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Using climatic credits to pay the climatic debt

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Abstract

Many organisms are accumulating climatic debt as they respond more slowly than expected

to rising global temperatures, leading to disequilibrium of species diversity with

contemporary climate. The resulting transient dynamics are complex and may cause over-

optimistic biodiversity assessments. We propose a simple budget framework to integrate

climatic debt with two classes of intervention: i) climatic credits that pay some of the debt,

reducing the overall biological change required to reach a new equilibrium, and ii) options to

adjust the debt repayment rate, either making a system more responsive by increasing the

rate or temporarily reducing the rate to buy more time for local adaptation and credit

implementation. We illustrate how this budget can be created and highlight limitations and

challenges.

Climatic debt, credit and the value of budgeting

In response to climate change, organisms must migrate, adapt via phenotypic or

evolutionary mechanisms, or face extinction [1]. Across many parts of the world and a range

of taxa, changes in species' distributions following recent decades of climate change have

been smaller than expected. The difference between observed and expected changes is

described as **climatic debt** (see Glossary; Fig 1), which is "repaid" when biodiversity

reaches equilibrium with the new climate. The prime focus of such analyses has been rising

temperatures. Recent studies suggest that climatic debt in contemporary plant and animal

assemblages could be equivalent to ~0.4–1.3°C of warming or more (e.g. [2–9]), and there is

widespread evidence for postglacial climatic debts in plant communities [10]. For some

species, other dimensions of climate could be more important than temperature, such as

precipitation [11] or seasonal maxima [9]. For simplicity, we focus on average temperatures,

but climatic debt could equally be quantified in other units (e.g. mm precipitation yr^{-1} [7]).

Climatic debts can be generated by limits to the rates of dispersal and establishment of more

thermophilic species, by the slow loss of cooler-climate species [12], and by relatively slow

changes in abundance amongst species that persist with increasing temperatures. The total

debt may be influenced by numerous factors, including species' traits and landscape

properties [5], which vary across spatial and temporal scales, and levels of biological

organisation [13]. Although some taxa appear able to keep pace with temperature changes

(e.g. [14]), the frequency of climatic debts suggests that many do not, which will lead to

under-estimates of climate change impacts and overly-optimistic conservation assessments.

Set against the debt is a range of local or regional scale strategies that may be able to lower

temperatures (e.g. by manipulating vegetation structure to increase shading) or reduce

temperature impacts without cooling the system down, such as reducing co-occurring

stressors; comparable manipulations are possible for moisture-based debt [15]. Small-scale

actions of this type can offset substantial temperature increases (e.g. 0.8–1.0°C [8,16]) and

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63 are more easily and rapidly achieved than globally coordinated climate action [17]. These

64 interventions could be conceptualised as **climatic credits** to help pay the debt [8] (Fig 1). In

65 the long-term, rising temperatures are likely to exceed the credits, but they should still

66 reduce the overall magnitude and rate of biodiversity changes, and the risk of catastrophic

67 changes, such as ecosystem collapse [18].

68

69 Inspired by Jackson and Sax's [19] 'biodiversity budget', in which **extinction debt** is

70 balanced against immigration credit, we outline a framework uniting climatic debts, credits,

71 and factors that could affect the **repayment rate** (Fig 1). Although a climatic budget is a

72 greatly simplified view of the manifold influences on species distributions, it would be

73 valuable for communicating with practitioners, conservation organisations, policy makers,

74 and other stakeholders including the general public [19]. The forecasts from climate models

75 are familiar to these groups, with time series of predicted temperature increases and maps

76 of future climate regularly appearing in the media. Climatic debts and credits could be

77 mapped directly onto these predictions, using the same units, to allow simple comparisons of

78 environmental change, biodiversity responses, and the extent to which management

79 interventions may be able to offset the impacts. Budgeting is readily understood and applied

80 by a wide range of stakeholders, and long-term conservation goals can be set in terms of

81 minimising the debt. Furthermore, such budgets are explicit about time lags in biodiversity

82 responses to global change – losses, gains and turnover – that are vital for understanding

83 ecological responses [20–22]. However, these lags are challenging to quantify and

84 communicate in simple terms, and are frequently overlooked, leading to biased assessments

85 of biodiversity.

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87

88 **Estimating climatic debts and credits**

89 Estimating climatic debt begins with quantifying the relationship between community

90 structure and temperature, so that temperature can be inferred from the observed species

91   composition (Figs 1 & 2). The most common approach is to calculate the **community**

92   **temperature index** (CTI) from the **species temperature indices** of the species present e.g.

