The resultant collection of up to 13 global ΔT values gave the range of global annual mean temperature rise as listed in Tables 2, 3, 4 and 5. In cases where a study has referred to an area larger than a group of nine grid cells, either a cluster of disjunct groups or contiguous orographic features, such as a mountain range or a plain, were aggregated into several clusters of grid cell groups across the region. The entries in the tables reflect also the average and range of outputs over the appropriate clusters of groups of grid cells.

Large local temperature increases can lie outside the range of the outputs of the GCMs held in the database. If this was the case, the study was not included in the upscaling calculations. GCMs with temperature changes that were too low to reach the study value(s) were excluded. Table 6 in the Appendix details which GCMs were used in the upscaling. If more than two GCMs were thus out of range, we assumed case f (Table 1) to avoid underestimating ΔT_g. Note that the GCM time series for ΔT_g are provided with respect to an observed mean over the period 1961–1990, ensuring that correct temperature reference points were maintained in all upscaling.

3 Results

Tables 2, 3, 4 and 5 provide the resultant summary of key impacts on various ecological systems, ranging from the global level to that of individual, endemic species. The supplementary information in Table 6 in the Appendix provides for each entry from Table 2a–d information on the GCM runs used in upscaling, the climate variables considered by the impact study, and the category of the upscaling method we applied (a–h, see Table 1). 71 studies were found to provide sufficient quantitative climatic and ecological information for inclusion in Table 2a–d. Projected impacts were found for all major world regions, but only one study focused on Asia. Most studies were on terrestrial systems, whilst relatively few covered changes in the marine environment. Range losses and extinctions (Tables 2 and 3) were projected for many important taxa with vascular plants, birds, and mammals being particularly well represented. A significant number of studies also projected impacts on amphibians, reptiles, fish, butterflies, and freshwater or marine invertebrates. Table 2 also shows many projections for major losses of regional ecosystems as climate changes. Table 4 shows projections for large scale collapse in ecosystems, i.e. thresholds at which major components of the world's ecosystems become irreversibly damaged, positive feedbacks emerge, or their functioning, collapse. As global temperatures rise, many of these thresholds start to be crossed at around $\Delta T_g = 2.5°C$ above the pre-industrial level.

A key finding is that some significant negative impacts for range losses and extinctions (Tables 2 and 3), and also damages to marine ecosystems (Table 4), were projected to occur for values of ΔT_g below 2°C, especially in some biodiversity hotspots, and also globally for the diversity rich coral reef ecosystems ($\Delta T_g = 1.7°C$). However, it is also noticeable that, given the analyzed literature, projected impacts increase in magnitude, numbers and geographic spread once a 2°C rise in global mean temperature is reached. Beyond this temperature rise the level of impacts and the transformation of the Earth's ecosystems become steadily more severe, with the potential collapse of some entire ecosystems, and extinction risks accelerating and becoming widespread. Additional positive feed-backs emerge causing land ecosystems to transition from their current status as a net carbon sink to a net carbon source.

4 Discussion

4.1 General

A large body of literature exists discussing the potential future impacts of climate change upon ecosystems, as reviewed in Fischlin et al. (2007). Much of this literature does contain only qualitative or no directly comparable quantitative projections of change or does not relate any quantitative estimates of change to quantitative changes in global climate. Previous integrating summaries of climate change impacts on wild species and ecosystems have suggested substantial ecosystem disruption with projected anthropogenic climate changes, and particularly the increased risk of species extinction (e.g. Thomas et al. 2004a, b). Such findings have been criticised partly because they did not reference the projected impacts to a consistent measure of climate change. In order to provide robust findings in a policy relevant manner, it is critical to reduce the uncertainty created by this lack of a common reference. Hence Warren (2006) and Hare (2006) both took steps to do so. The results reported here, through use of a common temperature reference point, confirm the likelihood of significant negative impacts of climate change first mooted in studies such as Thomas et al. (2004a, b), but provide a far clearer picture of the likely increase in scale of impacts with increasing levels of climate change, together with an indication of uncertainty associated with ΔT_g.

With our common referencing system, we can also address the question as to what extent the literature has sampled the range of climate change forcings of the next few centuries adequately for the observations made by this study to be valid. The likely range of temperature increase in 2100 is 1.1°C to 6.4°C above the 1980–1999 average (i.e. 1.6°C to 6.9°C above the pre-industrial level), showing that the literature currently does not sample the upper end of this range, with most studies considering only the range between 1.5°C and 4°C above pre-industrial). Within these limits however, a broad range of global annual mean temperature rises is sampled, owing to the many different scenarios and GCMs used. This is the case for those studies that are based on GCM scenario outputs as well as the many other regional scenarios based only upon potential local, non-GCM-scenario based climate changes. A small subset of the studies considers the effects of doubling CO_2 concentrations, whilst another subset is based on transient climate change simulations. Because different GCMs are used in these subsets, the resultant global mean temperature, and concomitantly precipitation, values vary considerably among climate models, in particular in cases where regional scenarios of climate change were derived. We believe the small subset of table entries referring only to CO_2 concentration doubling has not introduced a bias. Owing to a sampling of a relatively comprehensive temperature range similar to that covered by many scenarios (0.3–6.4°C, IPCC 2007), the overall interpretation of the results is not biased by any artificial clustering of data around a particular global mean temperature rise.

