Supplementary Materials for

Applying evolutionary biology to address global challenges

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This PDF file includes:

Materials and Methods
Supplementary Text
Tables S1 to S2

Other Supplementary Materials for this manuscript includes the following:

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Materials and Methods

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

In creating Figure 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 (*180*).

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 Figure 1.

Group	Generation time			Population size (individuals, cells, viruses)		
	Minimum	Central	Maximum	Minimum	Central	Maximum
All applied life sciences						
Viral and microbial pathogens, mutualists and commensals	*Escherichia coli* 17 min (*181*), HIV 1.2 d(*182*), Algae 11 hr (*183*,*184*)		*Mycobacterium leprae* 30 d (*185*)	Arbitrary limit at 10^6 (*186*)		$1.4x10^7$ to $1.95x10^8$ cells of a strain EA25 per gram of soil (*187*) (1.4 g/cm^3 soil assumed): 10^{14} to $1.4x10^{15}$ cells / 10 m^3 soil
Pests, weeds, invasive species	*Macrocheles muscaedomes -ticae* 4.5 d (*188*), *Drosophila* 14 d	Annual life cycles are common in weedy species	Generally less than 10 yr	Arbitrary limit at $5*10^4$ indicating large minimum global population sizes		Arbitrary limit at 10^{10} indicating large maximum global population sizes
Medicine						
Human myelocytes	2.9 days(*189*)			$7.0x10^8$ cells /kg x 80		

				kg $=5.6*10^{10}$ cells (189)	
Human epithelia		5 d (*190*) intestinal		$>1.0*10^{11}$ (*191*)	
Human adipocytes		8.4 yr (*192*)		$4.0*10^{10}$ (192)	$7.0*10^{10}$ (192)
Human neurons		<1 % of neocortical neurons turnover during human life (*193*), limit set to 100 yr		$86\pm8.1\ x10^{9}$ neurons in brain (*194*)	
Humans		25-30 yr (*195*)		~1 human	10^{9}, projected population size in 2050 (*196*)
Agriculture and Natural Resources					
Aqua/Agriculture/Biofuels			Tree: *Pinus sylvest*ris 14 yr (*197,198*)	Arbitrary limit at 10^{4}	*Eucalyptus globulus* $5.0*10^{9}$ (Australia) (*199*)
Natural resources	Small crustacean food sources 14 d (*200*)	Pollinators, e.g. 1 yr (*201*) Salmon 1-4 yr (*202*)	*Pinus ponderosa* 348 yr (*203*), *Eucalyptus* 30-200 yr (199)	Arbitrary limit at 10^{4}	*Eucalyptus globulus* $5.0x10^{9}$ (Australia) (199)
Conservation Biology					
Conservation biology	Arbitrary		Sabal palmetto	10-50 set as	10^{6} set as cut-off.

	limit at 30 d, representative of e.g., some fast reproducing insects	861 yr (180,*204),* Sea turtles > 20 yr (202), Elephant 33 yr (202)	lower limit.	Most species-level conservation plans deal with population sizes below 10^6

Table S2.

Expanded and referenced presentation of the examples shown in Figure 3.

				Management objective:		
Challenge	Strategy applied	Evolutionary principle	Tactic	Agriculture	Health	Environment
Control pests and pathogens	Slow evolution	Spatial heterogeneity in selection	Refuge: Gene flow from treatment-free space favors the preferred form	Slow pest adaptation to insecticidal GE crops by providing host plants on which susceptible pests can survive (74,75)	Slow chemoresistance evolution in tumors (80), and to antimicrobial resistance evolution in pathogens (81) by sheltering susceptible strains	Protect evolving resistance to non-native competitor (205); control evolution of undesirable traits in wild-harvested species (small size, early reproduction, 206)
		Temporal heterogeneity in selection	Alternating treatments slows adaptation to a single treatment	Slow pest adaptation by rotating crops or pesticides (98,207,208)	Slow resistance evolution in infectious disease by 'cycling' (94,209)	Little explored from evolutionary perspective; employing different techniques in sequence may improve efficacy (210); for counter-example see (211)