93   [3,6,7,23,24]. To calculate the current climatic debt, the **inferred temperature** (e.g. CTI) is

94   subtracted from the observed environmental temperature [2] (Figs 1 & 2): this is analogous

95   to the difference between the observed and expected species richness for extinction debt

96   [25]. Indebted communities have a greater frequency or abundance of cooler-climate

97   species than expected, leading to an inferred temperature that is below the observed

98   temperature (Fig 1). Calculating a future climatic debt follows the same process, using

99   predicted climate and community structure (Fig 2).

100

101 Estimating climatic debt is simple in principle, but it involves at least three important

102 methodological challenges. The first is obtaining reliable estimates of temperature

103 preferences based on distribution data, which is the familiar problem of trying to estimate

104 aspects of the fundamental niche from the realised niche. Climate change is likely to

105 generate novel communities and novel species interactions, leading to changes in the

106 apparent relationships between temperature and species occurrence [26]. Possible solutions

107 here include augmenting or corroborating distribution data with experimental data [26,27]

108 and modelling climate preferences without assuming equilibrium (see below). An added

109 complication is the risk of climatic debt in the data used to calibrate the relationships [28]:

110 this challenge can be reduced by using historical distribution data, prior to the rapid climatic

111 changes of recent decades (e.g. [2]). Finally, phenotypic plasticity and rapid evolutionary

112 change might write-off part of the climatic debt (e.g. [5,12,29–32]), further complicating debt

113 assessment and forecasting.

114

115 The second challenge is developing realistic non-equilibrium models to predict species

116 distributions and community structure. Disequilibrium can distort the predictions of traditional

117 climate envelope models [33], which use simple species associations to describe the climatic

118 niche and assume equilibrium. Such models will often fail to identify potential climatic debts.

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119   The solution is to adopt more mechanistic models that incorporate the biological processes

120   generating the debt, such as dispersal, demographics and biotic interactions (e.g. [12,34–

121   36]). Developing such models represents a major challenge, but rapid progress is being

122   made. Some researchers have extended conventional species distribution models to

123   incorporate mechanisms such as dispersal and then 'stacked' individual species' predictions

124   to estimate community structure. More recently, full **process-based models** have been

125   used to generate forecasts [37–39]. The challenge for implementing these models is

126   controlling model complexity and obtaining data to estimate process-based parameters [33]:

127   expanding species-level phylogenies and databases of ecological traits may help to

128   interpolate missing demographic data [38].

129

130   The third challenge is quantifying and reducing uncertainty in estimates of temperature

131   preferences and community responses to climate change. Uncertainty may be introduced at

132   numerous points, from limitations in species distribution data and uncertainty around climate

133   forecasts, through analytical aspects such as combining data from different spatial scales

134   and model selection, to the ways in which models are applied under novel environmental

135   conditions [40,41]. In addition, factors such as habitat loss and invasive species may

136   contribute to disequilibrium, and it could be challenging to distinguish climatic debt from

137   these sources. Given the complexities of different error sources and the potential for them to

138   propagate up, resampling methods are likely to be valuable for quantifying uncertainty

139   around debt and credit estimates [40,42]. For example, De Frenne *et al.* [4] modelled

140   individual species' temperature response curves, and then repeatedly sampled from these

141   curves to estimate the CTI with confidence limits. Methods to estimate the overall

142   disequilibrium, such as Markov chain and time series models [43,44], could also be valuable

143   to place the climatic debt in a wider context (e.g. [8]).

144

145   Estimates of climatic credit run in parallel to debt (Fig 2). Credit is the difference between the

146   inferred temperatures with and without management intervention (Fig 1). Typically, the aim is

147 to estimate credits delivered by potential management interventions, but alternatively the

148 consequences of past actions could be assessed. For example, a 0.9 mg l^{-1} reduction in the

149 mean biochemical oxygen demand of English and Welsh rivers 1991–2011 is estimated to

150 have contributed an environmental credit equivalent to 0.9°C of cooling [8]. Credit could be

151 estimated by simple correlative methods which assume equilibrium between community

152 structure and the credit source e.g. [8], but process-based modelling would make more

153 realistic predictions. For example, credit options that take time to be fully realised, such as

154 restoring tree cover for shading, will require models that capture transient dynamics and time

155 lags.

156

157 Interventions such as increasing habitat connectivity or translocating threatened populations

158 [45] may alter the repayment rate. With process-based models, repayment rates are factored

159 into the budget by making predictions of the change in debt by the assessment point (Fig 2),

160 which may be before the **relaxation time** has elapsed. Repayment rates are predicted to

161 vary along a continuum determined by ecological traits of the species and the environmental

162 conditions. Whereas some plant assemblages change very slowly and exhibit climatic debts

163 as large as 10°C [23], freshwater invertebrate assemblages are highly responsive, and

164 species composition can change 15–20% year^{-1} in response to water temperature and

165 quality [8].

166

167

168 **Climate accounting**

169 The magnitude of ongoing climate change has precipitated a paradigm shift from trying to

170 conserve current or historical conditions to managing ecosystem change [45,46] (Box 1).