The majority of the impacts found in the literature are negative, with the exception of those projecting increases in primary production. Whilst a higher productivity may indeed increase vegetation growth, this in itself can disrupt species assemblages and thereby degrade ecosystems. For example, in tropical forests increased concentrations of CO_2 are stimulating rapid growth by vines (Granados and Körner 2002), which can strangle large trees (Phillips et al. 2002); and increasing growth rate and turnover of trees could even result in lower carbon storage rates, thus reducing the forest's service as a carbon sink (Feeley et al. 2007). Hence, with the exception of enhanced growth at moderate climate change we have rarely identified definitively positive impacts of climate change upon ecosystems. Whilst some authors consider transitions from desert to grassland or grassland to forest as "positive" in terms of gains in net primary production, this often neglects the issue of transient dynamics between previous and new equilibrium, and threats to endemic and specialist organisms of the replaced environments. Some studies indicate transitionally an even lower productivity (e.g., Fischlin and Gyalistras 1997).

4.2 Uncertainties in the analysis

This study has considered the role of uncertainty only in a limited manner, as it is difficult to quantify. The uncertainty analysis carried out is limited by its dependency on downscaling and upscaling of pattern-scaled transient temperature outputs of GCMs, and thus is contingent on the assumptions of pattern regularity as assumed in most down-scaling procedures (e.g., Gyalistras et al. 1994), in particular that the patterns are constant over a particular temperature range. It is also assumed that the patterns are independent of the history of greenhouse gas forcing, whereas in actuality an equilibrium climate change pattern may differ from transient ones. Equilibrium patterns were not available for this analysis, but would be more suitable for use with studies of type b, or studies of type c or d which actually use outputs of equilibrium runs of GCMs. The uncertainty analysis also reflects only the different relationships between global and local temperature displayed by various GCMs, and not the relationship between global temperature and local precipitation changes. In some cases where impacts are strongly driven by precipitation and models differ widely for the location in question, for example entry 41, the loss of forest cover in the Amazon basin (Cox et al. 2004), this could be important.

Much of the literature reviewed here is based on a biogeographical or bioclimatic approach. Whilst this approach has been criticised for its shortcomings in largely ignoring some mechanisms such as physiological responses, the treatment of species–species interactions, the limited accounting for population processes or migration (Pearson and Dawson 2003; Pearson 2006), or the common assumption that current species distributions are in equilibrium with current climate, the approach has nevertheless proved capable of simulating known species range shifts in the distant and the recent past (Martinez-Meyer et al. 2004, Araujo et al. 2005), and furthermore, is generally corroborated by the observed responses of many species to recent climatic changes (e.g. Walther et al. 2002; Root et al. 2003; Rosenzweig et al. 2007) and climate-change induced changes in geographical species ranges, which are starting to be reported (Thomas et al. 2006; Foden et al. 2007). However the approach remains nevertheless to be comprehensively and explicitly tested against the observational record (Midgley and Thuiller 2005), an opportunity that should be taken as soon as possible. Most of the studies reported in Tables 2 and 3 result from detailed analysis of well-studied species and ecosystems in a given locality. In the case of the global extinction rate estimates (Thomas et al. 2004a) there has been a debate as to the validity of the particular species–area relationship used to estimate extinction rates (Thuiller et al. 2004; Thomas et al. 2004b; Buckley and Roughgarden 2004; Harte et al. 2004; Lewis 2006). Whilst these estimates are based on extrapolation of studies of endemics, Thomas et al. (2004b) argue that this creates only a small bias because such a large percentage of global species are in fact endemics. The study of Malcolm et al. (2006) provides an overall estimate of extinctions of endemics in biodiversity hotspots that does not rely on bioclimatic modelling of individual species, and generally supports the findings of Thomas et al. (2004a), though the use of endemic–area relationships rather than simple species–area relationships indicates some reduced impacts.

Responses of species to changing climate will also be affected by biotic interactions, which affect the levels of space occupancy and dispersal; e.g. in alpine plant communities, mutualists are expected to be able to tolerate greater climate change than competitors at slow rates of climate change, whereas at faster rates they may be excluded by competitors if these can easily disperse into newly climatically suitable areas (Brooker et al. 2007).

