Project Exam
Modelling and Analysis of Complex Systems (MEBI003-550453)
(100 points)

IMPORTANT GENERAL POINTS:

Submit your python codes (either as .py files or .ipynb files) and a single report (in pdf) for all your tasks. The report should contain a description of all figures produced and answers to the questions asked.

Indicate your full name clearly in all python codes and in the report.

Make sure that your figures are clear and informative, that is, figures should be self-explanatory and should include all labels in all axes and relevant legends. Additionally, axes should cover reasonable and informative ranges of values. The explanatory text should refer clearly to each figure included in the report. There is no need to include your python code into the report.

SUBMISSION DEADLINE:

Submit your exam by 18:30 (German time) of 17 December 2020 via email to agostino.merico@jacobs-university.de with the subject: 'Project exam MEBI003-550453 – *first name* and *family name*'.

The submission deadline is strict, any late submission, even if it is a perfect solution of the entire exam, will be considered as a failure.

Part 1 of 3 – Uncovering the history of Easter Island (35 of 100 points)

Easter Island or *Rapa Nui*, as it is called by its natives, has a contentious and elusive history. Hundreds of giant statues, known as *moai*, scattered on a treeless landscape are testimony of a once flourishing society. And yet, the first Europeans that officially landed there on 5 April 1722 A.D. and guided by the Dutch commander Jacob Roggeveen, were astonished by what they saw, how could the natives have built and transported such statues given that the island was devoid of any thick timber for building tools or machines?

Moai, monolithic human figures carved by the *Rapa Nui* people on Easter Island in eastern Polynesia between the years 1250 and 1500 A.D.. *Moai* can reach 10 m in height and 80 tons in weight.

An island once covered with a lush palm forest (as it was proved in the 20th century by archaeological and palynological data) was found deprived of trees and poor in ecological resources.

Early archaeological work in the 20th century contributed to form a theory of Easter Island history that still influences scientists today. This theory says that population growth, deforestation, soil erosion, overuse of bird and shellfish resources, and introduction of rats all contributed to a catastrophic social and ecological collapse of the island.

Deforestation is undisputed. However, no reliable evidence exists about the temporal dynamics of human population and deforestation and the timing of the potential collapse.

Because of the uncertainties in the dynamics of human population, two completely contrasting theories (or narratives) have been developed over the years about the history of Easter Island: ecocide and genocide.

Not surprisingly, these narratives differ greatly in the assumed population dynamics and in the causes proposed to explain a demographic collapse, advocating self-overexploitation of resources or the combined effects of diseases and slavery introduced by Europeans for, respectively, ecocide and genocide.

According to the ecocide theory, the human population increased steadily over several centuries and peaked at around 20,000 individuals before a rapid and drastic collapse occurred at around 1650 A.D., several decades before Europeans discovered the island in 1722 A.D. The human population grew too large to be sustained by the primary resource, the palm forest, and when the threes were depleted a dramatic fall followed.

While it is obvious that the islanders were not directly living from palm trees, the forest is considered a primary resource as it provided several invaluable and ecological services, including food from fruits and palm nuts, timber to construct houses and canoes, fuel, nutrients for the meagre soils after slash-and-burn clearance, and protection against soil erosion.

According to the genocide theory, the human population remained stable on a much lower level, at around 4,000 individuals, for a long period before the arrival of Europeans. The ultimate, determining reason for the eventual collapse of the human population is attributed to the arrival of Europeans who introduced devastating diseases and slavery.

Deforestation is attributed not only to humans but also to a rapidly growing population of rats, which effectively reduced the fertility of the forest by feeding on palm seeds.

Relicts of extensive agriculture indicate the establishment of a sustainable livelihood while large parts of the forest were disappearing.

Your tasks are:

Assuming that the island was initially colonised by a small group of 50 Polynesians in 1200 A.D., that this group carried 10 rats, and that when these Polynesians arrived a total of 8,000,000 palm trees were present on the island, develop a differential equation-based model of Easter Island comprising three state variables: humans, trees and rats. The model should be run over a time period of 500 years starting from 1200 A.D. and ending in 1700 A.D., thus excluding events and processes that started with the discovery of the island by Europeans.

Produce:

1) A list of all model ingredients, including variables, processes, parameters, etc.; (7 points)
2) A diagram representing a qualitative representation of the model; (7 points)
3) The complete set of equations in a mathematical format; (7 points)
4) A python code producing numerical solutions; (7 points)
5) Which type of narrative (ecocide or genocide) do your model results generate? Discuss why also with the help of figures additional to those of population dynamics. (7 points)

Suggestions:

- Use logistic functions for population growth

Part 2 of 3 – Coin exchange and the emergence of inequality (35 of 100 points)

Using the model structure learned during the course, develop an Agent-Based Model that shows how a very simple, random-choice exchange of coins between initially equal agents creates economic inequality.