171 Climatic debts are likely to grow until a system converges to a new equilibrium state –

172 perhaps involving catastrophic changes such as ecosystem collapse. Climatic credits could

173 permanently offset portions of the debt by reducing the extent to which the equilibrium point

174 moves, minimising biological change and risks of collapse (Fig 1). In such a dynamic

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175   system, budgets would be developed for explicit time points (e.g. 2050) forecasting the

176   changes in both climate and biodiversity within the time window.

177

178   A basic climate budget could be assembled by assuming that sources of credit and debt are

179   additive, allowing combinations of interventions to be appraised through simple summation

180   (Fig 3). More refined versions employing process-based models could capture antagonistic

181   or synergistic relationships among credit and debt sources. A budget could illustrate this by

182   showing the net credit or debt resulting from management interventions applied separately

183   and in combination. In addition to debt accrual from climate change, the budget could

184   highlight other contributors, such as increasing water extraction from river systems (Fig 3) or

185   harvesting that could thin forest canopies, leading to higher maximum temperature [9]. In

186   principle, budgets could be created across spatial scales ranging from local to national or

187   international, but will be most relevant where management interventions are feasible

188   (primarily local or regional scales). Budgets could be averaged over a spatial extent (as in

189   Fig 2) or calculated at the same resolution as the climate projections, producing maps for

190   debt, different credit options and the resultant net climatic debt.

191

192   Communities will have finite pools of climatic credit from the range of possible interventions.

193   Pollutants could be eliminated or reduced to technological or financial limits; microclimates

194   could be cooled by reduced grazing or mowing in grasslands, or encouraging denser forest

195   canopy, before major changes in community structure are likely to occur [15]; and local

196   refugia could be created within constraints such as space and cost, in addition to the

197   physical limits on their cooling effect. In the short term, a budget may show net credit if the

198   management intervention is sufficiently effective and the response rapid. For example, the

199   0.9°C of credit accrued by improving water quality in English and Welsh rivers (1991-2011)

200   exceeded the 0.6°C of concomitant warming, and was reflected by an increased prevalence

201   of cooler-water taxa e.g. Plectoptera [8]. However, any surplus will be temporary if climatic

202 debt continues to mount and credit sources are exhausted, such that declines in cool-water

203 species would be expected.

204

205 Many credit options qualify as **low-regrets interventions** [45], whereas others might involve

206 compromises with ecosystem services or involve greater risks (Box 1). Altering the

207 repayment rate could either minimise the debt and make a system more responsive to

208 climate change or could temporarily slow the rate of change to allow more time for

209 evolutionary adaptation [29] and implementation of climate credits (Box 1). In general,

210 altering the repayment rate is likely to incur higher risks than supplying credit: increased

211 repayment rates could encourage the system to move more rapidly to an undesirable state,

212 whilst reduced rates would inflate the climatic debt which could reduce ecosystem resilience

213 [47] and incur greater risks of dramatic and unpredictable changes [28]. As a consequence,

214 the risk-reward trade-off of such approaches would need careful evaluation.

215

216

217 **Concluding remarks**

218 Transient dynamics, such as climatic debt, are challenging to quantify and understand [21].

219 We propose a climatic credit-debt framework that builds on established concepts to assess

220 impacts of warming and provide intuitive tools for evaluating adaptation options. Although

221 this framework addresses the symptoms rather than the causes of climate warming, credits

222 have the potential to reduce the magnitude of biodiversity changes at local or regional

223 scales, and increase the scope for adaptation. Minimising climatic debts may also increase

224 the resilience of the system to pulse disturbances (e.g. climate variability). The climatic debt

225 concept is being used increasingly in ecology and the climatic credit idea has recently been

226 demonstrated empirically [8]. The next step is to bring these together into a climatic budget

227 for a model system to assess the full value of the approach.

228

229 Research priorities encompass both conceptual and applied issues (see Outstanding

230 Questions). Many centre on improving debt and credit forecasting, and ways to limit model

231 complexity. Most climatic debt studies have addressed community-level responses, but

232 could generalise from species to ecosystems and biomes (including ecosystem services

233 [48]) and into a broader context alongside other drivers of environmental change, including

234 land use change and nutrient enrichment. A few recent studies (e.g. [5,23,49–51]) have

235 started to look at factors mitigating or amplifying the debt, and this is an area that will benefit

236 from more work. Debts and credits can also be quantified on multivariate axes (e.g.

237 temperature and precipitation [52]), which could be valuable for some systems – albeit at the

238 expense of a simple currency (e.g. °C or mm yr^{-1}). Going further, budgets could be built for

239 other stressors, such as nutrient concentrations (e.g. creating a budget with units of mg l^{-1} in

240 aquatic environments).