4.3 Factors omitted or partly considered in this study and the underlying literature

4.3.1 Direct effects from raising atmospheric CO_2 concentrations

In Tables 2, 3, 4 and 5, the temperature column is essentially used as a proxy for the accompanying other changes, which will occur concurrently, such as precipitation change or elevated CO_2 concentrations. However, only a limited number of studies that project climate change impacts upon ecosystems consider concurrent changes such as the direct effects of elevated ambient CO_2 concentrations associated with local or global scenarios of temperature rise. This is particularly true of studies based on bioclimatic modeling, or niche-based modelling techniques that simulate species geographic range shifts. Despite increasing evidence that CO_2 fertilization effects on crop species have been somewhat overestimated in the past (Fischlin et al. 2007), those on wild plant species and particularly trees are corroborated by strong evidence (e.g., Ainsworth and Long 2005). This may remain a significant omission in the modeling of some ecosystem types. For example, CO_2 fertilization may differentially affect woody and herbaceous species, affecting the dynamics of forest–savanna–grassland conversions with major implications for biodiversity (Bond et al. 2003). Whilst a small number of entries in the tables derive from consideration of ocean acidification, the literature in this area is in its infancy. As oceans continue to acidify as atmospheric CO_2 concentrations rise concurrently with warming, there is significant potential for changes in marine food webs and hence the valuable ecosystem services that the oceans provide for humankind (Orr et al. 2005; Haugan et al. 2006).

4.3.2 Indirect effects of climate change

Tables 2, 3, 4 and 5, and the literature upon which they are based, largely document only the projected impacts on ecological systems resulting directly from climate changes such as changes in temperature and precipitation, the most commonly considered variables. However, there are a number of other impacts on ecosystems to be expected, that result from non climatic causes or indirectly via climatic changes. For example (1) wildfires and certain defoliating insects are projected to increase with warming (for example in boreal forests and the Mediterranean, e.g., Fischlin et al. 2007; Kurz et al. 2008), and decomposition rates will change by large percentages as rainfall changes (for example in deciduous forests in the USA, e.g. Lensing and Wise 2007) both of which is likely to have further impacts on forest and grassland ecosystems as well as causing substantive biotic feedbacks to the climate system; (2) secondary succession may last several centuries (Fischlin and Gyalistras 1997), thus delaying actual impacts and causing additional effects in other communities; (3) surprising ecological changes may also occur in marine and terrestrial communities with climate change if predators and prey become decoupled, or newly engage with each other, which could occur if they have differing phenological, geographical, and/or physiological responses to climate change (Price 2002; Burkett et al. 2005); (4) indirect impacts from sea ice melting, for example reductions in sea ice in the Antarctic are likely to have contributed to the dramatic 80% declines in krill observed since 1970 (Atkinson et al. 2004) with penguin populations already affected, and particularly if climate change shifts the Antarctic Circumpolar Current, krill could suffer further and the ecosystem could be severely impacted; (5) climate change is also projected to cause deglaciations, e.g. of the Himalayan region, which would adversely affect the hydrology of the downstream regions, e.g. of the Indian region including its ecosystems; (6) increases in the magnitude and/frequency of (intra-annual) extreme weather events are projected with climate change as climate variability increases (e.g. Schär et al. 2004; Meehl et al. 2007), all of which have a significant potential to affect ecosystems further (e.g. Fuhrer et al. 2006). Many impact models consider such effects only in a limited manner, e.g. because of a too coarse temporal resolution; (7) climate change may affect major modes of interannual cyclic variability such as El Nino, the North Atlantic Oscillation, or the Pacific Decadal Oscillation. GCMs do not capture such changes to a realistic extent and many impact models have only captured such climate variability effects to a limited extent if at all. Changes to these cycles are likely to affect ecosystems through for example, changed rainfall patterns and/or drought and fire incidence (e.g. Holmgren et al. 2001).

4.3.3 Land-use change

This meta-analysis focuses on the impacts of climate change and does not account for the effects of land-use change. More realistic impacts, notably those of species extinctions in 2100 and beyond, are likely to be greater than Tables 2, 3, 4 and 5 indicate, since land-use change is included in only one study (Sekercioglu et al. 2008), and is known to negatively impact biodiversity. These additional negative impacts from land-use change would only be avoided if effective stringent policies would soon be put into place that avoid further conversion of natural and semi-natural ecosystems to agriculture, landscape fragmentation, and/or other degradations within a given type of land use as for instance also caused by intensification of agricultural practices. Owing to the development of human systems and their adaptation to climate change, including the potential use of biofuels as a mitigation measure, both of which may force new areas into cultivation, and the projected increases in global human populations, there are in fact rather to be expected increased pressures on extant land uses than the reverse. Some scenarios of future land uses have been developed for and reviewed in the Millennium Ecosystem Assessment (2005) and evince this overall trend.

Since land-use change is well known to be of critical relevance for biodiversity conservation, Lewis (2006) raised the concern that recent literature on potential extinctions due to climate change could distract conservationist's efforts in preventing land-use change in existing ecosystems, in particular with respect to avoiding deforestation. Jetz et al. (2008) projects losses of current ranges for 21–26% of the world's approximately 8,750 bird species by 2050, and for 29–35% by 2100, due to the combination of climate change scenarios from Solomon et al. (2007) and land-use change scenarios from the Millennium Ecosystem Assessment (MEA 2005). The need to provide for species to disperse successfully to reach areas that become newly climatically suitable increases the need for protecting existing ecosystems from land-use change. These findings suggest that avoided deforestation policies offer a crucial double benefit of reducing both climate change and land-use change impacts upon biodiversity. Thus, for these reasons we consider evidence that climate change can have severe impacts on biodiversity as presented in this analysis rather to provide an additional strong incentive for preserving existing ecosystems, including their protection from land-use changes, than an invitation to neglect conservation policies.