The rules are:

- The number of agents is $N = 100$;
- At the beginning of the simulation, every agent should have one coin;
- At each time step, (1) randomly select one agent; (2) if this selected agent has at least one coin, then this agent donates one coin to another randomly selected agent, (3) repeat steps 1 and 2 N times; (4) move to the next time step.

Your tasks are:

1) Implement this model into python (10 points);
2) Run the model for 100 timesteps and present clear and informative plots showing histograms of the distribution of coins among agents at different times t = 0, 1, 2, 3, 10, 100 (8 points).
3) At each timestep, calculate the *gini coefficient* (https://en.wikipedia.org/wiki/Gini_coefficient) of this artificial society and present a clear and informative plot showing the evolution of the *gini coefficient* over time (9 points);
4) Interpret your results in a few sentences. For example, what economic implications can you draw from this model? What do you find interesting about this model? In what major aspects does this model not represent how our society works? (3 points);
5) Experiment with different initial number of coins that each agent has (e.g. in one experiment, every agent has 5 coins at the beginning; in a next experiment, every agent has 10 coins at the beginning). Plot, in clear and informative figures, the results of these experiments and briefly explain them (5 points).

Part 3 of 3 – Latitudinal gradients of biodiversity (30 of 100 points)

Here we will compare global latitudinal patterns of two components of phytoplankton diversity, i.e. species diversity and trait diversity. For this, we will develop a simple data analysis (tasks 1 to 5) and provide a plausible interpretation of the results by answering some questions (from 6.a to 6.e). The questions under point 6 can be answered simply by studying Lecture 9, entitled "The enigmatic concept of biodiversity", together with Righetti et al. 2019 (https://advances.sciencemag.org/content/5/5/eaau6253) and Acevedo-Trejos et al. 2018 (https://royalsocietypublishing.org/doi/full/10.1098/rspb.2018.0621).

Your tasks are:

1) Download global sea surface temperature data for the annual climatological fields at 1° by 1° spatial resolution from the World Ocean Atlas. Download the NetCDF file "t00_01.nc" from https://www.nodc.noaa.gov/cgi-bin/OC5/woa18/woa18.pl. Plot a map (for example, using 'cartopy', https://scitools.org.uk/cartopy/docs/latest/index.html) of the global sea surface temperature. IMPORTANT: dimension 'depth' in the data set refers to water depth with value 0 indicating the surface. (4 points)
2) Construct a Random Forrest (RF) model using the phytoplankton data from the Atlantic transect, just like we did in class (file name "RF_phyto.cvs"). However, in this case build a simpler RF model that uses only SST as a predictor variable and focus on predicting only phytoplankton size diversity. In addition, resample (using https://scikit-learn.org/stable/modules/generated/sklearn.utils.resample.html) the dataset to increase the number of samples to 100. Split the resampled data set into 75% training and 25% test subset. Then fit the RF model using the training subset. Finally, provide the score (R^2 or coefficient of determination) for the RF model using the test subset of the resampled data). (4 points)
MPORTANT NOTE: adopt the option random_state=0 when using the following methods:
- resample (https://scikit-learn.org/stable/modules/generated/sklearn.utils.resample.html)
- train_test_split (https://scikit-learn.org/stable/modules/generated/sklearn.model_selection.train_test_split.html)
- RandomForestRegressor (https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestRegressor.html)
3) Predict the global phytoplankton size diversity using the constructed RF model (Task 2) and the annual climatological field of SST (Task 1). Plot a map of the predicted global phytoplankton size diversity. IMPORTANT: replace all 'NaN' ('Not a Number') with an extreme value. (4 points)
4) Download the global species diversity data produced by Righetti et al. (2019 Sci. Adv). Follow this link https://advances.sciencemag.org/content/5/5/eaau6253/tab-figures-data to the supplementary material of the manuscript and download "data file S1" (at the bottom of the page) to obtain the NetCDF file called "aau6253_Data_file_S1.nc". Plot a map of the annual averaged phytoplankton species diversity. IMPORTANT: the dimension z in the data set refers to months. (4 points)
5) In a single graph, plot the average latitudinal size diversity (Task 1) and average species diversity (Task 4). Plot latitude on the Y-axis and the two diversities in the two opposite X-axes using the twin axis method (twinx). IMPORTANT: to compute the average diversity at a particular latitudinal location, average out all longitudinal values for all months at that particular latitude. (4 points)
6) Answer the following questions:
   a. What is the latitudinal diversity gradient? (2 points)

b. How do the latitudinal patterns of species diversity and size diversity differ from one another? (2 points)
c. Under what SST conditions (tropical, subtropical, temperate or polar) is it more likely to find higher species diversity? (2 points)
d. Under what typical SST conditions (tropical, subtropical, temperate or polar) is it more likely to find higher size diversity? (2 points)
e. What other environmental factors, apart from SST, could influence these latitudinal patterns? (2 points)