241

242 From a management perspective, the efficacy of climatic credits is likely to vary among

243 ecosystems and locations. Different interventions will be possible in different systems, based

244 both upon the nature of the system and wider landscape, and technical and financial

245 feasibility. The validity of credits depends upon how closely they replicate community

246 responses to declining temperatures. It is expected that the best results will be achieved

247 when temperature itself is modified (e.g. by shading) or where there is a mechanistic

248 relationship between the biotic variables, temperature, and the potential source of climate

249 credit. For example, Vaughan and Gotelli [8] related aquatic invertebrate community

250 structure to temperature and water quality improvement, both of which affect oxygen stress

251 [53]. Ultimately, credit sources are finite: once a stressor is eliminated or reduced to a

252 feasible minimum, the credit source will be exhausted. In many ecosystems, climate

253 warming will eventually exceed the available credit, so the aim is to minimise the overall

254 magnitude of change. Our hope is that this general framework of climatic debt and credits

255 will contribute to understanding and forecasting the potential value of local interventions to

256 reduce climate change impacts [17].

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387 **Figure legends**

389 **Figure 1: Basic principles of climatic debt and credit, and repayment rate, using the familiar**

390 **ball-in-landscape analogy.** Equilibrium community composition changes across the x-axis, with the

391 relative abundance of species favouring warm temperatures increasing from left to right. (**A**) The

392 system is at equilibrium (E) prior to climate warming, with the blue ball sitting at the bottom of the

393 valley. (**B**) 1.5°C of warming changes the landscape, shifting the equilibrium point to the right (E_{new},

394 red ball): ΔE represents the biological change between E and E_{new}. The community (white ball)

395 responds to the change, moving to the right, but at the time of observation has only moved part way

396 towards E_{new}: the distance by which it falls short is the climatic debt (D), which is equal to 1°C here.

397 (**C**) Climatic credit (C) offsets 0.5°C of the warming (e.g. via improved water quality), reducing ΔE and

398 D to 1.0 and 0.5°C respectively, and increasing the community's resistance. (**D**) Measures to alter the

399 repayment rate change the steepness of the valley sides. In this example, increased habitat

400 connectivity creates a steeper-sided basin (dashed white line = original basin shape), reducing

401 relaxation times: although ΔE is 1.5°C as in panel B, D is only 0.5°C.

402

403 **Figure 2: Workflow for budgeting using climatic debts and credits**. This example displays the

404 general workflow for calculating climatic debt (left-hand side) and the credit that could be supplied by

405 three possible scenarios (A–C) of pollutant reduction in a freshwater environment (right-hand side).

406 The process starts with the temperature preferences of all species (species temperature indices;

407 STIs) calculated during a calibration period. The current community temperature index (CTI) is then

408 calculated for each location by averaging the STIs of the species present: subtracting this value from

409 the observed temperature quantifies the current debt (0.5°C). In this example, the potential effects of

410 pollutant reduction (ΔP) are predicted using a process-based model of community structure,

411 developed during the calibration period, incorporating six forces shaping the community [33].

412 Predictions of community change for the three pollution reduction scenarios are made and converted

413 into change in the CTI by using the STIs. The difference between predicted CTIs and observed

414 temperature quantifies the credits (equivalent to 0.1–0.6°C of cooling), completing the present-day

415 climate budget. For a future budget, a process-based model is developed for the community response

416 to warming and predictions made for a selected climate scenario, leading to estimates of increased

417 debt (0.8°C). Updated predictions for the pollutant reductions, in light of warmer environmental

418   temperatures, are then made (or for new interventions), leading to new credit estimates (0.1-0.5°C of

419   cooling) and completing the future climate budget.

420

421   **Figure 3. Basic accounting with climatic credits, debts and altered repayment rates.** (**A**)

422   Climatic debt, D, accumulates as the observed temperature (T_{obs}; solid red line) increases more

423   rapidly than the reconstructed temperature (T_{rec}; solid black line). At the start of the period, the

424   community is in equilibrium with the environment (overlapping lines). The debt is estimated at time t

425   (D_t) after which measures are implemented to pay part of the debt with climatic credit (solid blue

426   shading) and change the repayment rate (red and blue hatching). Climatic credit moves the

427   equilibrium temperature (T_{eqm}; solid orange line) to a lower value than T_{obs}, whilst the repayment rate

428   can be increased or decreased, leading to smaller (blue hatching; T_{r2}) or larger (red hatching; T_{r3})

429   debt by t_1 respectively (D_{t1}). T_{rec} is the endpoint at t_1 assuming a 'business as usual' scenario. (**B**) A

430   hypothetical climate budget at t, comparing the estimated benefits of interventions for a river system.

