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A Preliminary Framework for Modeling Human Migration Flows Impacted by Climate Change–Induced State Carrying Capacity Changes

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ABSTRACT

This paper develops a preliminary framework for modeling human migration flows where climate change (mean annual temperature increase) impacts state carrying capacity and movement is constrained by finite migration rates. It begins with a brief discussion of the assumptions underlying the model and the scope of the model's application to continental Africa for the years 2020-2100. The model's ability to simulate population flows and state carrying capacity is then demonstrated, and sensitivities of model output to parameter changes are explored. Experimentation with model parameters indicates a potentially catastrophic inability of human populations to adapt quickly enough to changing carrying capacities as climate change stresses existing population regions such as the Sahara and the Sahel. Actionable policy approaches to address the concerns identified by the model are presented. The ongoing need for human migration research focused on its interaction with climate-induced collapse frames this paper. Suggested improvements to the model to better address the limitations of the model's scope are reviewed.

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Chapter 1

Introduction

The 2022 Intergovernmental Panel on Climate Change (IPCC) report made global headlines with its dire warning about the state of the climate and humanity's future. The IPCC report indicates we are heading toward disastrous consequences if radical systemic, social change does not occur in the next few decades (IPCC, 2022). The report found specifically that:

Regions and people with considerable development constraints have high vulnerability to climatic hazards (high confidence). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (high confidence). (IPCC, 2022)

These hotspots of climate vulnerability are a reasonable testing ground for developing models dependent on climate change impact. The model developed in this paper uses continental Africa as the testing ground because of the high environmental vulnerability to climate change, the identified high human vulnerability, the high variability of climatic zones across the continent, and the ease of access to temperature data for each state.

The Sahara and Sahel regions of Africa are anticipated to have decreased livability due to climate change. The resulting livability crises will force the populations to relocate to livable areas. Consider the Middle East for an example of climate change and its expected impact on the livability of the region (Timofte, 2021). Rising temperatures due to climate change has deleterious effects on the livability of the region in terms of the human temperature limit (the "wet bulb temperature" or 35°C) and in the impacts the temperature rises have on the ability to support the population through food infrastructure, appropriate shelter, and temperature-mediated living (Timofte, 2021). The number of people the state can support diminishes as the resources become strained, hence the supported conclusion of many climatologists and political scientists alike that climate change induces political strife (Timofte, 2021). To represent the livability of a state, the model here uses the term “carrying capacity” as it relates to the number of people a state can reasonably support; rising temperatures act upon the carrying capacity in an inverse relationship of an increase in temperature to a decrease in carrying capacity.

The model developed here explores the migration dynamics where climate change (proxied as mean annual temperature) reduces the livability (carrying capacity) of states. The resulting decreases in carrying capacity forces populations to emigrate to neighboring states as they become “climate refugees” escaping the consequences of environmental disaster. The model used in this paper is a non-homogeneous Markov chain model based on previous applications of the model to population movements (Hirst, 1976; Huang & Unwin, 2020; Pan & Nagurney, 1994). “Non-homogeneous” allows transition state probabilities to be dependent on time; that is, each epoch can have a new transition probability matrix. The “chain” prevents each node in the model from connecting directly to each other; that is, a refugee cannot migrate from Morocco to South Africa without first transiting the intermediate states.

Climate refugee modeling can aid governments in determining the most efficient and beneficial allocation of resources in anticipation of refugee movement. Climate refugee modeling also enables governments to develop appropriate preventative measures to avoid the worst outcomes predicted by this model. The World Meteorological Association predicts that upwards of 118 million impoverished people in Africa will be exposed to drought, floods, and extreme heat by 2030, the first decade of the temperature data used in this paper. The IPCC states that “soft limits” to human adaptation to climate change include financial, governance, institutional, and policy constraints which includes degrees of international cooperation on aid, cross-border travel, and legally binding agreements between countries on how to treat the presently undefined category of “climate refugee“ (IPCC 2022; Gautam, 2020; Meek & Nene, 2021).

A key part of the effort in this paper is to explore the impact of a migration rate constraint on the population of states, overcapacity crises, and the flow of migrants between states. The migration rate constraint can encapsulate several factors restricting cross-border migration including international legal agreements, household economic capability to fund migration, asylum-seeking policies, and political acceptance of immigrants. The experimentation with the constraint in this paper is concerned first with proving the model’s capability and second with producing politically applicable results. The model developed here and experimented with provides a picture of migration behaviors under conditions that presently lack real-world data for climate change–induced mass migration; hence, the model allows one to produce several scenarios that may arise and develop plans for each possibility. Various adjustments made to the migration constraint parameter to reduce the number of refugees that can leave in a single month causes many states to suffer overpopulation crises and traps populations in states that can no longer support them. The model has specific parameters that can act as policy foci for change such as the constraint on migration, which can be affected by real-world “soft limits.”

Finally, the framework of this model can be improved upon to better predict real-world migration movements and to better model the complex impacts of climate change on migration rate and direction. As time progresses, observational data that can be fed into this model to tune its parameters and so to better predict future migration behavior under climate change. The model is adaptive in its ability to augment the parameter set and add new means of affecting carrying capacity such as severity of drought. The migration constraint can be subdivided into variables which better represent the complex web of soft limits that affect migration. Additionally, the model can be used to model internal displacement by using state-regional temperature data supplied by the same dataset used in this paper and tuning parameters to fit the new unit of analysis.

Chapter 2

Literature Review

Climate Modeling

Climate modeling is a well-populated field focused on modeling not only the climate itself, but also the impact of climate on a variety of subjects in the broader ecosystem. There are several climate studies projecting changes in temperature (Hassan & Nile, 2021; Li & Thompson, 2021), precipitation (Abbasian et al., 2021; Lim Kam Sian et al. 2021; Mamalakis et al., 2021), agricultural productivity and growth changes (Ogundari et al., 2021; Ortiz-Bobea, 2021), and more. One of the principal temperature datasets assessed and utilized by the IPCC is the Coupled Model Intercomparison Project (CMIP), with the latest IPCC report based on CMIP Phase 6, abbreviated CMIP6. The CMIP6 is created by the World Climate Research Programme (WCRP) and its Working Group on Coupled Modeling (WGCM). CMIP synthesizes coordinated climate model experiments with international modeling teams to develop various climate projections. There are five datasets of projected environmental variables coinciding with the IPCC Shared Socioeconomic Pathway (SSP) stories: SSP-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5. Each of these stories coincides with a different expected economic development pattern and its subsequent impact on the environment, respectively: sustainability, middle-of-the-road, regional rivalry, inequality, fossil-fuel development (IPCC, 2022). For the experimentation with the migration constraint parameter, I utilize the SSP5-8.5 temperature projections as provided by the World Bank and as also utilized by the IPCC. The model has the ability to accommodate any of the temperature projections from the various SSP scenarios; selecting the fossil-fuel development pathway provided the model with the most extreme temperature data to provide the most poignant, visible results in migration movements.

