Supplementary Materials for

Applying evolutionary biology to address global challenges

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Materials and Methods

Choice, sources and explanation of information used to create Fig. 1.

In creating Fig. 1 we focused on organisms in all or some of areas of the applied life sciences that are the main focus of the manuscript, namely the areas of Medicine, Agriculture and Natural Resources, and Conservation Biology.

The aim here was to show that these areas of the applied life sciences share concerns for the two evolutionary dilemmas and that these concerns can be mapped through the traits of the organisms. Secondly we also wanted to illustrate characteristics that help to differentiate some disciplines from others such as the management of small population sizes in some contexts of conservation biology and medicine.

Since it can be argued that every organism is affected by human management actions to some degree, it follows directly that a conceptual figure trying to span such a diversity of life necessarily must make some very rough generalizations and omit many interesting exceptions to the rule.

We focused on organisms important in all areas of the applied life-sciences as well as those important in sectors which are the main focus of the manuscript, namely Medicine, Agriculture and Natural Resources, and Conservation Biology.

The data

We gathered representative estimates of minimum and maximum generation times and population sizes for organisms that are direct or indirect targets of management actions in the applied life-sciences). These estimates were used to draw the lower and upper boundaries of ovals on the x- and y-axes. Estimates were gathered from the published literature, supplemented with estimates of woody plant generation times from the COMPADRE III database (178).

Table S1 outlines the sources and assumptions for each estimate. For some minimum and maximum values we could not find good published estimates and therefore chose artificial cutoff values that reflect the general notion of how the organisms in each group (oval) relate to the organisms in other groups. It was especially hard to find estimates for minimum and maximum population size. In this case we chose several of the cutoff values to reflect the general notion that conservation biology often operates to protect smaller global population sizes than do agriculture and natural resource management.
Table S1. References for Fig. 1.

<table>
<thead>
<tr>
<th>Group</th>
<th>Generation time</th>
<th>Population size (individuals, cells, viruses)</th>
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<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Central</td>
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<td><strong>All applied life sciences</strong></td>
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<td>Viral and microbial pathogens, mutualists</td>
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<td>and commensals</td>
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<tr>
<td><em>Escherichia coli</em> 17 min (179), HIV</td>
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<td>1.2 d (180), Algae 11 hours (181, 182)</td>
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<td>Pests, weeds, invasive species</td>
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<tr>
<td><em>Macrocheles muscaedomestica</em> 4.5 d (186),*</td>
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<tr>
<td><em>Drosophila</em> 14 d</td>
<td>Annual life</td>
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<td>cycles are common in weedy species</td>
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<td>Generally less</td>
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<td>than 10 yr</td>
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<td><strong>Medicine</strong></td>
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<td>Human myelocytes</td>
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<td></td>
<td>2.9 days (187)</td>
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<td>Human epithelia</td>
<td>5 d (188)</td>
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<td>intestinal</td>
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<tr>
<td>Human adipocytes</td>
<td>8.4 yr (190)</td>
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<td>Human neurons</td>
<td>&lt;1% of neocortica neurons turnover</td>
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Table S2. Expanded and referenced presentation of the examples shown in Fig. 3.

