Modeling Stable Growth:
A multi-cohort dynamic human population model
and new formula for two-way coupling with climate models

Abstract:

A realistic projection of greenhouse gas (GHG) emissions and the resulting anthropogenic climate change can only be achieved through the inclusion of human population impacts with feedbacks onto global climate models. The growth of population itself depends on the fertility age and the total fertility rate (TFR), however, detailed distributions of these parameters can make a large impact on the total growth. To investigate these impacts, we have developed a series of multi-cohort dynamic population models with different numbers of fertile cohorts. Census data for various regions can be used as input for these models. These models can eventually be integrated through bidirectional couplings into a climate model such as the Community Earth System Model (CESM), to project future birth rates, total population, and subsequent GHG emissions. We have also developed a new formulation that better demonstrates how total population growth depends on the fertility age, TFR, and average lifetime. We will compare the results of the dynamic model simulations to the predictions from the theoretical equation. Our results show that delaying the age at which a woman gives birth, or spacing out her child-bearing years to accommodate a professional lifestyle, can lead to less rapid population growth, and thus slower climate change.

Curving upwards, the world's population at 7.6 billion currently is a mathematician's textbook example of exponential growth with implications for both our planet and the humans that compose it. Indeed, growth of population is linked to a plethora of environmental and sustainable challenges our generation will have to confront including the increased emission level of greenhouse gases, resource depletion, rising global mean surface temperature and water levels, and catastrophic climate events caused by global warming. To study the coupled impact of population and emission growth, Navarro et. al developed a population model for a global climate model and found that "population projections [can] be used to improve the estimates of CO2 emissions, thus transcending the bulk approach of existing models and allowing more realistic non-linear effects to feature in the simulation," (Navarro, 2017). Thus, I plan to mirror my modeling efforts closely to their goals, but will plan to eventually achieve 100 one-year cohorts. In addition the POPEM model of Navarro uses FORTRAN, and I plan to use Python, to allow for a more flexible script.

Furthermore, this modeling approach of incorporating human feedbacks onto earth system feedbacks is still relatively new. In order to understand the dynamics of both systems, earth system models must be coupled in a bidirectional fashion with human system models (Motesharrei et. al, 2016).

Parallel to this project, we also realized that many people do not have an innate sense for exponential mathematics and that representing the formula in a discrete fashion would be a clearer way to relate total fertility rate, maternal age, and total lifetime. In our quest to do this, we also realized the current discrete representation, utilized in Warren as well as many population texts, is true only for insects because it does not take into account the accumulation of past generations over time.

Bongaarts and Feeney brought forth the discussion of tempo and quantum effects, as well as why total fertility rate is an insufficient measure of a total country's growth. Period fertility relates to a specific time period, whereas cohort fertility measures the fertility experience of a certain generation of women defined by when they were born. Therefore, Ryder has also pointed out the shortcomings of the traditional TFR by instead espousing the benefits of using a cohort TFR, which would instead calculate total fertility. By taking into account the accumulation of generations, our formula calculates a completed fertility rate for a generation.

Traditionally, the child-bearing years for women are assumed to span the ages from 15-50 (Warren, 2015). In our study we initially examined a single fertile age cohort of 15-44, and then further broke that single fertile age cohort into three ten-year cohorts. We developed these equations to find what birth rate would be the "equilibrium condition" or would produce a stable population for at least 1000 years. The value was determined to be .046 births per woman per ten-year age-span cohort. This was achieved through integration modeling in Vensim program.

Now that this condition has been verified both through a system of five differential equations and the integration software of Vensim, we are transferring the code over to Python, which will be a more robust language for its ability to create reproducible scripts, to more easily produce a larger matrix of one-year cohorts, and for its ease of accessibility in reading in Census data files.

The basic demonstration of population levels decreasing with a total fertility rate of 1 was achieved through our sum equation and code as well. Furthermore, the curve for total fertility rate equaling total lifetime (the "insect case" which is above all else, not realistic for humans) is much lower than the cases when total lifettime is twice the total fertility age or three times it. Finally, in the total fertility rate equaling 1 case, the decay of the youngest maternal or total fertility age at age 20 is much faster than the 30-year maternal age. This may seem counterintuitive but this formula then helps us understand the not-so-trivial nature of exponential growth and reinforces the validity of the 2.1 replacement rate. For example, a total fertility rate less than two indicates decay whereas greater than two indicates growth. In both cases the rate of growth or decay will be faster for the 20-year old maternal age, and thus demonstrates why the 20-year maternal age begins to dominate at total fertility rate equaling three.

This run-away effect will have serious implications for both the Earth and humans. This model and new summation formula will be able to realistically project how much of an effect population will continue to have if education of population growth is not disseminated.

References:

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