Carrying Capacity

Studies examining the relationship between climate change and carrying capacity tend to focus on environmental ecology and the carrying capacity of a biotic ecosystem (Chapman & Byron, 2018; Woodworth-Jefcoats & Drazen, 2017); various studies project animal populations and measure adaptability of the ecosystem to the changing climate (Goyert et al., 2018). In biotic ecological studies, particularly those centered on population projections, carrying capacity is a function of the means of supporting the population such as food supplies, livable temperature ranges, water supply, and predator-prey balance (Chapman & Byron, 2018; Goyert et al., 2018). These studies find that the ecosystem cannot adapt quickly enough to the changing climate and, thus, general catastrophe and death occurs given the general inability of subjects in the ecosystem to migrate or adapt to more livable zones (Goyert et al., 2018; McKechnie & Wolf, 2010). This lagging adaptive response of ecosystems to climate change has not yet been similarly modeled in relation to human populations as it relates to our ability to migrate away from increasingly hostile environments as those environments decrease the livability of the population centers (states).

There are various scientific theories that identify specific environmental input as causes of migration reaction. Gray and Wise find that migration tends to increase with temperature anomalies in Uganda and tends to decrease with temperature anomalies in Kenya and Burkina Faso, with other countries demonstrating zero relationship with temperature and migration (2016). Studies broadly demonstrate that precipitation rate has no consistent migratory response and has a positive effect on agricultural growth zones, though it presents a weaker positive relationship than the negative relationship between temperature anomalies and agriculture. Migration induced by climate change has been found to be a lagging response by at least two years and it is influenced more by temperature rises and, to a lesser extent by, precipitation rate than by natural disasters (Bohra-Mishra et al., 2014).

Human-environmental scholars have long predicted a climate change-induced “Malthusian wave” of climate refugees (Myers, 2002). There is a significant body of research challenging the Malthusian wave claim which uncovers evidence that climate extremes can increase human migration, but the effect is not as simple as the Malthusian literature posits. For short-distance or temporary migration, climate variability has a larger effect on migration and precipitation has a weaker effect on human migration relative to temperature (Gray & Wise, 2016). There are also entrapping effects to climate variability that leave vulnerable populations unable to migrate; theoretical developments in migration studies problematize the ability of humans to migrate based on their socioeconomic level. Vulnerable populations can become trapped due to socioeconomic status where wealthier households can afford the high cost of migration (Black et al., 2011; Bowles, 1970; Massey, 1993).

The framework in this paper seeks to briefly sideline discussions of the complex specifics of migration motives in favor of using simple inputs for initial development. Assumptions of the model such as the equal impact of temperature across states and equality of migration ability are necessary to develop the framework and prove it can produce observable results regarding carrying capacity changes that affect migration flows as well as quantitative data regarding migration rate and direction. Carrying capacity represented as a maximum allowable population is an effective proxy for livability because a population limit is an implicit calculation of support for human life in each state. The model can be improved by introducing the complexity identified by human-environmental scholars, but the framework to introduce that complexity is established in this paper.

Model Types

There are a variety of modeling methods to perform population forecasting and predict migration behavior, among them being agent-based models (ABMs) and Markov chain models (MCMs). ABMs are a popular modeling method due to the ability to assign specific behaviors to individual agents and simulate predefined rulesets based on an initial starting condition; ABMs are computationally complex and often require more powerful hardware to run. Both ABMs and MCMs are memoryless algorithms that rely only on starting condition data and pre-defined behaviors to simulate. ABMs and MCMs are especially useful in circumstances where large amounts of historical data is missing, incomplete, or the historical data cannot accurately predict future events because there is an unknown mathematical relationship between historical data and future events. Although there is a substantial amount of scholarship in understanding previous climate regimes and their impact on human society (Camenisch & Rohr, 2018; Ljungqvist, 2021), historical reviews of how climate changes impacted human society are restricted to historical periods such as the "Little Ice Age" in Europe where the temperature changes were not global phenomena in the same way anthropogenic climate change is expected to be (Neukom et al., 2019). The severity of anthropogenic climate change is not comparable to previous temperature regimes experienced by human civilization (Neukom et al., 2019). As such, this model does not rely on historical data to develop mathematical relationships for behaviors in an uncertain future; the model instead seeks to develop the framework to produce multiple outcomes for behaviors under a new climate regime.

Where ABMs model each refugee individually and have each refugee make independent choices, MCMs model macro-level dynamics by treating refugee populations as large groups. Scholars Huang and Unwin use a non-homogeneous Markov chain to model refugee movements based on data from the 2015 Burundi refugee crisis (2020). Refugee movement between conflict sites, neutral sites, and camp sites is a function of distance and time. Huang and Unwin compare their results to an existing agent-based model of the same refugee crisis and conclude MCM provides a "modest improvement" over the agent-based model, lending support to the use of MCMs in place of ABMs for modeling accuracy (2020). The scope of their model is restricted to conflict modeling as it affects refugee movement; the model developed in this paper is concerned with modeling the impact of climate change on state carrying capacity as it affects population movement. While their contribution to proving the slight advantage of MCMs over ABMs, their model does not address migration under climate change. The effort in this paper seeks to adopt their migration modeling methodology and apply it to migration behaviors under climate change.

