BE/Bi 101: Order-of-Magnitude Biology
Homework 4
Due date: Friday, February 6, 2015

"To do successful research, you don't need to know everything. You just need to know of one thing that is not known."

—Arthur Schawlow

Some comments before starting the set.

1) There are lots of estimates in this problem set that might appear daunting. Remember the first principle of estimation: Fear not! Forge ahead!
2) These problems are best done working with your classmates. The problems are designed to get you pondering big questions in biology as you dive into your estimates. We always find we get more out of these exercises while discussing it with friends.
3) We remind you to try to use your life experience and pure thought to do the problems. Looking something up is absolutely the last resort. This is not because we think that having the collective knowledge of humanity on the internet and at your fingertips is a bad thing. Rather, performing educated guesswork with limited information gets you thinking and can lead you into territory you might not have thought of at the outset. That, and it's a great skill to have at parties.
4) With number 3 in mind, you can nonetheless refer to the slides from lecture. They are posted on the course website.
5) Finally, when as you answer the problems, if there is something that excites you, surprises you, or makes you curious, please say so and why.

1. Exploring biological diversity.

In class we talked a great deal about biodiversity over the history of life. Part of our effort was devoted to diversity in the fossil record, punctuated by the great mass extinctions, and part was devoted to the nature of current diversity on Earth and how it is changing as a result of the presence of humans. In this problem, we will pursue some of these same issues in more depth with you in the driver's seat.

a) Write a paragraph containing three answers to why the study of biodiversity is important to the study of biology, the study of evolution, the study of ecology and to efforts at "conservation" (if you deem that a worthwhile endeavor). Please send your answer as a PDF to me, Justin, David and Pradeep. This part of the problem will only be accepted by email and will not be looked at if not in PDF format (i.e., no MS Word files).
b) In this part of the problem, we briefly take stock of the kingdom fungi, an important contributor to global biodiversity that we didn't even mention in class. Begin by writing a few sentences about the members of this kingdom. What are the fungi? In his wonderful article in Scientific American on the subject of biodiversity (which you can download

here), Robert May tells us of the exploits of David Hawksworth who, like Terry Erwin in the context of insects, has tried to make reasonable preliminary estimates of the diversity of fungi. In Great Britain, where generations of biologists and interested amateurs have studied fungi, the claim is made that fungi outnumber vascular plants by a factor of 6:1. Use this estimated ratio to figure out the number of species of fungi in the world.

c) In their paper on "Prokaryotes the unseen majority" (downloadable here), Whitman *et al.* give us their estimates of the number of microbes to be found in various environments. Figure 1 reports the number of prokaryotes in the ocean, in the seafloor sediments and in the terrestrial subsurface. Using Figure 2, which comes from more recent work, make an estimate of the number of cells in the ocean sediment. Also, given the claim from Whitman *et al.* that there are 1.2×10^{29} microbes in the ocean, if we assume that all of those microbes are in the top 200 meters of the ocean, what is the typical number of bacterial cells per mL?

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Perspective

Prokaryotes: The unseen majority

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ABSTRACT The number of prokaryotes and the total amount of their cellular carbon on earth are estimated to be $4–6 \times 10^{30}$ cells and 350–550 Pg of C (1 Pg = 10^{15} g), respectively. Thus, the total amount of prokaryotic carbon is 60–100% of the estimated total carbon in plants, and inclusion of prokaryotic carbon in global models will almost double estimates of the amount of carbon stored in living organisms. In addition, the earth's prokaryotes contain 85–130 Pg of N and 9–14 Pg of P, or about 10-fold more of these nutrients than do plants, and represent the largest pool of these nutrients in living organisms. Most of the earth's prokaryotes occur in the open ocean, in soil, and in oceanic and terrestrial subsurfaces, where the numbers of cells are 1.2×10^{29}, 2.6×10^{29}, 3.5×10^{30}, and $0.25–2.5 \times 10^{30}$, respectively. The numbers of heterotrophic prokaryotes in the upper 200 m of the open ocean, the ocean below 200 m, and soil are consistent with average turnover times of 6–25 days, 0.8 yr, and 2.5 yr, respectively. Although subject to a great deal of uncertainty, the estimate for the average turnover time of prokaryotes in the subsurface is on the order of $1–2 \times 10^3$ yr. The cellular production rate for all prokaryotes on earth is estimated at 1.7×10^{30} cells/yr and is highest in the open ocean. The large population size and rapid growth of prokaryotes provides an enormous capacity for genetic diversity.