4.3.4 Dynamics

There are very few studies in the literature, which take into account the effect that the rate of climate change exerts upon ecosystems. This is also likely to be a key factor, since the slower the rate of change the greater is the potential for adaptation by dispersal or through natural selection for physical or behavioural characteristics better suited to a changed climate (for a recent review see Fischlin et al. 2007, notably Section 4.4.5). For very small amounts of warming there may be benefits in terms of increased productivity in ecosystems which are below their thermal optimum, for example in boreal forests. However, as temperature increases further the thermal optimum is passed, and the ecosystem begins to decline. It is the passing of such thresholds or "tipping points", the onset of negative impacts, which are the focus of the literature underlying this paper.

Some such "tipping points" are breached when a certain magnitude of climate change is reached. Regional features of the earth's climate system might also be disrupted, with concurrent un-quantified impacts upon ecosystems. For example, the Indian Monsoon might be disrupted (Zickfield et al. 2005). At the Earth system scale, as temperature continues to rise, additional positive feedback mechanisms may be activated. Examples are the saturation of the net carbon sink land ecosystems currently provide, the transition to a net source (Fischlin et al. 2007, Fig. 4.2), or the risk for the potential release of methane from tundra yedoma and permafrost (Fischlin et al. 2007) and perhaps beyond 2100 even clathrates from shallow seas. The weakening of the land sink, let alone the turning into a source, as well as a release of substantive amounts of methane would cause a strong amplification of the greenhouse effect, greatly exacerbating the ongoing climate change.

Some such "tipping points" are breached when a certain rate of climate change surpasses the rate by which ecosystems can adapt naturally. During past phases of large climate changes, species have typically responded by shifting range rather than by evolving in situ (Davis and Shaw 2001). Ecosystems have been estimated to be able to withstand a temperature increase of only 0.05–0.1°C/decade (van Vliet and Leemans 2006), much slower than the current rate of 0.13°C/decade (Solomon et al. 2007) and hugely slower than the current rate near the poles of 0.46°C/decade, considered sufficient to cause serious ecosystem disruption. Foden et al. (2007) show how the currently observed migration rate of *Aloe dichotoma* (quiver tree), a Namib desert plant, in response to observed climate change, would be insufficient to keep pace with a moderate climate change scenario for 2050. Based on a comprehensive review of these issues Fischlin et al. (2007) concluded that "The resilience of many ecosystems is likely to be exceeded this century" for business-as-usual emissions scenarios (e.g. IS92a, A1FI, A2). Resilience is here understood as the capacity of ecosystems to adapt naturally and sufficiently fast to their changing environment without altering their mode of operation entirely.

This meta-analysis is based on impact studies that assume in many cases a new hypothetical equilibrium between the projected climate change and the impacted ecosystems. Typically the forcing climate change is then assumed to have remained constant indefinitely at the ΔT_g for which the impact was assessed and that the ecosystems are given sufficient time to adapt till the new estimated equilibrium has been reached. Most of the literature used in this analysis does not explicitly discuss the time dimension, but it can nevertheless be assumed in most cases that the ecosystem impacts in Table 5 might also occur if the temperature thresholds are breached transiently (i.e. local or regional temperature "overshoots") as simulated in various studies of the dynamics of climate change (O'Neill and Oppenheimer 2004).

Den Elzen and Meinshausen (2006) show that transient probabilities of exceeding various temperature thresholds might either be higher, or lower, than the equilibrium probabilities of exceedance of that threshold. Similarly Mastrandrea and Schneider (2006) show how probability of exceedance of temperature thresholds in stabilisation scenarios is a strong function of the pathway to stabilisation. Thus, one may argue that our assessment may indeed be questioned as the evolution of temperature and other concomitant climate change variables differ. However, the advantage of our approach is that the ranking of the impacts relative to the temperature increase as an indicator of climate change is unlikely to be affected even if the absolute values might have to be corrected as our understanding of these relationships progresses. In this respect our results can be viewed as being quite robust and conservative.

The question remains whether the impact models used have realistic sensitivities. Otherwise overestimations or underestimations of the impacts would have to be expected. The majority of the impact models we used here have considered changes in temperature as well as precipitation and many have also considered the beneficial effects from CO_2 fertilisation, in particular at the global level. This makes the models more likely to exhibit realistic responses to climate change than this was the case for many earlier studies, which followed less integrative approaches.