In “A Markovian Analysis of Inter-Regional Migration in Uganda”, Hirst explores the applicability of a Markov model to matching observed migration dynamics in Uganda (1976). Hirst identifies three advantages to using a Markov model:

> Firstly, and as already indicated, Markov chain models allow one to consider the dynamics of migration phenomena by conceptualising migration as a probability process….Secondly, one is able to separate the migration process from the population that is undergoing that process and thus be able to focus on upon the process itself….Thirdly, the characteristics of Markov chain models are easily estimated via elegant matrix methods which themselves can be readily programmed for digital computers. (1976, p. 81)

Hirst also identifies disadvantages to using a Markov model, two of which are remedied by the modeling framework in this paper. The first disadvantage is the lack of available observation data to reverse-engineer the matrix probabilities; the second disadvantage is the homogeneity of the model restricting the accuracy of the model to real-world conditions because the probabilities are not dependent on time. Hirst uses various regression models on existing Ugandan migration data to determine the transition matrix probabilities of the Markov model; a lack of substantial migration data hinders the project. In contrast, the modeling effort explored here does not rely on existing migration data to reverse-engineer transition matrix probabilities for migration under rising annual temperatures; this model, instead, provides a means of testing various unknown behaviors based on the manipulation of input parameters. In contrast to the model used by Hirst, the model here is non-homogeneous to accommodate the changing temperatures over time and allow the probability of migration to be annually recalculated. Additionally, the model developed here is a closed system insofar as there is no ability for migrants to cross bodies of water, but it is an open system in comparison to the model Hirst uses because it studies international migration on continental Africa.

In “Using Markov Chains to Model Human Migration in a Network Equilibrium Framework”, Pan and Nagurney create a non-homogeneous (time varying) Markov model that captures migration “chaining” in that refugees must travel through intermediate nodes to get to a final destination node (1994). The modeling effort explored in this paper also models migration as non-homogenous, with temperature as the time-varying parameter, which results in continually varying migration probabilities. The model also chains population movement through nodes and simulates real world obstacles to population movements by preventing direct migration from, for example, Morocco to South Africa.

Chapter 3

Model Framework

The overall approach is to create a model that addresses the need to understand and predict migration behaviors under climate change. To do so, the model initializes the continent of Africa as a series of population centers (states, also referred to as nodes) that are interconnected by lines of population movement (arcs), thus forming a graph that the population will move through (Figure 1). Time is broken into a series of epochs (monthly) where during each epoch, a proportion of the population in each node moves to neighboring nodes; the proportion moving is based on the current carrying capacity of the node, the number of neighboring nodes, and the emigration limit. Favorable conditions for a node mean no members of the population migrate from the node; unfavorable conditions lead to immigration to neighboring nodes.

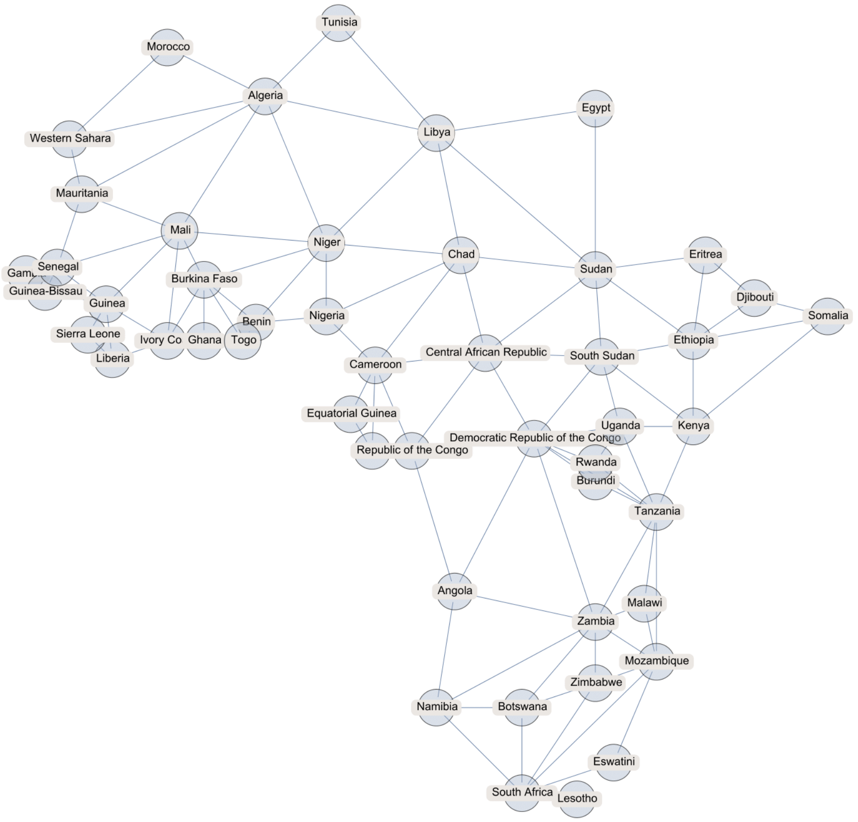

Figure 1. A map of Africa as the model understands it in nodes, arcs, and starting populations.

Emigration from a node is finite, capped at 250,000 emigrants per month by default, though this parameter is adjustable. Monthly migration is also set arbitrarily at 20% of the excess population per month and is limited by the migration constraint parameter; the monthly migration standard is similarly adjustable and is set at 20% in the absence of literature which identifies a universal monthly refugee emigration rate. The maximum allowed rate of migration is an unknown parameter, limited by the total population as the maximum allowed migration in one month, but anticipated to be some proportion of the emigrating population per month.

Migration occurs monthly whereas the temperature impact on carrying capacity is calculated on a yearly basis. The annual carrying capacity calculation permits time for nodes to engage in corrective behavior to accommodate any carrying capacity changes so that system behavior can be more easily observed. If 20% of excess population that leaves per month is larger than the migration constraint, the constraint engages; this causes an excess population of emigrants who are unable to leave in that month to be carried over to the following month.

A limitation of this model is the absence of a death and birth node to take away populations well over the capacity of the node and to add population given a positive birth rate. Projecting birth rates to 2100 is the task of another model that can focus solely on the forces which influence birth rate; similarly, this model does not posit which level of overcapacity causes population death, but the model's identification of nodes which will accumulate a population well over the capacity permitted by temperature changes offers projections for states which will be experiencing trouble supporting their populations. From this observed overpopulation, one can postulate crises that result in human casualty.

"Pinch point" nodes between collapsing regions, such as on the edges of the Sahara, are pinch points because of their geography. African geography lends itself to areas of geographic isolation and population trapping due to an inability to migrate to another location that has not already collapsed. Certain countries in sub-Saharan Africa are better connected to less temperature-vulnerable nodes that will allow migrants to diffuse south where temperature increases are not as severe and carrying capacity remains high. Given enough time for climate change to impact carrying capacity and for migration to begin, nodes in the south will experience immigration from collapse in the northern part of the African continent; the model demonstrates the very beginning of this anticipated behavior in countries such as Zambia.