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Figure 1: Prokaryotic diversity as reported by Whitman *et al.*.

d) In light of the results of part (c), work out the amount of carbon present in the prokaryotes of Earth. To carry out your estimate, use the standard bacterium, *E. coli*, as a way to get

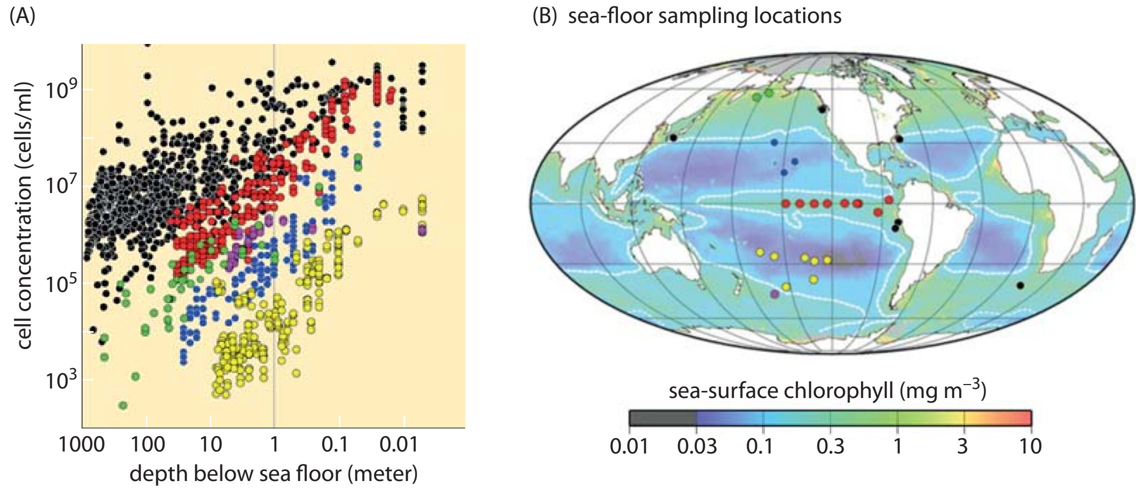


Figure 2: Cell counts in sea floor sediments. Adapted from S. D'Hondt *et al.*, *PNAS*, **106**, 11651, 2009.

a sense of the numbers. If *E. coli* is a rod of about 2 µm in length and 1 µm in diameter, what is its volume? Choose a simple round number. What is its mass? What fraction of that mass is the dry mass (i.e. not water)? Give an argument as to why roughly half of that dry mass is protein and then try to figure out how much carbon it takes to make a single bacterium. With this result in hand, how do your numbers jibe with what is claimed about the overall carbon stored in prokaryotic organisms in the abstract of the Whitman paper (see Figure 1)?

e) It is very interesting to contemplate the relative proportion of the animal mass on Earth that is due to wild animals versus domesticated animals. Justify the main features of Figure 3. That is, explain the claims made in that figure—how did you make the estimates you made and do you agree with what is shown there? Add to your insights by making an estimate of the amount of water consumed by humans and their domesticated partners.

f) Bats are of great interest for many reasons, including that they are one of the few mammals that reach oceanic islands and also because of their importance as reservoirs for viruses that can jump into humans (so-called zoonoses). In fact, it is thought that the current Ebola outbreak started with infection of a two-year-old boy in Guinea by a fruit bat. Rodents are also interesting because of their abundance and also because they, too, host zoonoses. Approximately 20% of known mammal species are bats and 40% are rodents. Estimate the mass of bats and mass of rodents on Earth. Next, estimate the number of bats and the number of rodents. Finally, estimate the collective mass of insects and fruit (their main diets) that bats eat each day.

g) A puzzling pattern has been noticed in the Aleutian Islands. The sea otters have been disappearing. At first, scientists were quite baffled. However, infrequent observations began to provide clues. In particular, it was found that orcas were eating the otters. One