Nevertheless, the particular approach that many current state-of-the-art impact models follow may lead to biases. First in cases where the climate change was assumed to remain constant after having reached ΔT_g, the impact models that have not yet reached the new equilibrium tend to underestimate the impacts. Secondly, if the magnitude of climate change exceeds rapidly certain tolerances, i.e. the fundamental niches, of impacted species, even long-lived species such as trees are likely to suffer mortalities before they are replaced by newly arriving, other species for which the new, climatic situations are more benevolent. Thus, in general the more rapid climate change, the more likely such transient ecosystem degradations become. Indeed, the modelling approaches generally followed do incompletely mimic such effects and for these reasons tend to rather underestimate than overestimate impacts. Finally, for other processes such as coral bleaching and local extinction of sensitive species, which can occur within a relatively short time span of a few years, transient temperature peaks might be very critical. If emissions are reduced in a manner such that there is transient overshooting of the final equilibrium temperature, impacts may then be considerably greater than indicated in Tables 2, 3, 4 and 5.

Therefore we consider the results from our meta-analysis to be in general rather conservative and it appears to be unlikely that they are biased towards overestimating the severity of the consequences of climate change for ecosystems. However, critical uncertainties remain, in particular because most impact models depend to a large extent on knowledge about the realized niches only. Should fundamental niches be significantly larger than the realized ones, overestimations of climate change impacts are bound to result. Indeed, the difficulties to assess the true fundamental niches of most species remain a relevant source of uncertainty (Kirschbaum and Fischlin 1996), a fact that still significantly constrains the ability of most currently used kinds of ecological models to assess climate change impacts.

5 Conclusions

A literature-based integrated assessment of the effects of climate change upon a wide range of ecological systems has shown that the negative impacts accrue as annual global mean temperature rise as little as 1.6°C (low end of the likely range of IPCC scenarios,[1] IPCC 2007) above the pre-industrial level, already with several examples of projected severe damages, range losses, and extinctions. As global temperatures reach and exceed 2°C above pre-industrial levels, negative impacts rapidly increase. This includes increases in range losses and extinctions and increasing damage to some critical ecosystem structure and functioning. As global temperatures increase further beyond 2°C above pre-industrial, the literature and models increasingly project impacts accruing to entire systems and becoming more widespread across a range of different species groups and regions. Several critical aspects of ecosystem functioning are projected to begin to collapse at a temperature of 2.5°C (Table 4). These represent either the potential collapse of entire ecosystems e.g. wide-spread impoverishment of coral reefs, or comprise impacts, which are in our judgement dangerous, because they likely imply irreversible damages, such as extinctions of key species, or the onset of positive feedbacks, such as CO_2 emissions, accelerating climate change. In our judgement, risking the widespread collapse of multiple global

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[1] This value considers the multi-model projected lower end of the likely range of the IPCC SRES B1 scenario (IPCC 2007, Table SPM.3) of +1.1°C warming by 2100 relative to 1980–1999 and adding +0.5°C already realized global warming for period 1980–1999 relative to preindustrial climate.

ecosystems (Table 4) represents "dangerous anthropogenic interference" and would comprise a breach of compliance with Article 2 of the United Nations Framework Convention on Climate Change.

This meta-analysis confirms and expands upon the results of other assessments (Houghton et al. 2001; Hare 2006; Warren 2006; Fischlin et al. 2007), which have shown that climate change is a threat to ecosystems and species worldwide, with coral reef, Arctic, Mediterranean, and mountain ecosystems including many biodiversity hotspots being particularly at risk. Hare (2006) also identified substantial increases in risks to ecosystems and species beyond the EU 2°C target using "burning ember" diagrams. We consider that our study, with a more extensive literature review, using a tabular approach and including some uncertainty analysis, provides further strong justification for policies constraining annual global mean temperature change relative to preindustrial climate to no more than 2°C—at least from an ecosystem preservation point of view. This temperature would avoid the projected breaching of the aforementioned large-scale ecosystem collapses, as well as a large proportion of the onset of many of the projected negative impacts such as range losses, extinctions, ecosystem damages including disruptions of their structure and functioning. Since we identified some significant impacts in biodiversity hotspots such as amphibian extinctions in tropical forests and wide spread coral bleaching in reefs below a 2°C warming, protection of the majority of ecosystems would however require a more stringent target, as argued by Rosentrater (2005) for the Arctic.

Many of the impacts tabulated here appear to be clearly in conflict with Article 2 of the United Nations Framework Convention on Climate Change in not allowing ecosystems to adapt naturally. Minimising the rate of climate change is expected to also reduce the risks of climate change for ecosystems, although this aspect can not yet be well analysed with current techniques available to assess impacts. According to the precautionary principle it appears that a reduction in current and future land use change will give ecosystems and species the best chance to adapt to the climate changes that are projected to occur in the twenty-first century even under stringent mitigation policy. In particular, avoided deforestation is a policy which meets both these goals, although alone this policy is of course not sufficient to constrain climate change to 2°C above pre-industrial levels. Further analyses of many of the findings from this study made in an even broader context of climate change impacts on ecosystems can be found in Fischlin et al. (2007).