Chapter 4

Setting up the Model

Each node contains the following information that defines its current state:

- State Name
- Neighboring Centers
- Population in 2020
- Temperature projections by year until 2100
- Current population

The following variables are instrumental in calculating the model's movement and capacity formula:

- T = temperature 2020-2100 by year
- H = present month
- C = carrying capacity at month (H)
- P_0 = starting population in 2020
- P_h = current population at month (H)
- R = proportion of excess population to leave at month (H)
- M = migration constraint

To simulate the movement of climate refugees, each node has its carrying capacity, measured as maximum population supported and calculated on a monthly basis. The value of the carrying capacity is denoted in the maximum population allowed in a state's borders; any population which exceeds the calculated limit will migrate to a neighboring node. The calculation of carrying capacity is a function of an initial carrying capacity determined in year 2020 multiplied by a function of temperature increase. The default function for initial carrying capacity is 5% greater than the current population 2020. Initial carrying capacity is set based on the assumption that the states are generally operating close to their maximum capacity; this parameter is adjustable and the accuracy of this parameter to real world conditions is less important than the dynamics that result from carrying capacity changes. Rising mean annual temperatures are used as a proxy for climate change. Carrying capacity for a node will only start to decrease if the temperature exceeds 29 Celsius, an identified upper limit of the human livability niche (Xu et al., 2020). If the current population in a node exceeds its carrying capacity (if $P_h > C$), then a proportion (β = 0.20) of those wanting to leave will migrate out equally to neighboring nodes at each time tick until the population is equal to or below the carrying capacity. Emigration from a node has a default, restricted maximum at 250,000 people per month as previously discussed, though this parameter will be adjusted and remains adjustable.

Formally, the equation for the carrying capacity at epoch *k* is defined as

$$C_{k+1} = C_k \times \begin{cases} 1 - (T_k - T_{k-1}) & 0 < T_k - T_{k-1} < 1 \\ 0.1 & T_k - T_{k-1} > 1 \\ 1 + (T_{k-1} - T_k) & T_k - T_{k-1} < 0 \end{cases}$$

Where T_k is the temperature at epoch *k*. An assumption held by this formula for the relationship between temperature and carrying capacity is that a whole degree Celsius increase in one year will cause catastrophic collapse. The IPCC projects whole degree global temperature rise over several years and thus if a single state experienced a whole degree rise in a single year, one would anticipate severe consequences on the system. Hence, the formula sets carrying capacity to 10% of the previous carrying capacity as a mathematical encapsulation of those severe consequences. If the temperature rises above 29 Celsius, the carrying capacity is multiplied by the difference of the current temperature minus the previous temperature; the reverse is applied if the temperature decreases and thus carrying capacity increases.

Emigration occurs over the 12-month period, where each month 20% of the excess population leave, thus the excess undergoes an exponential decay over the year. This is limited by the maximum emigration rate parameter M, which constrains the emigration, and may result in an excess carryover from year to year. The equation for emigration is the excess for the year, *E,* defined as $E = P - C$. Each month a number of refugees emigrate according to $R = \min(0.2E, M)$, with E decremented each month by the number of refugees that leave. The refugees disperse equally to all neighboring nodes. In order to avoid introducing unnecessary rounding error, “portions” of refugees can migrate to nodes (i.e., 0.6 of a refugee migrates to a node); the “partial person” issue is resolved by rounding at the end of the model’s run.

Chapter 5

Experimentation with the Migration Constraint

The finite limit on migration under rising annual temperatures is unknown, but the behavior can be explored by the model developed here. I hypothesize a sensitivity of the outcome parameters to the migration constraint input parameter such that the resulting diffusion of excess population between nodes will be significantly different between parameter changes. Five constraints explored in this model are two universal limits (250,000 and 100,000), a low proportional limit (2% of the population), a moderate proportional limit (5%), a high proportional limit (10%), and no migration constraint. The moderate proportional rate is inspired by the recent statistics from the UN Refugee Agency regarding the 3.3 million that have fled the crisis in Ukraine over the past month to neighboring countries with roughly 2 million going to Poland (UNHCR, 2022). I chose the lower proportional rate under the assumption that Europe has easier means of accommodating migrants than less developed regions of the world, which I suspect would apply to continental Africa; the upper limit is double the moderate and the universal limits are arbitrary choices.

To understand the regional impacts, I compare four countries in Western Africa, Central Africa, and the Sahel (the most vulnerable regions to rising temperatures) under the different migration constraint choices: Western Sahara, Benin, Ethiopia, the Central African Republic. The graphs of each state's population from 2020-2100 under the aforementioned migration constraint changes are below.