<table>
<thead>
<tr>
<th>Management objective:</th>
<th>Challenge</th>
<th>Strategy applied</th>
<th>Evolutionary principle</th>
<th>Tactic</th>
<th>Agriculture</th>
<th>Health</th>
<th>Environment</th>
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</thead>
<tbody>
<tr>
<td>10⁹, projected population size in 2050 (194)</td>
<td>Humans</td>
<td>25-30 yr (193)</td>
<td>~1 human</td>
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<td>Arbitrary limit at 10⁴</td>
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<td>Arbitrary limit at 10⁴</td>
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<tr>
<td>Tree: Pinus sylvestris 14 yr (195, 196)</td>
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<td>Pinus ponderosa 348 yr (201), Eucalyptus 30-200 yr (197)</td>
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<td>Arbitrary limit at 10⁴</td>
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<td>Eucalyptus globulus 5.0*10⁹ (Australia) (197)</td>
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<tr>
<td>Eucalyptus globulus 5.0x10⁹ (Australia) (197)</td>
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<tr>
<td>Arbitrary limit at 30 d, representative of e.g., some fast reproducing insects</td>
<td>Small crustacean food sources 14 d (198)</td>
<td>Pollinators, e.g., 1 yr (199) Salmon 1-4 yr (200)</td>
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<td>Sabal palmetto 861 yr (178, 202), Sea turtles &gt; 20 yr (200), Elephant 33 yr (200)</td>
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<td>10-50 set as lower limit.</td>
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<tr>
<td>10⁶ set as cut-off. Most species-level conservation plans deal with population sizes below 10⁶</td>
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<tr>
<td>Control pests and pathogens</td>
<td>Slow evolution</td>
<td>Spatial heterogeneity in selection</td>
<td>Refuge: Gene flow from treatment-free space favors the preferred form</td>
<td>Slow pest adaptation to insecticidal GE crops by providing host plants on which susceptible pests can survive (74, 75)</td>
<td>Slow chemoresistance evolution in tumors (80), and to antimicrobial resistance evolution in pathogens (81) by sheltering susceptible strains</td>
<td>Protect evolving resistance to non-native competitor (203); control evolution of undesirable traits in wild-harvested species [small size, early reproduction (204)]</td>
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<tr>
<td>Temporal heterogeneity in selection</td>
<td>Alternating treatments slows adaptation to a single treatment</td>
<td>Slow pest adaptation by rotating crops or pesticides (97, 205, 206)</td>
<td>Slow resistance evolution in infectious disease by 'cycling' (94, 207)</td>
<td>Little explored from evolutionary perspective; employing different techniques in sequence may improve efficacy (208); for counter-example see (209) Target multiple vulnerabilities at once (e.g., via multiple modes of action [physical, chemical, ecological (214)])</td>
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<tr>
<td>Diversify selection to exploit adaptive tradeoffs</td>
<td>Apply multiple stressors with different modes of action together</td>
<td>Slow pest adaptation to control measures with integrated pest management (4, 96, 210)</td>
<td>Slow resistance evolution in infectious disease by 'mixing' (139) multitarget vaccines (211); complementary tumor therapies (81); complement partial vaccines with transmission control (212); increase longevity of live attenuated vaccines (213)</td>
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<tr>
<td>Action</td>
<td>Strategy</td>
<td>Description</td>
<td>Outcome</td>
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<tr>
<td>Reduce adversary fitness</td>
<td>Select for acceptable traits in adversaries</td>
<td>Field management, e.g., frequent mowing of forage crop selects for weeds that shade less (215)</td>
<td>Increase relative survival of more benign strains (28)</td>
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<tr>
<td>Add mutational load</td>
<td>Select for less injurious genotypes</td>
<td>Increase relative survival of more benign strains (28)</td>
<td>No cases found</td>
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<tr>
<td>Transgenic deleterious mutation</td>
<td>Field management, e.g., frequent mowing of forage crop selects for weeds that shade less (215)</td>
<td>Increase relative survival of more benign strains (28)</td>
<td>No cases found</td>
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<tr>
<td>Reduce fitness of insect vectors of crop viruses (216)</td>
<td>Accelerate rate of deleterious viral mutations (217, 218); reduce dengue virus vector populations (219)</td>
<td>Assist migration of threatened populations to more suitable environments (226, 227); alter land use regime to improve habitat for natives (228)</td>
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<tr>
<td>Promote adaptation of desired organisms</td>
<td>Reduce phenotype-environment mismatch</td>
<td>Migration of agricultural economies (220); switch crops (221); factor mismatch in cues like photoperiod in breeding programs (222)</td>
<td>Assist migration of threatened populations to more suitable environments (226, 227); alter land use regime to improve habitat for natives (228)</td>
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<tr>
<td>Reduce selection in situ or shift to better environment</td>
<td>Modify environment or move population to a suitable one</td>
<td>Migration of agricultural economies (220); switch crops (221); factor mismatch in cues like photoperiod in breeding programs (222)</td>
<td>Assist migration of threatened populations to more suitable environments (226, 227); alter land use regime to improve habitat for natives (228)</td>
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<tr>
<td>Increase adaptation to present and environments</td>
<td>GE, hybridization and artificial selection</td>
<td>Preserve Vg in wild crop relatives (229); favor heat and drought resistant cereals (230); enhance artificial selection with molecular breeding (54); novel GE and hybrid phenotypes (230)</td>
<td>Employ recombinant DNA technologies for vaccine (231) drug (232) and hormone (233) production; gene therapy (234).</td>
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<tr>
<td>GE, hybridization and artificial selection</td>
<td>Preserve Vg in wild crop relatives (229); favor heat and drought resistant cereals (230); enhance artificial selection with molecular breeding (54); novel GE and hybrid phenotypes (230)</td>
<td>Employ recombinant DNA technologies for vaccine (231) drug (232) and hormone (233) production; gene therapy (234).</td>
<td>Select for tolerance and resistance in reintroduction or translocation (235); introgress genes across existing gradients (79, 236); facilitate in situ evolution (237, 238), use hybrid introgression of resistance genes (239).</td>
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<tr>
<td>Increase group performance</td>
<td>Group selection, cooperation, intrapopulation diversification</td>
<td>Select or produce variants based on group performance</td>
<td>Productivity ((240, 241)); resource use efficiency ((242)) weed suppression ((119))</td>
<td>Formalize public health strategies to incorporate public and private benefits ((161))</td>
<td>Manage environment to produce more diverse phenotypes, reducing intrapopulation competition and increasing population resilience ((243)); reduce unwanted selection with marine reserves ((79, 204))</td>
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</tbody>
</table>
Supplementary Text