	Diversify selection to exploit adaptive tradeoffs	Apply multiple stressors with different modes of action together	Slow pest adaptation to control measures with integrated pest management (4,97,212)	Slow resistance evolution in infectious disease by 'mixing' (141) multitarget vaccines (213); complementary tumor therapies (81); complement partial vaccines with transmission control (214); increase longevity of live attenuated vaccines (215)	Target multiple vulnerabilities at once (e.g., via multiple modes of action (physical, chemical, ecological (216))
	Selection for acceptable traits in adversaries	Select for less injurious genotypes	Field management, e.g., frequent mowing of forage crop selects for weeds that shade less (217)	Increase relative survival of more benign strains (218)	No cases found
Reduce adversary fitness	Add mutational load	Transgenic deleterious mutation	Reduce fitness of insect vectors of crop viruses (219)	Accelerate rate of deleterious viral mutations (220, 221); reduce dengue virus vector populations (222)	No cases found

Promote adaptation of desired organisms	Reduce phenotype-environment mismatch	Reduce selection in situ or shift to better environment	Modify environment or move population to a suitable one	Migration of agricultural economies (223); switch crops (224); factor mismatch in cues like photoperiod in breeding programs (225)	Employ adaptive dietary and lifestyle approaches to reduce cardiovascular disease (226), cancer (227) and adult and offspring metabolic disease (228)	Assist migration of threatened populations to more suitable environments (229,230); alter land use regime to improve habitat for natives (231)
		Increase adaptation to present and environments	GE, hybridization and artificial selection	Preserve Vg in wild crop relatives (232); favor heat and drought resistant cereals (233); enhance artificial selection with molecular breeding (54); novel GE and hybrid phenotypes (233)	Employ recombinant DNA technologies for vaccine (234) drug (235) and hormone (236) production; gene therapy (237).	Select for tolerance and resistance in reintroduction or translocation (238); introgress genes across existing gradients (79,239); facilitate in situ evolution (240,241), use hybrid introgression of resistance genes (242).
	Increase group performance	Group selection, cooperation, intrapopulation diversification	Select or produce variants based on group performance	Productivity (243, 244); resource use efficiency (245) weed suppression (121)	Formalize public health strategies to incorporate public and private benefits (**Error! Bookmark not defined.**)	Manage environment to produce more diverse phenotypes, reducing intrapopulation competition and increasing population resilience (246); reduce unwanted selection with marine reserves (79,206)

Other Supplementary Materials

Image credits for Figure 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. Gray whale, *Eschrichtius robustus*, with whale watcher. Photo credit: Joe McKenna. 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/jpmckenna/4480425668/in/photolist-7PVmsq-8982GL-2YT6yC-dFFBjK-2YReMj-5kPokJ-eeKiRu-dtS35s-adYEqw-6i5hiT-2YT3Gf-gciEK8-9VG7wS-6KRzp3-773npp-eiBz4-dVU2f6-6u9yJs-8i1wEZ-fK6td9-fQFRBQ-7bDsJu-guYwrC-6eiXrn-5cBPUA-8yWTCN-guYPGM-6YVeDC-778dSq-773rnB-776er5-773erv-8Dgh4f-8vJu3y-8vFrEi-dNCDCk-5rMNzS-aWHfV2-gfTDav-fQLZJr-8DdaRB-584WjW-fPvSn8-77579h-777rq5-2YRScE-2YT8nN-6i5qAF-6i9r37-2YEvQg

Image credits for Figure 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-do33qb-aaq1jL-aancAK-aaq1gd-9XM1gh-jxueq5-76tSgJ-do33iN-do33Au-do334N-do33kW-do32L9-do33y1-do2VMe-do2W7n-do2VPv-do33go-do32S5-do2Wqx-do32NN-do2VDn-do
C. Dam removal. Photo credit: Penobscot River Restoration Trust. License: Copyright: Penobscot River Restoration Trust.

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Author contributions

S.P.C., P.S.J. and M.T.K. conceived and wrote the initial manuscript with subsequent contributions from all coauthors. B.E.T. contributed to writing about resistance management and to overall editing. C.T.B. and R.F.D. led the review of regulatory mechanisms and evolutionary manipulation of crops, respectively. P.S.J. and S.P.C. coordinated the work process and conducted the review of management examples, with further contributions from all coauthors.