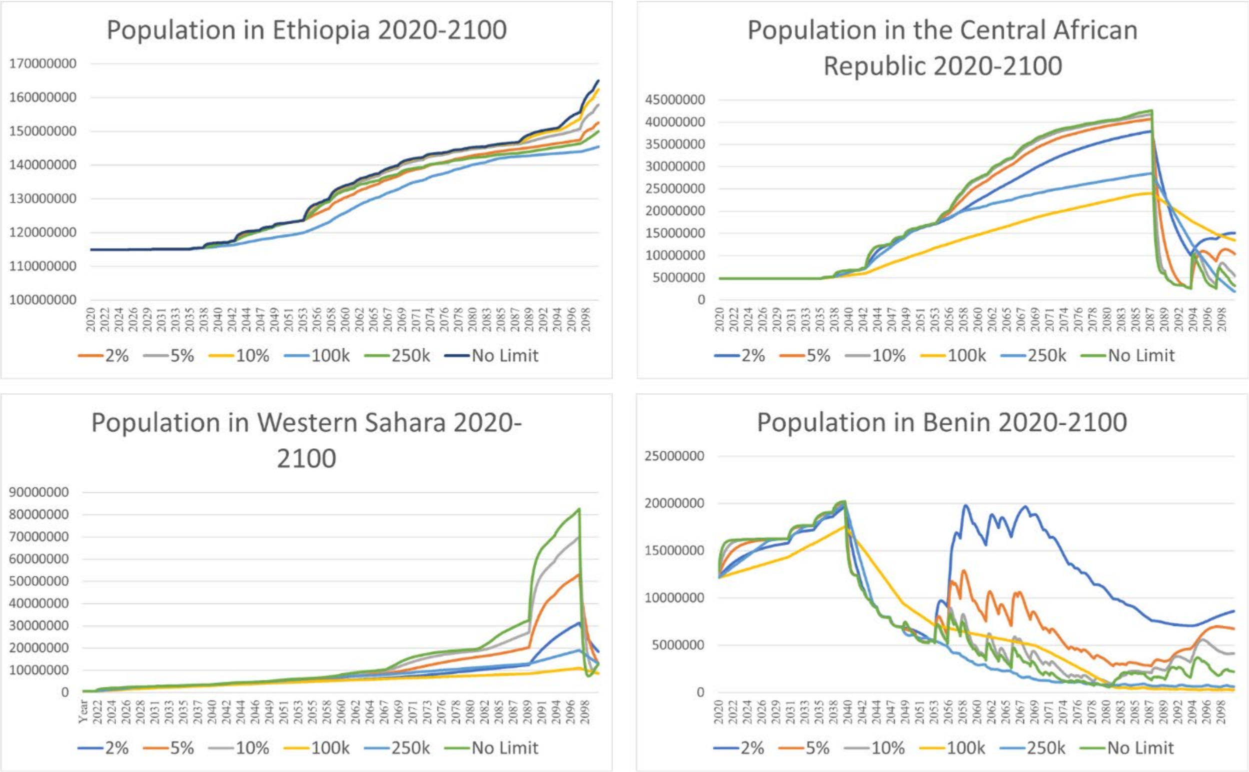

Figure 2. A grid of four states and their populations over time under various migration constraints.

Various migration restraints on Benin cause catastrophic overpopulation due to the inability of the population to leave fast enough. The graph demonstrates the behavior of overpopulation prior to any temperature-induced carrying capacity decreases caused by the critical temperature (*T**). Neighboring states of Benin begin to have their own carrying capacity decreases and thus Benin sees an influx of refugees and corresponding growth in population before its own temperature reaches *T** in 2039, forcing emigration. In 2055, multiple neighboring nodes begin to collapse and send refugees to Benin, causing an observable outpacing of immigration over emigration and ballooning Benin's population.

The graph points to the conclusion that multiple neighboring nodes experiencing simultaneous carrying capacity decreases can result in significant overpopulation in the central node. The model allows researchers to explore the severity of the resulting migration in each node at various hypothesized migration constraints. Proportional limits on migration have a comparatively severe impact on smaller countries than do proportional limits on larger countries or than the universal limits on smaller countries.

Most of Benin’s neighbors have higher populations than Benin in 2055 and can therefore send more immigrants into Benin than Benin can emigrate.

The Central African Republic is, for most of the century, an “absorber.” Due to its geographic location, it does not suffer carrying capacity decreases until 2087, at which point there is a precipitous drop in population that suggests the carrying capacity decrease was severe and swift. The case of the Central African Republic is a node which results in situations such as Benin. The population at the time of mass emigration is very high and thus allows for a large migration population to disperse into neighboring nodes. Some countries, such as the Democratic Republic of the Congo, are large enough to accommodate the refugees. Other neighboring nodes, such as South Sudan, are already suffering from the mass migration of a collapsing neighbor (Sudan) and struggle to accommodate an additional neighbor sending migrants.

Ethiopia is also an “absorber,” although it does not suffer a carrying capacity decrease as the Central African Republic does. Instead, Ethiopia only suffers an overpopulation crisis. The population increase over time is very large, pointing to the collapse of either one large neighbor or multiple smaller neighbors. Each of the modeling results from the various parameter choices reveals a different ending population in 2100; the steepest population line under a limitless migration suggests that a neighboring node is experiencing a swift decrease in carrying capacity and has a large population attempting to emigrate at once.

Western Sahara suffers from the greatest proportional overpopulation of all countries in continental Africa, likely due to its “pinch node” status and propensity for receiving migrants from multiple collapsing nodes; the migrants become trapped and unable to find a node which can accommodate them. Based on this graph of population over time, one would assume that T* occurs at the precipitous drop marked on the graph above. However, a comparative examination of Western Sahara with its carrying capacity and with a neighbor experiencing a large collapse indicates otherwise.

