ACTIVITY PART I: GETTING FAMILIAR WITH THE MODEL

Author's Notes: Insight answer key is available at https://insightmaker.com/insight/113968/Silver-Biogeochemical-Cycling-v2-answer-key. The paper that informs the model is Rauch, J. N., & Pacyna, J. M. (2009). Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles. Global Biogeochemical Cycles, 23, GB2001, doi: 10.1029/2008GB003376.

If any errors or omissions are found, please contact me at megwagn@umich.edu. Additionally, if you would like to help me improve the model, please email me.

Open the Insight Maker model "Silver Biogeochemical Cycling" found at https://insightmaker.com/insight/109267/Silver-Biogeochemical-Cycling-v2. Make a copy of this model (i.e. clone the Insight) to use for your own explorations. In this model, silver mass in reservoirs is given in Gg (gigagrams) and flow rates are given in Gg/yr (gigagrams per year).

1. Identify the:
    a. Three largest silver reservoirs by mass.
       In order from largest to smallest: Upper Continental Crust, Ocean Crust, and Soil.

    b. Three smallest silver reservoirs by mass.
       In order from smallest to largest: Atmosphere, Ocean Biomass, Freshwater.

2. Click on "Settings" and set the following:
   Simulation start = 0;
   Simulation Length = 1000;
   Time Units = Years;
   Pause Interval = No Pause;
   Analysis Algorithm = Fast (Euler);
   Simulation Time Step = 20

   Click Apply. Press the button that says Simulate to run the model. You can set the run speed of the model in the lower right-hand corner of the graph that appears. When the model run finishes, click on Configure. Under Data, select "OceanCrust". Set the minimum value for the y-axis to zero. For the Secondary Y-axis Data, select "TerrBiomass". Again set the minimum value for the secondary y-axis to zero. Give the graph a descriptive title and click Apply.

   Describe the results for OceanCrust and TerrBiomass. Why are they so different?
   When viewed with the y-axis range from 0 to 2.8E8, OceanCrust appears to have no change over 1000 years. Zooming in, we see that in fact OceanCrust gains mass relatively slowly: 2200 Gg over 1000 years. In contrast, TerrBiomass visibly decreases over the 1000-year time period, from a starting value of 170 Gg to 70 Gg. With the given model setup, OceanCrust only has one inflow from OceanRegolith. The vast size of the

OceanCrust reservoir (2.6E8 Gg) coupled with the much smaller flux from OceanRegolith (2.2 Gg/yr) results in a seemingly unchanging reservoir. In contrast, the TerrBiomass reservoir is much smaller than OceanCrust. The net flux for TerrBiomass is -0.1 Gg/yr; in other words, slightly more silver leaves TerrBiomass than enters each year. The closer match in scale between the net flux and the reservoir size means that the flux out of the reservoir has a relatively larger impact, and this is reflected in the graph.

3. Close the graph. Click on the flow SoiltoFreshwater. The flow rate should be set at 71 Gg/yr. Change this flow rate in any way you wish and run the model (i.e. click Simulate). Make sure your graph displays the results for Freshwater and Soil. Describe how you changed the flow rate and the results of your change.
   The results will obviously depend on how the student chooses to change the flow rate. The goals here are simply to build confidence in using the model and to explore how changing environmental conditions (in this case, changing how much silver enters lakes and rivers from weathering and erosion) affects silver cycling.

4. Reset the SoiltoFreshwater flow rate to 71. Add a flow into or out of the Freshwater reservoir. To do this, let your mouse pointer hover over the box labeled Freshwater. A blue arrow should appear in the center. Click this arrow and drag outside the box. You now have a new flow. To change the direction of the flow, click the button at the top of the workspace showing two arrows pointing in opposing directions. Give the flow a name, a flow rate, and units of Gg/yr. Run the model, then describe below the flow you added and the results of your change. Make sure your graph displays the results for Freshwater and any other reservoirs that interest you.
   Again, the results will depend on how the student chooses to modify the model. Students should at least describe the changes in Freshwater; more motivated students may investigate what happens to other reservoirs as well.

ACTIVITY PART II: SOCIO-ENVIRONMENTAL IMPACTS ON SILVER CYCLING

5. Now let's explore the effects of silver mining and use in products. Create a new stock called ResourcePool, and create a flow from the Upper Cont Crust to the ResourcePool. Label this flow Extraction. Set the initial value of ResourcePool at 345 Gg. Set the initial flow rate for Extraction at 20 Gg/yr and create a value slider. Set the value slider max at 200 and the slider min at 0.

   Now create a flow from ResourcePool to Atmosphere. Label the flow in a meaningful way and set the initial flow rate at 0.44 Gg/yr.

   Create a flow from ResourcePool to Freshwater. Label the flow in a meaningful way and set the initial flow rate at 1.137 Gg/yr.

Create a flow from ResourcePool to Soil. Label the flow in a meaningful way and set the initial flow rate at 9.93 Gg/yr.

Create a flow from ResourcePool to Ocean. Label the flow in a meaningful way and set the initial flow rate at 0.72 Gg/yr.