431   The expansion of riparian shading and reduction of two stressors could accrue credit, whilst an

432   increase in water withdrawal would add further debt. Interventions could either increase the

433   repayment rate (e.g. removing barriers to increase connectivity) or decrease the rate (e.g. by

434   maintaining cool-water salmonid populations via regular re-stocking), leading to smaller or larger

435   debts respectively. The effects of altered repayment rates are estimated for a fixed time period (e.g.

436   20 or 50 years), allowing a rate to be converted to °C.

437
438

439   **Figure legend for Box 1**

440   **Figure I**. Credit and repayment options mentioned in the text classified into the four

441   quadrants (A–D) on the axes of Prober *et al*. [45]. Repayment options are distinguished by

442   italic font.

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446 **BOX 1: conservation strategies and tackling the climatic debt**

447 There is an emerging consensus that, given the magnitude of predicted climate change,

448 ecosystems will change over coming decades in spite of conservation efforts. In response,

449 management can either accept the changes, with little or no intervention, or attempt to either

450 steer the changes or slow them [54]. Management priorities may include increasing stability

451 and adaptive capacity, rather than trying to maintain the status quo from a previous climate

452 [45,46].

453

454 In terms of the climatic budget, long-term biodiversity change is captured by ongoing drift of

455 the equilibrium point towards higher temperatures (Fig 1). Climatic credits focus on limiting

456 the shift in the equilibrium position, increasing community **resistance** to climate change.

457 Altering the repayment rate changes the speed with which the observed community tracks

458 the drifting equilibrium point, causing the debt to wax or wane (Fig 1).

459

460 Prober *et al.* [45] split climate change adaptations into four, reflecting quadrants based on

461 two axes (Fig I): i) interventions to 'evade or ameliorate' climate effects versus developing

462 the adaptive capacity of ecosystems; and ii) conservative, 'low regrets' options versus more

463 proactive and potentially risky 'climate targeted options'. Many credit options qualify as low

464 regrets and aim either to ameliorate rising temperatures (e.g. restoring riparian tree cover for

465 shading [55]) or increase adaptive capacity (e.g. by reducing co-occurring stressors [16]).

466 Other credit options might involve compromises with ecosystem service provision, such as

467 reducing the harvesting intensity in forests [56] or adopting smaller fishing quotas [57], or

468 involve higher-risk interventions such as actively reshaping local topography to alter

469 microclimates and create refugia [15], or planting non-native trees to cast deeper shade in

470 forests [58].

471

17

472   Increasing repayment rates often involves higher risk 'climate-targeted' actions, such as

473   translocating warm-adapted species or genotypes (e.g. corals on the Great Barrier Reef

474   [59]). Creating habitat corridors [60] may span low- and high-risk categories, reflecting the

475   potential for wider conservation benefits but also side effects e.g. rapid convergence on an

476   undesirable state. Options for reducing the repayment rate qualify as low regrets in the short

477   term, acting to ameliorate rising temperatures, but failure to adapt may be higher risk in the

478   long term. An example of this approach is augmenting existing populations of cooler-climate

479   species to prevent local extinctions [45]). In practice, such repayment rate reductions might

480   be combined with credit options (e.g. encouraging denser tree canopy cover [9]), to minimise

481   change whilst the credit option is fully implemented.

482

483

484   **GLOSSARY**

485   • **Climatic credit** – a change in the environment that offsets part or all of a climatic debt,

486   and can be quantified in the same units as the debt (e.g. °C or mm year^{-1}). Typically

487   relates to management interventions that could reduce the debt.

488   • **Climatic debt** – usually defined as the difference between the observed environmental

489   temperature and the temperature at which the observed community would be at

490   equilibrium with the environment (see 'inferred temperature'), in degrees Celsius. Equally

491   applicable to other environmental variables, such as annual precipitation.

492   • **Community temperature index (CTI)** – the average species temperature index of the

493   species present in a community, reflecting the mix of warmer- or cooler-climate species

494   • **Extinction debt** – the number of species predicted to become extinct in the process of a

495   community reaching a new equilibrium with the environment. Habitat loss is the primary

496   focus of most extinction debt studies, but climate may also contribute

497   • **Inferred temperature** – the predicted environmental temperature based on the