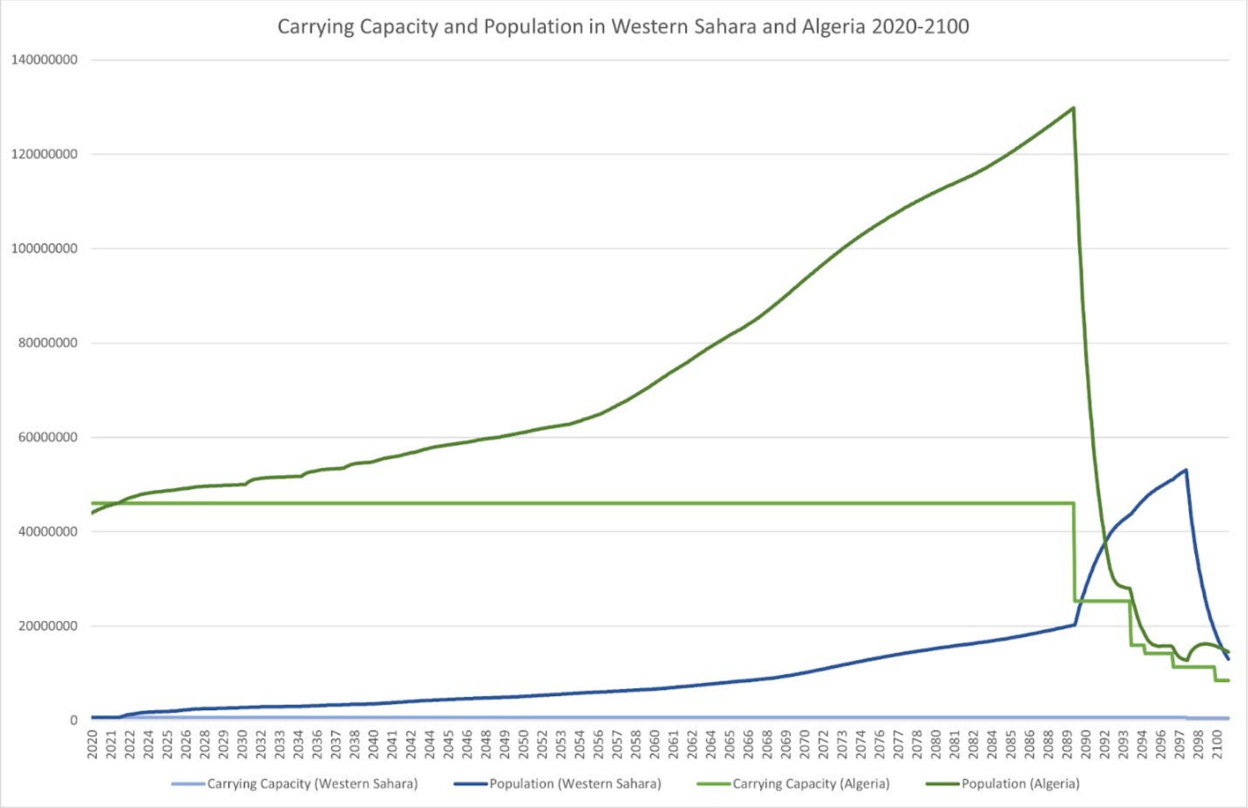

Figure 3. A comparison of carrying capacity and population in Western Sahara and Algeria (2020-2100).

Western Sahara borders Algeria, a country vulnerable to rising temperatures due to its Saharan location. Western Sahara's carrying capacity is low for the entire century, receiving minute drops in carrying capacity as the region warms above the human temperature niche. Although Western Sahara does not experience a devastating temperature increase, it does experience being a low-capacity, high-population node. Once compared with Algeria, it becomes clear that the large increase in population starting in 2089 can be partially attributed to Algeria's carrying capacity decreases.

The universal limitations on migration are expected to aid smaller countries in emigration and immigration flows due to the smaller proportion between the total population the migration constraint. For example, the starting population of Benin is 12,123,198 people which is roughly 48 times larger than 250,000. The Democratic Republic of the Congo which has 89,561,404 and is roughly 358 times larger than 250,000. Benin will be able to evacuate its population much faster than countries with large populations.

The proportional limitations on migration will act equally among states such that the limit grows as the population grows. In this scenario, Benin and the Democratic Republic of the Congo can evacuate the proportion of their population that is allowed; however, this means that larger population states are able to send more refugees than smaller population states and the subsequent overpopulation problem may become much more pronounced, particularly if multiple larger neighbors of a small state begin collapsing. The results produced by the model demonstrate such behaviors and mathematical relationships between universal and proportional limits.

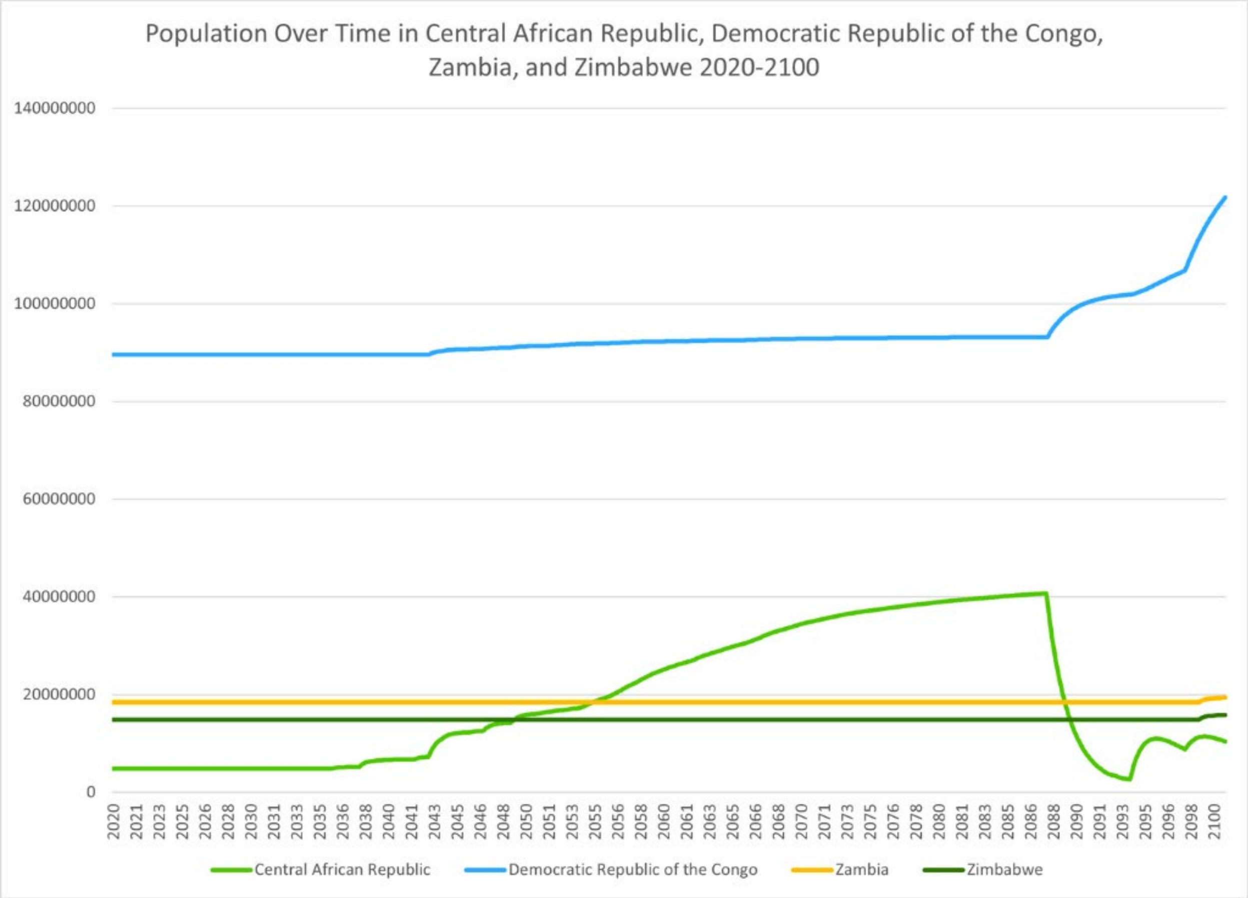

Figure 4. Population over time in the Central African Republic, Democratic Republic of the Congo, Zambia, and Zimbabwe (2020-2100).