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Appendix

The Table 6 below contains detailed information concerning the underlying studies used in each entry of Tables 2–5, where column 1 is identical to column 1 of Tables 2–5, and the following abbreviations are used: **E** indicates an empirical derivation, **M** indicates a modelling study, a **number** refers to how many GCMs were used in the original literature. Other codes indicate if model projections included precipitation (**P**), ocean acidification (**pH**), sea ice (**SI**), sea level rise (**SLR**), sea surface temperature (**SST**) or anthropogenic water use (**W**); dispersal assumptions from the literature. **D**—estimate assumes dispersal; **ND**—estimate assumes no dispersal; **NR**—not relevant since species/ecosystem has nowhere to disperse to in order to escape warming (e.g. habitat is at top of isolated mountain or at southern extremity of austral landmass). **IMAGE**, **BIOME4**, **LPJ**, **MAPSS** refer to specific models as used in the study, to assess climate change impacts, e.g. LPJ denotes the Lund–Potsdam–Jena dynamic global vegetation model (Sitch et al. 2003). **DVGM** refers to dynamic global vegetation model. GCM abbreviations used here: **H2**—HadCM2, **H3**—HadCM3, **GF**—GFDL, **EC**—ECHAM4, **CS**—CSIRO, **CG**—CG, **PCM**—NCAR PCM. Lower case a–h refers to how the literature was addressed in terms of up/downscaling and these are defined in Table 1. The GCM outputs used in the upscaling calculations are those used in the IPCC Third Assessment Report (TAR IPCC 2001) and are at 5° resolution: HadCM3 A1FI, A2, B1, B2 where A2 is an ensemble of 3 runs and B2 is an ensemble of 2 runs; ECHAM4 A2 and B2 (not ensemble runs); CSIRO mark 2 A2, B1, B2; NCAR PCM A2 B2; CGCM2 A2 B2 (each an ensemble of 2 runs). Where GCM scenario names only were provided further details were taken from: HadCM2/3 (Mitchell et al. 1995; Hulme et al. 1999; Arnell et al. 2004), http://ipcc-ddc.cru.uea.ac.uk.

Table 6 Supplementary to Tables 2, 3, 4 and 5: the table below contains detailed information on models and how the upscaling and downscaling were performed for each entry in Tables 2, 3, 4 and 5 and uses the same numbering scheme

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
2	1, 4, 9	M, 5, ND, c; ref. quotes 13.8% loss in Rocky Mountains for each 1°C rise in JJA temperature, upscaled with CS, PCM, CG
2	2, 15	M, 5, IMAGE, a; authors confirmed temperature baseline is year 2000 which is 0.1°C warmer than 1990
2	3	M, D, b; no GCM used in ref.; upscaled with H3, EC, CS, PCM, CG
2	14, 32	M, P, GDD, D&ND, a; ref uses B1 and A2 of H3 with ΔT rise of 2.4°C and 3.7°C respectively compared to the 1961–1990 mean
2	6, 7	M, P, NR, e; upscaled at several sites using H3, EC, CS, PCM, CG
2	5	M, H3, E4, P, D&ND, a; GFDL based estimates omitted due to lack of access to global temperature time series
2	10	M, H3, W, a; ref. uses B2 of H3 in 2070 that has a ΔT rise of 2.1°C with respect to the 1961–1990 mean
2	11	M, P, D, d; UKCIP02 high emission scenario used as central value; upscaled for Hampshire from UKCIP02 (Hulme et al. 2002) regional maps using H3, EC, CS
2	12	M, SLR, a; analysis based on transient 50% probability of sea level rise using the US EPA scenarios for ΔT of 2°C above 1990 baseline

Table 6 (continued)

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
2	13	M, H3, SLR, a; IS92a median ΔT 2.0°C above 1990 (Kattenberg et al. 1996, Fig. 6.20) and range 1.4–3.0°C
2	16	M, GE, P, NR, d; GENESIS GCM with 2.5°C rise for CO_2 doubling from 345 to 690ppm, 345 ppm corresponds quite closely to the 1961–1990 mean; upscaling then gives the range; across locations variously used H3, EC, CS, CG
2	17	M, NR, b; upscaled with H3, EC, CS, and CG
2	18	M, P, D, HadCM3, ECHAM4, GFDL, a; Huntley et al. (2006) give 2.5°C relative to 1961–1990 mean
2	19	M, 2, P, d, g; range is due to importance of ΔP, GFDL CO_2 doubling is from 300 ppm which is close to 1900 climate sensitivity in ref of 3.7; UKMO in 2050 is 1.6°C above 1961–1990 mean, 1.9°C above preindustrial
2	20, 21	M, H2, BIOME4, P, NR, c; A1 scenario of H2GS has ΔT of 2.6°C relative to 1961–1990 mean
2	22	M, BIOME3, P, d, f; H2 2080s has global ΔT of 2.6°C above 1961–1990 mean
2	23	M, H3, W, a; ref. uses A2 of H3 in 2070 that has a ΔT of 2.7°C with respect to the 1961–1990 mean and hence 2.5°C with respect to 1990
2	24	M, H3, GF, EC, P, D&ND, a
2	25	M, CS, P, d; upscaled with H3, EC, CS, CG
2	26	M, H2, SLR, NR, a; H2 2080s without aerosols has global ΔT of 3.4°C above pre-industrial (Hulme et al. 1999)
2	27	M, 2, P, D, d; study used CO_2 doubling scenarios—CCC ΔT at doubling is 3.5°C relative to 1900 whilst GFDL R30 is 3.3°C relative to 1900; upscaling gives range H3, EC, CG
2	28	M, D, b; upscaled with H3, EC, CS
2	29	M, CCC, P, D, d; CO_2 equilibrium doubling scenario has ΔT of 3.5°C relative to 1900; downscaled with CGCM and upscaled with H3, EC, CS, CG
2	30	M, 5, IMAGE, P,a; authors confirmed temperature baseline is year 2000 which is 0.1°C warmer than 1990
2	31	M, P, D (based on empirical calibration), d; upscaled with H3, EC, CS, PCM, CG
2	33	M, D, f; Meehl et al. (2007), Fig. 10.3.5 shows this occurs for ΔT $\geq$3.5°C above 1990
2	12, 34	M, D&ND, P, HadCM3, a; Ohlemüller et al. (2006) use HadCM3 projections quoted as '2.0, 4.8°C above 1931–1960 mean for entries 12, 34 respectively, add 0.1°C to convert to pre-industrial