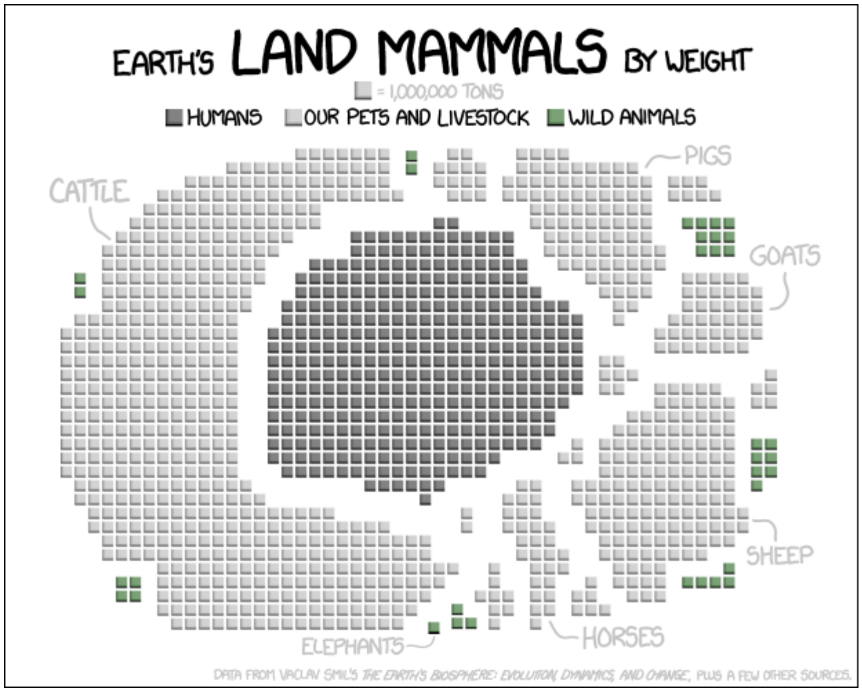


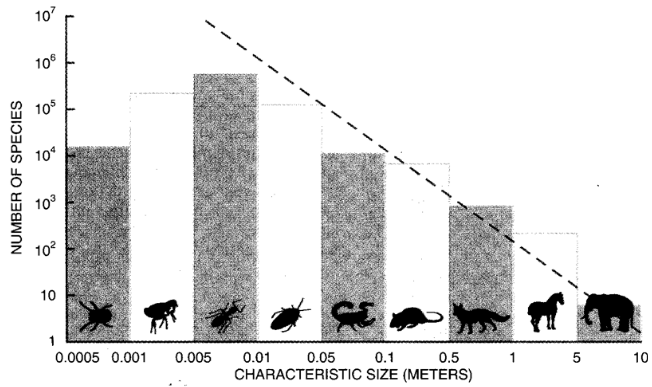
Figure 3: Mass of land mammals. Taken from an xkcd comic, http://xkcd.com/1338/.

school of thought is that this change in eating patterns is a result of over-whaling which resulted in turn in a huge diminution of the whale populations which were part of the natural prey of the orcas. Read this intruiging (and gruesome) article for the observations that support this. Not everyone is in accord with this hypothesis and others argue that it is overfishing and the lack of fish for the otters that is the more substantive problem. In any case, orcas have to eat! Estimate how many pounds of meat an orca needs per day. Then, try to estimate the number of otters you would expect would live around a typical island and how many orcas it would take to actually kill off an otter population around such an island.

After completing this problem you may be interested to read the careful analyses by James Estes and colleagues in their papers in the journals *Science* and *Ecology*.

2. Noah's Ark and biodiversity.
Using Figure 4 showing number of species as a function of size, figure out which size scale would place the largest demands on packing all species onto a modern version of Noah's Ark. Note that this graph tells us the number of different species at each size scale. The question is: how

much volume and mass is taken up by the species at each of these scales if they are packed into the ark in single male-female pairs? As a start, provide some analytic insight into how the values on the x-axis in the figure provide insights into the volume of each of the organisms. Use the graph (which has probably been significantly changed since the 1992 Scientific American article of Robert May) to estimate the number of different species to be put on the Ark.



SIZE RELATION offers a crude way to guess the number of species. In general, there are systematically more species of small animals than of large ones. The relation appears to break down for creatures less than one centimeter long, perhaps because taxonomists tend to overlook such species. If the relation holds for organisms as small as a millimeter long, there are about 10 million species.

Figure 4: The number of species as a function of size of organism. Taken from R. M. May, "How many species inhabit the earth?", *Scientific American*, October 1992, 18–24 (available for download here).