The model also allows us to visualize the north-south diffusion of emigrating populations. A case study of the migration chain Central African Republic → Democratic Republic of the Congo → Zambia → Zimbabwe indicates that there is not a large population migrating south. Instead, absorber states and migration limits prevent dispersing populations from reaching southern Africa. Given enough time, however, populations eventually reach southern nodes. Zimbabwe and Zambia both receive a small population increase in the final years of the model.

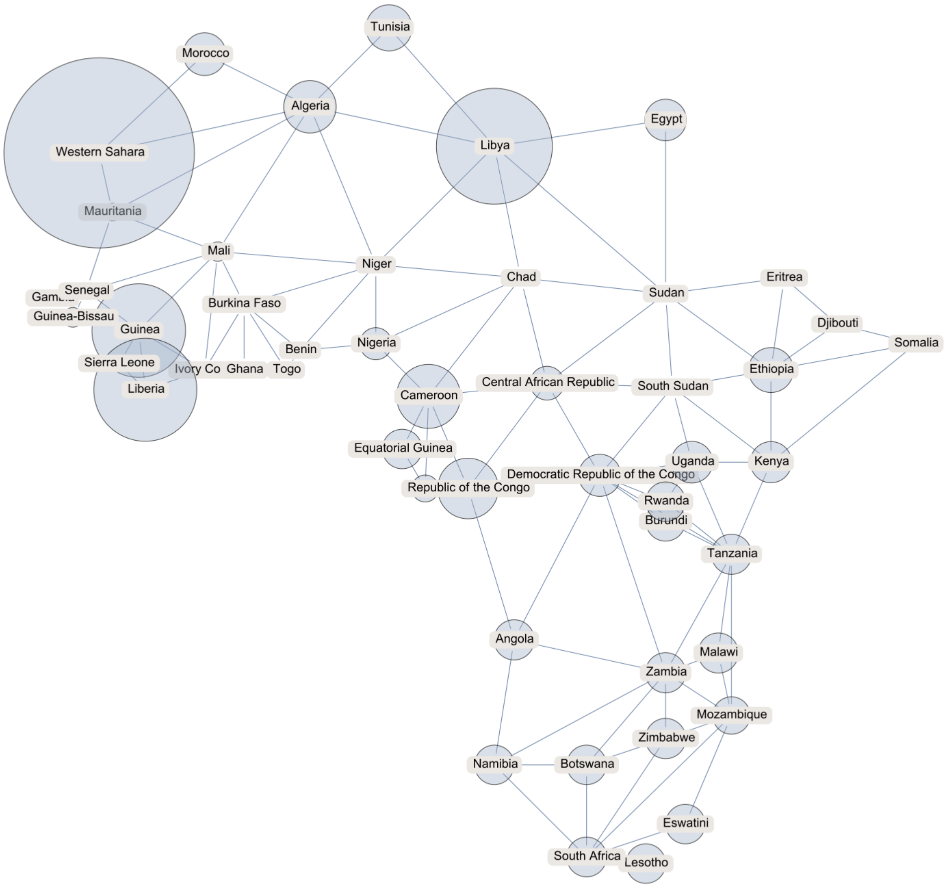

Figure 5. The model at the end (2100) of the 250,000-person run with each node circle proportional to the starting population in 2020.

The model correctly follows the temperature dynamics as predicted by the SSP5-8.5 in that the Saharan and Western African regions empty its populations. The model reveals populations trapped in states such as Libya, Western Sahara, Guinea, and Liberia that are geographically confined by neighboring states which have already collapsed or are actively sending migrants. The regions most affected by temperature rises are expectedly low in population by the end of the simulation. The absorber states on the boundary of southern Africa (Central African Republic, Ethiopia, Cameroon, etc.) are largely able to contain the southern migration and are acting as geographic barriers to southern diffusion.

Although Figure 5 does not present this visually, countries in southern Africa begin to witness small migration flows, pointing to an eventual impact of climate crisis in the north as it affects the south.

Chapter 6

Actionable Policy Responses

The model produces observable overpopulation crises as well as demonstrates the relationship between carrying capacity decreases and subsequent overpopulation crises in neighboring nodes. It furthermore allows for the exploration of the relationship between geography and trapped migrating populations. The model's parameters offer a framework for developing policy responses addressing the behaviors produced by the model.

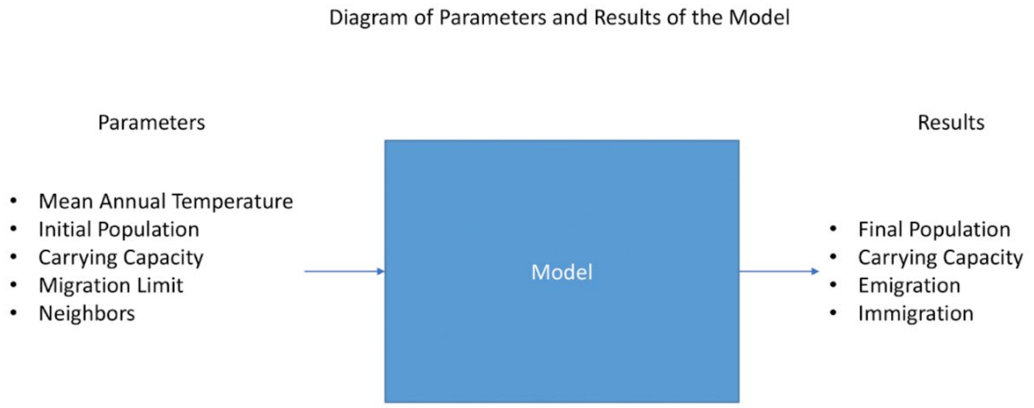

Figure 6. A diagram of input parameters and output results of the model.

Each input parameter represents a potential policy focus, with some parameters more sensitive to change than others. This paper explored various limits on migration and how that parameter change would impact the results of the model as well as how sensitive the model is to that parameter's alteration. The real-world migration limit is impacted both by physical limits of human movement but also by institutional barriers to migration. The results of the model indicate that a greater restriction on migration causes overpopulation in states. Policies that ease the ability of migration can reduce the likelihood and severity of overpopulation as well as reduce the associated deaths that would result from populations pouring into states that cannot support them.