Table 6 (continued)

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
2	35	M, 3, P, a
2	36	M, SLR, a; US EPA scenario of 4.7°C above 1990.
3	37	E
3	38	M, D&ND, a; 18% matches minimum expected climate change scenarios which Table 3 of Thomas et al. (2004a) lists as ΔT of 0.9°–1.7°C (mean 1.3°C) above 1961–1990 mean; 8 of 9 sub-studies used H2
3	39, 55, 71, 78, 82	M, D, a;
3	40	M, H2, P, ND, d; table 3 of Thomas et al. (2004a) gives global ΔT of 1.35°C above 1961–1990; HHGSDX of H3; downscaled with H3 then upscaled with H3, EC, CS, PCM, CG
3	41	M, H2, P, D&ND, d; Beaumont and Hughes (2002) give global mean temperature rise of 1.8°C relative to the 1961–1990 mean
3	42	M, D, P, a
3	43	M, D, b; upscaled using H3, EC, CS, PCM, CG
3	44	M, H3, P, D, d; H3 2050 SRES mean
3	45	M, H2, P, D, d, g; table 3 of Thomas et al. (2004a) gives global ΔT of 1.35°C above 1961–1990; upscaled with H3, EC, CS, PCM, CG; uses a local ΔT range across Australia
3	46	M, H3, P, D&ND, d; ref. uses B1 of H3 in 2050 with a ΔT of 1.8°C above the 1961–1990 baseline; downscaled with H3 and then upscaled with H3, EC, CG
3	47	M, H2, P, D&ND, d; studies used global annual mean ΔT of 1.7–2.0°C above 1961–1990 mean
3	48	M, P, D&ND, a; table 3 of Thomas et al. (2004a) mid-range climate scenarios have a mean ΔT of 1.9°C above 1961–1990
3	49	M, H2, P, D&ND, d; ref. refers to A2 of H3 in 2050 that has a ΔT of gives as 1.9°C above 1961–1990 (Arnell et al. 2004); downscaled with H3 then upscaled with H3, EC, CS, PCM, CG
3	50	H; upscaled using maps from WGI, chapter 10
3	51	M, 2, P, NR, d; scenarios on CRU website used with ΔT of 2.0°C above 1961–1990, agrees with Table 3 of Thomas et al. (2004a) which gives ΔT of 2.0°C above 1961–1990 mean; downscaled with H3 then upscaled with H3, EC, CS, PCM, CG
3	52	M, H2, P, D, d; the 66% is from a suite of 179 representative species, table 3 of Thomas et al. (2004a) lists global ΔT of 2.0°C above 1961–1990 mean, upscaled with H3, EC, CS, CG
3	53	M, H2, P, D&ND, d; table 3 of Thomas et al. (2004a) which gives ΔT of 2.0°C above 1961–1990 mean using HHGGAX; downscaled with H3 then upscaled with H3, EC, CS, PCM, CG

Table 6 (continued)