498   assemblage of species present e.g. by calculating the CTI. Where a climatic debt is
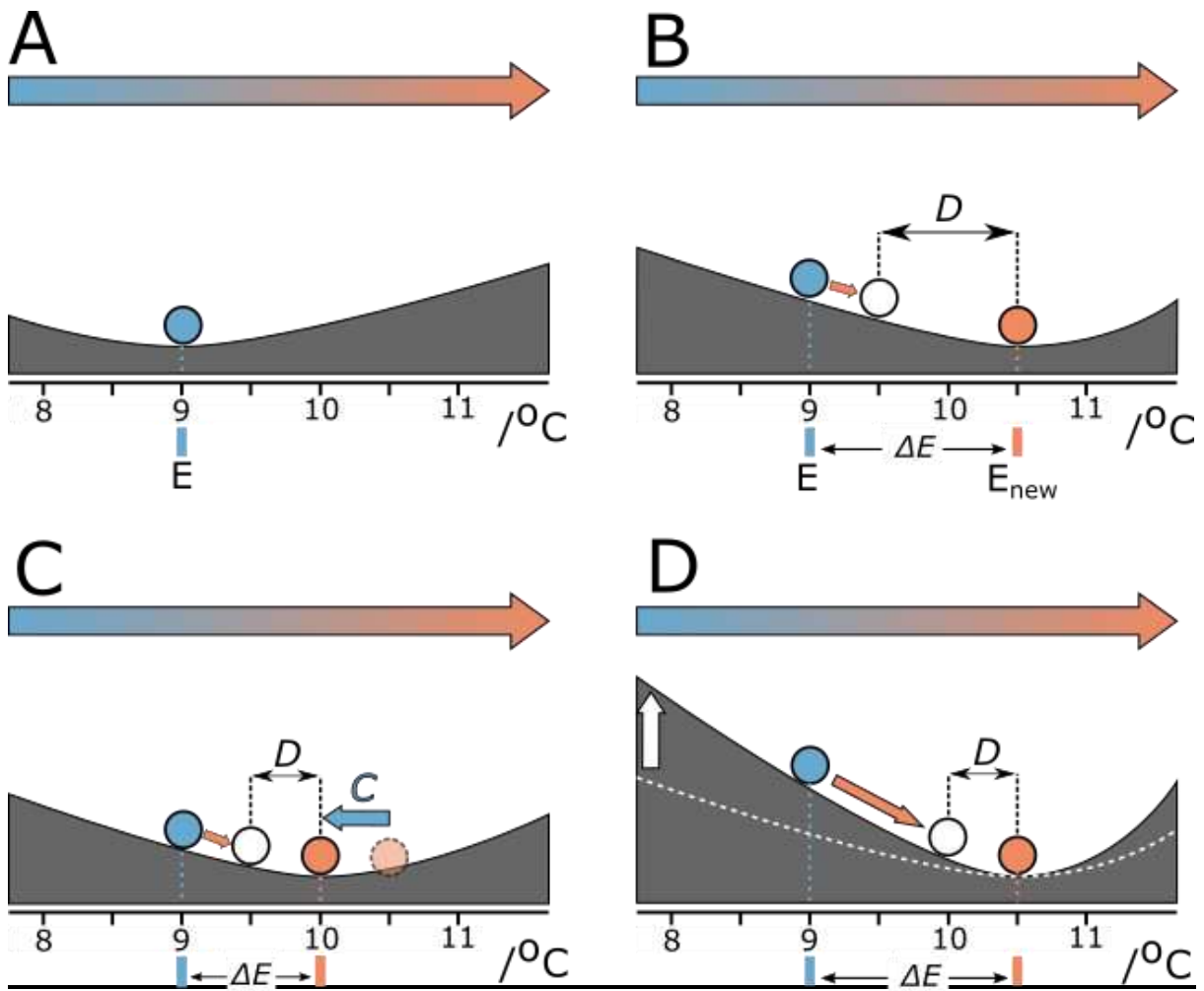
499 present, the inferred temperature will be lower than the observed temperature. Also

500 known as the reconstructed temperature.

501 • **Low-regrets interventions** – management interventions that involve little risk of

502 undesirable consequences and are likely to confer wider benefits to biodiversity or

503 ecosystem service provision.

504 • **Process-based models** – mechanistic models of community structure that incorporate

505 aspects of colonization, population growth, species interactions and extinction. Such

506 models can make predictions under both equilibrium and non-equilibrium conditions.

507 • **Relaxation time** – the time taken for a system to reach equilibrium with current

508 environmental conditions

509 • **Repayment rate** – the amount of climatic debt that can be paid off per unit time (e.g. °C

510 yr^{-1}). The inverse of the relaxation time.

511 • **Resistance** – the extent to which a community changes in response to a perturbation.