Using the case study of north-south diffusion of migrants Central African Republic → Democratic Republic of the Congo → Zambia → Zimbabwe, one can surmise that migrant-favorable policies reducing the migration constraint parameter would aid in the diffusion of migrants south to more favorable living conditions. Migrants trapped in low-capacity states or migrants trapped in high-capacity, low-institutional-strength states such as the Central African Republic are inevitably going to experience strife (Mwanyika, 2021). The model does not make any predictions about what occurs in overpopulated states, but there is evidence to suggest that refugees stress economic and state capacity which can lead to general repression and, eventually, armed conflict (Wright & Moorthy, 2018). There are also current legal challenges that present obstacles to legally recognized migration due to climate change and international obligations that would arise from legally binding agreements and to state support for displaced person that are encompassed by the migration constraint and carrying capacity variables, respectively.

The example of Mozambique in the aftermath of the March 14th, 2019 tropical cyclone Idai and the April 26th, 2019 tropical cycle Kenneth provides a unique view into the state struggle to accommodate refugees from mass environmental disaster and the lack of an international legal framework to address climate refugees (Gautam, 2020; Meek & Nene, 2021). The international legal system is unequipped to deal with the rise in climate refugees in part due to the lack of legally binding agreements obligating states to support climate refugees and from a lack of an acknowledged definition of “climate refugee” (Gautam, 2020; Meek & Nene, 2021). Internally displaced refugees needed state assistance for basic amenities that Mozambique struggled to provide, and that the international community failed to provide aid for (Gautam, 2020; Meek & Nene, 2021). In the coming years, it will become more apparent which policies will be implemented to handle the issue of climate refugees; as those policies appear, the migration constraint parameter can be adjusted to reflect these changes.

Chapter 7

Conclusion

The model developed, tested, and experimented with in the paper accomplishes the goal of modeling migration behavior under the conditions of carrying capacity decreases due to rising temperatures, with rising temperatures as a proxy for climate change. The migration constraints resulted in varying levels of overpopulation crises in response to carrying capacity decreases. The lower the limit on migration, the more severe the overpopulation crisis. States that have multiple, temperature-vulnerable neighbors will inevitably experience an unsupportable influx of migrants. The Sahel region is particularly vulnerable to overpopulation crises due to the vulnerability of Saharan and Sahel states to climate change. Additionally, the model identifies states which become “pinch nodes” and “absorbers”; respectively, states which are trapped between collapsing nodes and overpopulate due to the inability of populations to migrate to healthy nodes (Western Sahara) and nodes which have a high carrying capacity and can accommodate migrants (Ethiopia).

There are several improvements that can be made to the model, foremost of which includes adding more parameters to greater represent the impact of climate change on carrying capacity. As discussed in the literature review, temperature is known to have a varying effect on population movement unlike the uniformity that is assumed by this model. States in southern Africa, while not projected to experience unlivable temperature increases, are already suffering from droughts that cause irregular and underperforming agricultural yields (Lobell et al., 2011; Motha, 2011). Models exist to anticipate the behavior of droughts and other extreme weather on agricultural yields, so incorporating the data into this model would require borrowing their projected yields and developing a mathematical relationship between agricultural yields and carrying capacity (Lobell et al., 2011; Mangani et al., 2018). When data becomes available regarding the real-world dynamics of migration under rising temperatures, the technique employed by Hirst (1976) in “A Markovian Analysis of Inter-Regional Migration in Uganda” to determine the transition probabilities from regression models can improve the predictive capacity of the model. Finally, this model focuses on international migration dynamics and overlooks domestic migration and displacement within states. Temperature projections are available for regions within states and the carrying capacity calculation can be applied to regions within states as easily as it is to states in the international system.

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ACADEMIC VITA

Education

The Pennsylvania State University, University Park, PA **May 2022**

Schreyer Honors College

B.A. in International Politics

B.S. in Cybersecurity Analytics & Operations

Sungkyunkwan University, Seoul, South Korea **Fall 2019**

Student

Work Experience

Research and Development Engineer **May 2019-May 2022**

Applied Research Lab at Penn State University, University Park, PA

- Worked as a programmer and research assistant on projects related to cybersecurity and cyber tools development.
- Coded predominantly in Python with working knowledge of C++, Javascript, Bash, Powershell, and Golang.
- Presented progress to team, supervisors, and project sponsors in monthly meetings and conferences.
- Utilized knowledge of Windows and Linux system architecture and software for penetration testing and system hardening.

Peer Tutor for Advanced Java Programming **August 2020-December 2020**

College of Information Sciences and Technology, University Park, PA

- Dedicated 4 hours weekly on Thursday evenings to helping students across the college with Java programming.
- Explained difficult programming concepts such as object-oriented programming to students struggling with the topic.
- Managed tutoring time effectively in order to help the greatest number of students in a limited time window.
- Contacted professors of IST 242 for course materials to help students.

Learning Assistant **August 2020-December 2020**

College of Information Sciences and Technology, University Park, PA

- Graded student work for Dr. Rimland's IST 242 course and provided constructive feedback for improvement.
- Coordinated meeting times with students to provide help with assignments.
- Created teaching material to aid students with course topics comprehension.

Campaign Fellow **March 2019-May 2019**

Marc Friedenberg for Congress 2019, State College, PA

- Canvassed for the campaign in neighborhoods around Central Pennsylvania.
- Plotted routes for volunteers to canvass.
- Persuaded voters to register to vote and vote in a special election.
- Recruited volunteers for the campaign to phonebank and canvass.

Campus Organizer **September 2018-November 2018**

Feminist Majority, Arlington, VA

- Worked at the Penn State University main campus giving frequent presentations to classes on voter registration procedures.
- Created a website detailing absentee ballot procedures for each state, how to research candidates, and requirements for first-time voters.
- Coordinated with other campus organizers to do public outreach campaigns.

Involvement, Honors, and Awards

Participant, Student Conference on US Affairs at the United States Military Academy
November 2021

Participant, Guest Lecturer to Present Thesis Research
September 2021

Recipient, 2021 Annual Applied Research Lab Student Contribution Award
January 2021

Participant, Penn State Student Exchange with Sungkyunkwan University
August 2019-December 2019

Participant, Co-Chair for PA High School United Nations Conference
September 2018-November 2018

Member, Penn State International Affairs and Debate Association
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