Uncertainty in Ecological Models of Climate Change Impacts

Richard Pearson

(a) Global mean temperature

Observed changes

AOGCM predictions
Session overview:

• Observed ‘fingerprints’ of climate change
• Predicting future impacts
• Some promising ways forward
• Communicating uncertainty
Data from two surveys in 1993 and 2003 that used the same transect and sampling strategy.
Elevational displacement of distribution midpoint between 1993 and 2003 for 30 species of reptiles and amphibians surveyed at Tsaratanana.

(Raxworthy et al. 2008 *Global Change Biology*)

Mean displacement = 65m upslope ($n=30$, $p<0.01$)
Evidence of recent warming in Madagascar

Changes in mean annual temperature between the decades 1984-1993 and 1994-2003
Evidence of recent warming in Madagascar

Changes in mean annual temperature between the decades 1984-1993 and 1994-2003

Right axis shows the corresponding change in isotherm height, lapse rate of 6°C/1000m

Expected upslope displacement: 17-62m
Overall, similarity between observed ($\mu_{65m}$) and expected (17-62m) upslope displacement suggests distribution shifts are being driven by warming

But... *uncertainty*... only two points in time, a single massive, possible confounding effects of phenology...
There is very high confidence that climate change is already affecting living systems.

IPCC 2007
20-30% of species are likely to be at increased risk of extinction if global average warming exceeds 2.5°C

IPCC 2007
40-70% of species are likely to be at increased risk of extinction if global average warming exceeds 3.5°C

IPCC 2007
Potential upslope extinction vulnerability in Madagascar

**Elevation:**
- 2864 m
- 0 m
- <300 m from massif summit (~1.8°C*)
- 300—600 m from massif summit (~3.6°C*)

(*assuming a lapse rate of 6°C/1000m)
Potential upslope extinction vulnerability in Madagascar

Examples of species from massifs in Madagascar, known only from <600m from the highest summit:

<table>
<thead>
<tr>
<th>Massif</th>
<th>Species</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andohahela</td>
<td><em>Spinomantis guibe</em></td>
<td>Amphibians</td>
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<tr>
<td></td>
<td><em>Calumma capuronii</em></td>
<td>Reptiles</td>
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<tr>
<td>Itremo</td>
<td><em>Lygodactylus pauliani</em></td>
<td>Reptiles</td>
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<tr>
<td>Ibitry</td>
<td><em>Lygodactylus arnoulti</em></td>
<td>Reptiles</td>
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<td><em>Lygodactylus blanci</em></td>
<td>Reptiles</td>
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<td></td>
<td><em>Arundinaria ibityensis</em></td>
<td>Bamboos</td>
</tr>
<tr>
<td>Ankaratra</td>
<td><em>Mantidactylus pauliani</em></td>
<td>Amphibians</td>
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<tr>
<td></td>
<td><em>Lygodactylus mirabilis</em></td>
<td>Reptiles</td>
</tr>
<tr>
<td>Marojejy</td>
<td><em>Microgale monticola</em></td>
<td>Tenrecs</td>
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<tr>
<td></td>
<td><em>Calumma peyrierasi</em></td>
<td>Reptiles</td>
</tr>
<tr>
<td></td>
<td><em>Calumma jejy</em></td>
<td>Reptiles</td>
</tr>
<tr>
<td></td>
<td><em>Blechnum longepetiolatum</em></td>
<td>Ferns</td>
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<tr>
<td></td>
<td><em>Cheilanthes sp. nov. 1</em></td>
<td>Ferns</td>
</tr>
<tr>
<td></td>
<td><em>Cyathea allicola</em></td>
<td>Ferns</td>
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<tr>
<td></td>
<td><em>Lindsaea sp. nov. 1</em></td>
<td>Ferns</td>
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<tr>
<td></td>
<td><em>Arundinaria marojejyensis</em></td>
<td>Bamboos</td>
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<tr>
<td>Anjanaharibe-Sud</td>
<td><em>Microgale monticola</em></td>
<td>Tenrecs</td>
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<tr>
<td>Bemanivika</td>
<td><em>Microgale jobihely</em></td>
<td>Tenrecs</td>
</tr>
<tr>
<td>Montage d’Ambre</td>
<td><em>Pseudoxyrhopus ambreensis</em></td>
<td>Reptiles</td>
</tr>
<tr>
<td></td>
<td><em>Calumma amber</em></td>
<td>Reptiles</td>
</tr>
</tbody>
</table>

(Raxworthy et al. 2008 *Global Change Biology*)
Models to predict future impacts

Correlative/statistical vs. Mechanistic/process-based

- ‘Bioclimatic envelope’ models
  - Assume current distribution gives a good indicator of ecological requirements
  - Good for rapid ‘first pass’ assessment, can model many individual species at fine resolution

- E.g., Dynamic Global Vegetation Models
  - Do not rely on ‘realised’ ecological niches
  - Require detailed physiological data, tend to operate above the species level (e.g., biomes) at coarse resolution

(for a review see Kearney and Porter Ecology Letters 2009)
Ecological Niche Model

\[ y = f_1(x_1) + f_2(x_2) + f_3(x_3) + \ldots \]

(Peterson et al. 2011 *Ecological Niches and Geographic Distributions*)
Predicted distribution shifts under climate change

*Upslope range contraction*

*Pole-ward range expansion*

‘Bioclimate envelope’ predictions for Twinflower (left) and White-beaked sedge (right)

(Pearson et al. 2002 *Ecological Modelling*)
Extinction risk from climate change

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Abstract: Extinction taking place climate change.