Image credits for Fig. 1

- A. Methicillin-resistant *Staphylococcus aureus* bacteria; MRSA (yellow) being ingested by neutrophil (purplish blue). Photo credit: NIAID. License: Creative Commons Attribution 2.0 Generic, https://creativecommons.org/licenses/by/2.0/legalcode. Web: https://www.flickr.com/photos/niaid/5614218718/.

- B. Killer whale, *Orcinus orca*, viewed by child. Cropped. Photo credit: cmiper. License: Creative Commons Attribution-NonCommercial 2.0 Generic (CC BY-NC 2.0), https://creativecommons.org/licenses/by-nc/2.0/. Web: https://www.flickr.com/photos/cmiper/666163487/in/photolist-21Sgcn-dEwNMP-dEwY68-dEwReZ-dECmRQ-bVGQav-cd5aSs-Juysf-7HzMs-7cV6tM-9RNj3j-itCDm-itCmg-itCoJ-itCgn-itCL6-itCmv-itCk3-dMYi3y-YWkUF-7DBsjF-2THYc5-2THXAb-acDTat-ejQD7x-mRlhre-dBA89W-7236f4-4j5w2T-5

Image credits for Fig. 2

- A. Bt corn comparison. Photo credit: Gary Munkvold, Iowa State University
- B. Measles vaccination. Photo credit: Pete Lewis/Department for International Development. License: Creative Commons Attribution 2.0 Generic, https://creativecommons.org/licenses/by/2.0/legalcode. Web: https://www.flickr.com/photos/dfid/5815109843/in/photolist-9RRXyx-9wwhXH-cHXCff-NgLky-NgLjA-a5BCyY-LAg1G-do33qS-aaq1jL-aancAK-aaq1gd-9XM1gh-ixueq5-76tSgJ-do33iN-do33Au-do334N-do33kW-do32L9-do33y1-do2VMx-do2W7n-do2VPv-do33go-do32S5-do2Wqx-do32NN-do2VDn-do


Image credits for Fig. 4

- Images have been chosen for their illustrative value and conveying of message. None of the images relate specifically to works cited in the manuscript.
- D. Meat packages: Photo credit: Mattes, License: Creative Commons ShareAlike, Web: http://commons.wikimedia.org/wiki/File:Meat_packages_in_a_Roman_supermarket.jpg
Author contributions

SPC, PSJ and MTK conceived and wrote the initial manuscript. PSJ and SPC led the subsequent revision and work process, with input from MTK, and conducted the review of management examples with important contributions from all coauthors. BET contributed especially to writing about resistance management and to overall editing. CTB and RFD led the review of regulatory mechanisms and evolutionary manipulation of group performance in crops, respectively. PDG contributed especially to the analysis of evolutionary mismatch and implementing applied evolution in medicine and public health. TBS and SYS contributed text and perspectives on evolutionary conservation management and participated in general editing.

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