512 Highly resistant communities show little or no change to a disturbance.

513 • **Species temperature index (STI)** – the average temperature experienced by a species

514 across its range. Can be calculated from presence-absence or abundance data.
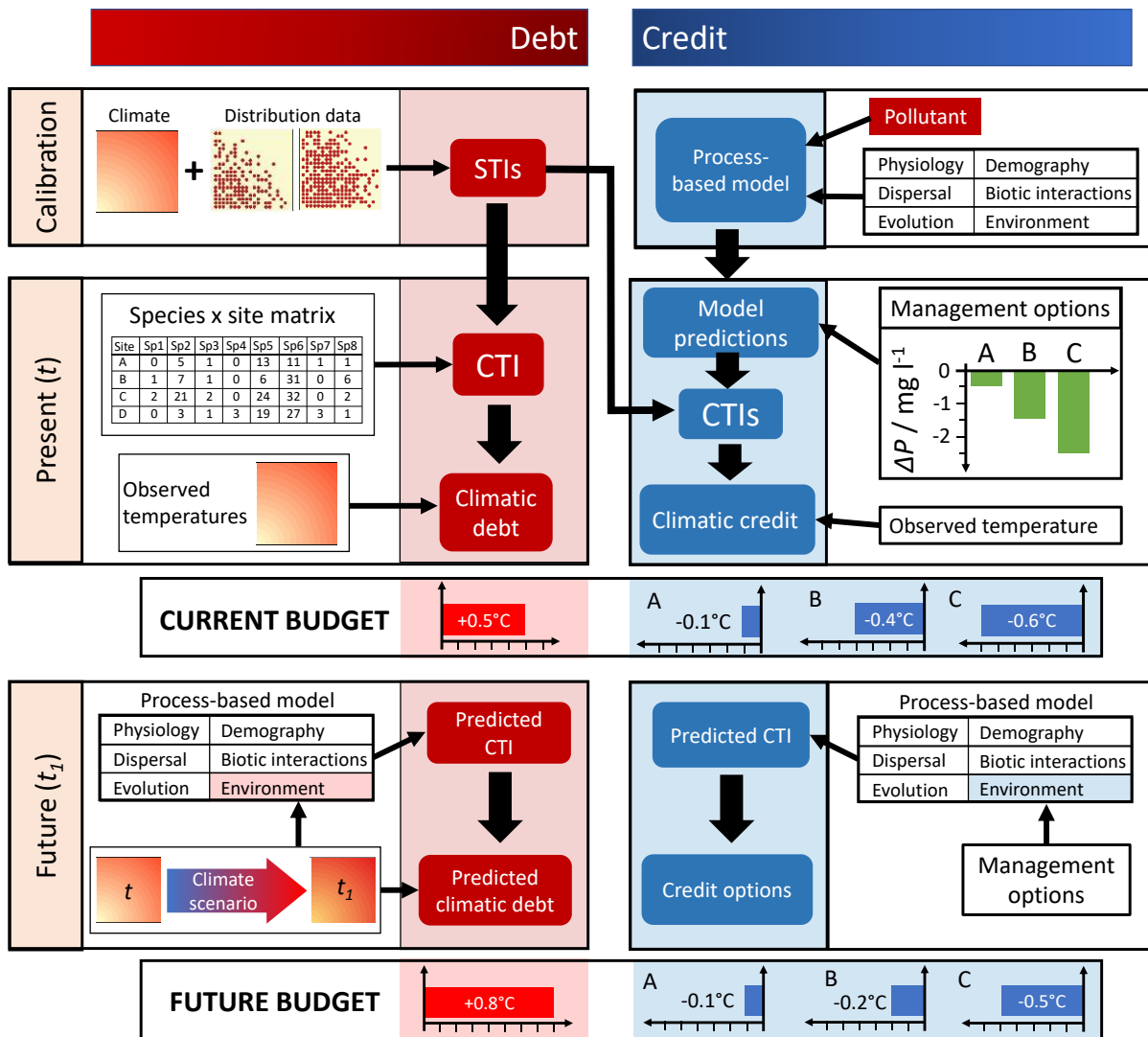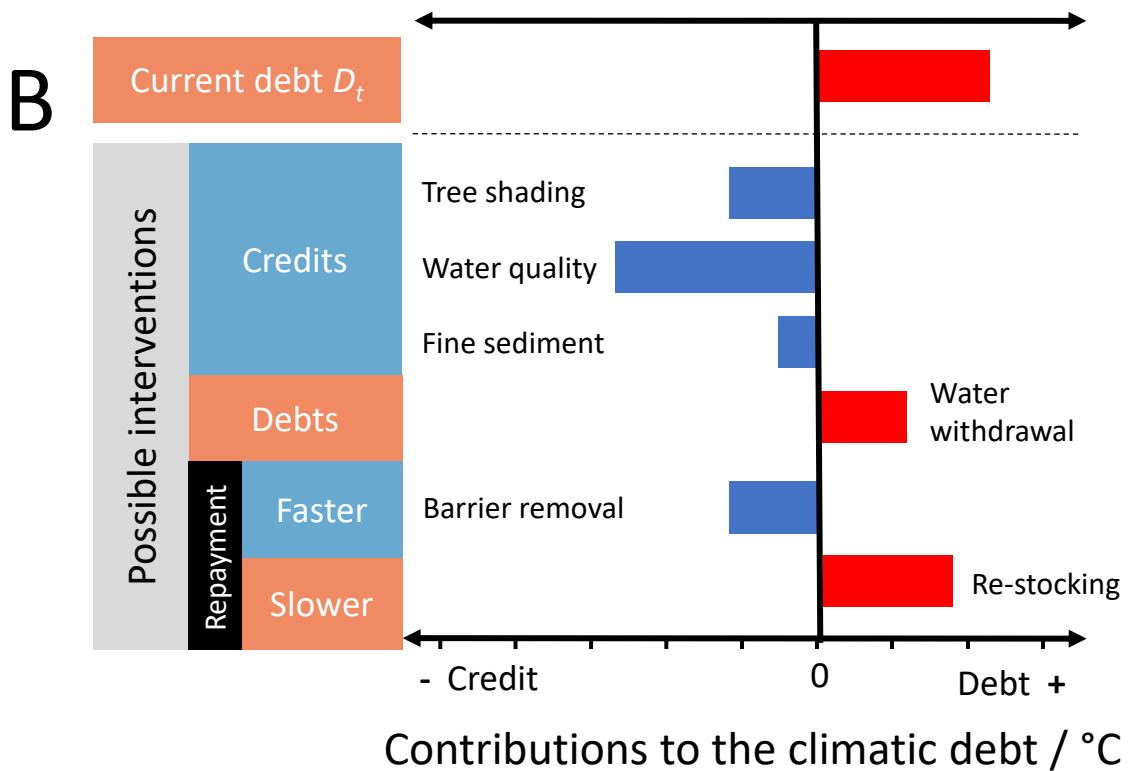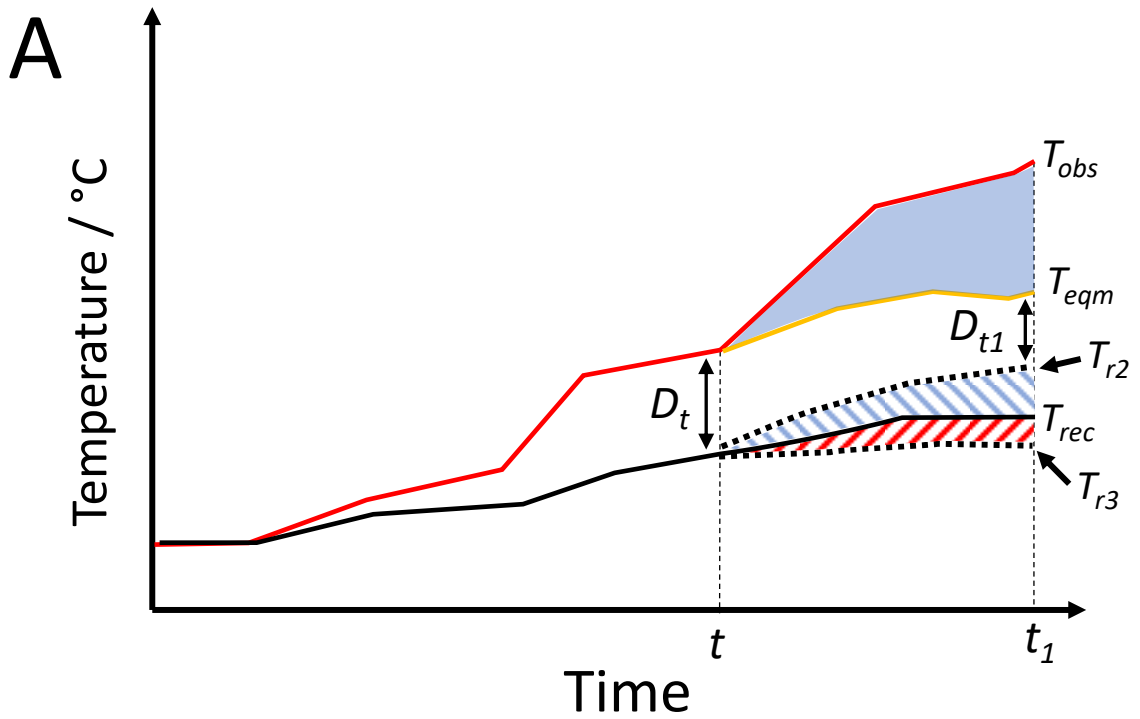
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516

517   **Fig 1.**

Fig 2.

Fig 3

529

531

Evade or ameliorate

A	B
Restore native tree cover	Reshape local topography to create refugia
Reduce harvesting intensity	
Reduce grazing or mowing	Plant non-native trees for shade
Augment populations of cooler-climate species	

'Low-regrets' options ← → 'Climate-targeted' options

C	D
Reduce co-occurring stressors	*Translocate warm-adapted species or genotypes*
Create habitat corridors	

Build adaptive capacity

532