In a recent series of papers (1-3) the authors have highlighted the rapid rate of climate change and the associated risks to biodiversity. They argue that the current rate of climate change is unprecedented in the geological record, and that it is likely to have serious consequences for global biodiversity. In this paper, we present a quantitative assessment of the risks to biodiversity posed by climate change.

INTRODUCTION
Networks of vulnerable ecosystems (4-6) and potential hotspots (7,8) have been identified in many regions. However, the extent of these areas is uncertain and their potential for future extinction is unknown. In the present study, we have used a modelling approach to assess the potential impacts of climate change on biodiversity.

METHODS
We used a combination of climate models and a biodiversity model to estimate the potential impacts of climate change on biodiversity. The climate models were run for the period 2000-2099, and the biodiversity model was run for the period 2000-2100.

RESULTS
The results show that climate change will have a significant impact on biodiversity. The areas most at risk are those with the highest current biodiversity, and those with the most vulnerable species. The results also show that the impacts of climate change will be greatest in the short term, and that the long-term impacts will be more severe.

CONCLUSIONS
Climate change poses a serious threat to biodiversity, and urgent action is needed to protect biodiversity. The results of this study provide a powerful case for action, and we urge policymakers to take urgent action to prevent the loss of biodiversity.

ACKNOWLEDGEMENTS
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“we predict, on the basis of mid-range climate-warming scenarios for 2050, that 15-37% of species in our sample of regions and taxa will be ‘committed to extinction’”

(Thomas et al. 2004, Nature)
Uncertainties in predictions of future impacts of climate change

<table>
<thead>
<tr>
<th>Ecological</th>
<th>Algorithmic</th>
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<tbody>
<tr>
<td>• Dispersal capacity</td>
<td>• Model selection</td>
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<td>• Biotic interactions</td>
<td>• Coarse scale of analysis</td>
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<td>• Non-analogue climates</td>
<td>• Climate scenarios</td>
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<td>• Rapid evolutionary adaptation</td>
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<td>• Direct impacts of CO₂</td>
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<td>• Thresholding</td>
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</table>

Thuiller, Araújo, Pearson *et al.* 2004 *Nature*
Pearson 2006 *TREE*; Pearson *et al.* 2006 *J. Biogeog.*
Will species be able to ‘keep up’ with changing climate?


species-level extinction estimated to be 21-32% with universal dispersal, and 38-52% with no dispersal (under maximum projected climate change)
Alternative mechanisms to explain rapid colonization of trees in response to late-glacial warming

1. Long-distance dispersal

2. Local dispersal from refugia

(Pearson 2006 *Trends in Ecology & Evolution*)
Uncertainty example 2: complex ecological networks
Uncertainty example 2: complex ecological networks
Uncertainty example 3: Model-based uncertainty

Predicted percentage range gain/loss by 2030

Methods for dealing with uncertainty and improving predictions
Ensemble forecasting to reduce model-based uncertainty

Figure 1. Examples of alternative approaches to analysing ensemble forecasts using artificial data projected onto the map of Africa: (a) Individual results from five hypothetical biomimetic models (shown by coloured lines) predicting the area occupied by a key species under a climate change scenario (no combination of the ensemble forecast is performed); (b) a bounding box showing the area where at least one (purple) or all models (green) predict species presence in the future, and a consensus forecast (blue) showing the area where at least half the models (the median) forecast species presence; (c) a frequency histogram, showing the number of models (1–5) forecasting the presence of the species at any point; and (d) a probability density function showing the likelihood of species presence estimated from a large ensemble.

(Araújo & New 2007 TREE)
Linking Ecological Niche Models and Demographic Models

1. Ecological Niche Model
   - habitat suitability model
   - probability of occurrence

2. For each habitat patch:
   - carrying capacity ($K$)

3. For new habitat patches:
   - carrying capacity ($K$)

4. If $K \geq N$, vital rates unaltered
   - survival rates
   - growth rates

5. In patch at current time step ($t$)
   - population size ($N$)

6. Calculate population size in patch at time ($t+1$)

Climate and soil data - present day
Species occurrence - present day
Climate data - GCM scenarios 2001–2050

Keith et al. 2008 Biology Letters
Brook et al. 2009 Biology Letters
Fordham et al. 2012 GCB
40-70% of species are likely to be at increased risk of extinction if global average warming exceeds 3.5°C

IPCC 2007
The ongoing challenge is to communicate the state of knowledge concisely and accurately, avoiding exaggeration and hyperbole.

In light of recent controversies, more measured and nuanced messages are needed to ensure that public trust in science is maintained.
Are conservation scientists “crying wolf” over climate change?

correct

evidence to prove wrong the skeptic who denies that climate change is a threat

... global warming will lead to extensive and irreversible transformations of ecosystems
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Madagascar case study
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Dáithí Stone

Extramural funding
Known species occurrence record

Occupied distributional area, $G_O$ (left panel)/
Occupied niche space, $E_O$ (right panel)

Abiotically suitable area, $G_A$ (left panel)/
Scenopoetic existing fundamental niche, $E_A$ (right panel)

Pearson 2007; Peterson et al. 2011
Ecological niche model

Pearson 2007; Peterson et al. 2011