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
3	54	M, H2, P, ND, d; table 3 of Thomas et al. (2004a) which gives ΔT of 2.0°C above 1961–1990 mean using HHGGAX; downscaled with H3 then upscaled with H3, EC, CS, PCM, CG
3	56	M, IMAGE, P, D&ND; Bakkenes et al. (2002) gives the global temperature change relative to 1990
3	57	M, P, D&ND; ref. uses B1 in H3 in 2080s from (Arnell et al. 2004)
3	58	M, SST, h
3	59	M, H2, D&ND, d; ref. uses global ΔT of 2.3°C above 1961–1990 mean; downscaled with H3 and upscaled with H3, EC, CG
3	60, 76	M, P, D & ND, a
3	61	M, 15, SI, a; Arzel et al. (2006) uses 15 GCMs with A1B for 2080s, ΔT A1B 2080s multi-model from WGI, chapter 10, Fig. 10.3.2 is 2.5°C above 1990; ACIA uses 4 GCMs with B2, multi-model ΔT is 2.2°C over 1961–1990 or 2.0°C above 1990
3	62	M, P, D, HadCM3, ECHAM4, GFDL, a; Huntley et al. (2006) give 2.5°C relative to 1961–1990 mean
3	63	M, 10, P, D, d, g; Beaumont and Hughes (2002) give global mean temperature rise of 2.6°C relative to the 1961–1990 mean
3	64	M, P, D, ND, a; Table 3 of Thomas et al. (2004a) maximum climate scenarios have a mean ΔT of 2.6°C above 1961–1990 or 2.3°C above 1990
3	65	M, SST, h
3	66	M, P, NR, e; upscaled for several sites taken from maps in ref., using H3, EC, CS, CG
3	67	M, NR
3	68	M, 3, a, P, cloudiness, D & ND
3	69	M, NR, b; % derived from Table 1 in Benning et al. (2002) for all forest areas combined on the 3 islands studied; upscaling considers changes averaged over 3 islands and uses H3, EC, CS, CG
3	70	M, H3, P, D&ND, d, f; table 3 of Benning et al. (2002) lists global ΔT of 3°C above 1961–1990 mean
3	72	M, 7, BIOME3, MAPSS, P, D&ND, a; uses CO_2 doubling scenarios from Neilson and Drapek (1998) Table 2; control concentrations were obtained directly from modellers; thus deduced mean global mean ΔT for this study
3	73	M, H3, P, D&ND, d; ref. uses A2 in H3 in 2080 that has a ΔT of 3.3°C above 1961–1990 (Arnell et al. 2004)
3	74	M, H3, P, D, d, f; ref. lists ΔT of 3.6°C for A1 in H3 in 2080 relative to 1961–1990, downscaled with H3 and upscaled with H3, EC, CG

Table 6 (continued)

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
3	75	M, NR, b; upscaled with H3, EC, CG
3	77	M, NR, b, f; Meehl et al. (2007), Figs. 10.3.5 and 10.3.2 suggest global ΔT of 3.5°C relative to 1990
3	79	M, NR, b, f; Meehl et al. (2007), Fig. 10.3.5 shows this occurs for ΔT ≥3.5°C above 1990
3	80	M, NR, b, f
3	81	M, 3, P, a
4	83	M, SST, h
4	84	M, a
4	85	M, 2, P, LPJ; upscaled with H3, EC5
4	86	M, SST, h
4	87, 88	M, 5, IMAGE, a; authors confirmed temperature baseline is year 2000 which is 0.1°C warmer than 1990
5	89	M, 4, SST
5	90	E, SI
5	91	M, SST, h
5	92	M, P, NR, d; HadRM3PA2 in 2050, Fig. 13 in Moriondo et al. (2006) shows ΔT matching B2 of H3 of 1.6°C above 1961–1990 mean; downscaled with H3 and upscaled with H3, EC, CS, PCM, CG
5	93	M, P, D (based on empirical calibration), d, upscaled with H3, EC, CS, PCM, CG
5	94	E, P, D, b; upscaled using H3, EC, CS, PCM, CG
5	95	M, H2 with aerosols in 2050, a, 6 DVGMs, global temperature taken from Raper et al. (2001).
5	96	E, P, NR, a
5	97	M, a; Williams et al. (2007) use the B1 scenario from a mean of 9 GCM simulations used in IPCC (2007) which have a global temperature increase of 1–2.5°C averaging approximately 1.9°C above 1990 (hence 2.4 above pre-industrial)
5	98	M, d; upscaled using H3, EC, CS, PCM, CG
5	99	M, P, NR, d; HadRM3PA2 in 2050, taken from Fig. 13 of Moriondo et al. (2006)
5	100	M, CS, b; upscaled with H3, EC, CS, PCM, CG
5	101	M, 15, SI, a; Arzel et al. (2006) uses 15 GCMs with A1B for 2080s, ΔT A1B 2080s multi-model from WGI, chapter 10, Fig. 10.3.2 is 2.5°C above 1990; ACIA uses 4 GCMs with B2, multi-model ΔT is 2.2°C over 1961–1990 or 2.0°C above 1990
5	102, 103	pH, g; IS92a in 2100 has 788 ppm CO_2 and ΔT of 1.1–3.6°C above 1990
5	104	M, a;
5	105	E, P, D, e; upscaled with H3, EC, CS
5	106	M, H2 with aerosols in 2100, a, 6 DVGMs, global temperature taken from Raper et al. (2001)

Table 6 (continued)

Table no.	Entry no.	Details on type of study, models, model results, and methods used to derive the sensitivities as tabulated in Tables 2–5 for each table entry
5	107	pH, a; impact is at CO_2 doubling, T range given by IPCC (2007) for equilibrium climate sensitivity
5	108	M, a; Williams et al. (2007) use the A2 scenario from a mean of 9 GCM simulations used in IPCC (2007) which have a global temperature increase of 2–4°C averaging approximately 3.5°C above 1990 (hence 4°C above pre-industrial)

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