Run the model. How do the long-term evolutions of Atmosphere, Freshwater, Soil, and Ocean compare to Part I, without Extraction?
-With Extraction, Atmosphere decreases to 0 Gg in just over 1.5 years. Without Extraction, Atmosphere decreases to 0 Gg in less than a year.
-With Extraction, Freshwater increases rapidly from 28 to 1165 Gg over 1000 years. Without Extraction, Freshwater remains constant at 28 Gg.
-Soil does not change much, compared to the size of the reservoir. With Extraction, Soil loses 1571 Gg over 1000 years. Without Extraction, Soil loses 11501 Gg over 1000 years.
-With Extraction, Ocean increases from 3500 to 3903 Gg over 1000 years. Without Extraction, Ocean decreases from 3500 to 3183 Gg over 1000 years.

6. Which reservoir(s) is(are) most affected by extraction of silver from Upper Continental Crust? Which reservoir(s) is(are) least affected? Explain why this is the case.
   Resource extraction accelerates the transfer of silver from the lithosphere (upper continental crust) to surface reservoirs. Smaller reservoirs are relatively more affected by the transfer; larger reservoirs are relatively less affected. While the upper continental crust itself is a very large reservoir (2.7E8 Gg), Rauch and Pacyna (2009) note that mineral resources amount to only 780 Gg. The large reservoirs also tend to have long residence times, on the order of millions of years. The small reservoirs tend to have short residence times, often less than a year. Silver cycles in and out of these reservoirs more quickly, but the accelerated inflow due to extractive activities causes the size of the reservoirs to increase rapidly.

   Note: Residence times are given for each reservoir in the "Notes" section for the answer key Insight. Not all of the reservoirs are at steady state, so the calculations should be treated as estimates. However, order of magnitude is probably correct.

7. Some parts of the silver cycle have been omitted for clarity and simplicity in the model. For example, the Insight Maker model shows no inputs to Upper Cont. Crust. In reality, input from the mantle does occur. Ocean crust that re-supplies the mantle is returned on the timescale of plate tectonics, or tens of millions of years. Regeneration of silver resources in the upper continental crust is therefore dependent on plate tectonics. What does this mean for our continued ability to extract new silver resources?
   Plate tectonics, and therefore renewal of a natural resource, operates on timescales much longer than the average human lifespan. The current rate of extraction implies that all available silver will be mined out within decades and the Earth will not be able to re-supply those resources within a useful timeframe. We will need to make greater use

of recycling and potentially recover silver from reservoirs where it is now accumulating, such as the ocean.

8. Silver extraction rates have not been constant through time. For example, advances in mining techniques during the 20th century greatly increased silver production. In contrast, in times of war silver production has decreased. Using lead (Pb) isotopes measured in a Greenland ice core, researchers have pinpointed a number of events that affected Roman silver output during antiquity (McConnell et al., 2018). In this question you will explore how society, economics, and technology can affect resource extraction.

    a. Add (a) variable(s) to the model modifying the extraction rate accordingly for each scenario below.
    A sample solution for modifying the model is available in the Insight answer key. Answers will depend somewhat on how students choose to simulate the events described below. The outflows from ResourcePool will also need to be affected by the Extraction Rate.

    b. Decrease the Extraction flow to 1 Gg/yr as a baseline value to simulate the lower overall extraction rates during antiquity. Extensive Roman silver mining activities occurred in southern Spain during the Roman Republic and Imperial periods. Warfare in Spain between 196 and 182 BC dropped annual lead flux in the ice core to roughly 10% of its pre-war level at some points. Assume that silver production dropped accordingly to 10% of its pre-war level (baseline value). How do the Atmosphere, Freshwater, and Ocean reservoirs change in response to warfare?
    Outflow to these reservoirs should decrease compared to the baseline value.

    c. The Pax Romana was a long period of peace and prosperity during Imperial Rome. During this time lead emissions imply that silver production was high, and Roman currency, the denarius, consistently showed high silver bullion content. At maximum, lead flux increased approximately 30 times over its prior level. Increase silver extraction 30-fold over your imposed baseline. How do the Soil, Freshwater, and Ocean reservoirs change in response?
    Outflow to these reservoirs should increase compared to the baseline value.

    d. The Pax Romana ended with the Antonine Plague, which again lowered silver production (how can you mine silver without slaves, er, workers?). Decrease silver extraction to 30% of its baseline value. How do the Soil, Freshwater, and Atmosphere reservoirs change in response?
    Outflow to these reservoirs should decrease compared to the baseline value.

e. Imagine that the Romans began to melt down old denarius coins and re-use the silver. How would this affect the ResourcePool reservoir? How would this affect downstream environmental reservoirs such as Ocean?
   Depending on whether silver mining (extraction) decreased concomitantly, ResourcePool might increase or stay the same. If silver recycling replaced mining, we might expect that outflow to Ocean and other reservoirs will decrease.

ACTIVITY PART III AND PART IV

There is no absolute right or wrong answer for these parts, but rubrics are provided in the teaching guide for assessment purposes.