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How Will Climate Change Affect Fragility?

People living in fragile states are more vulnerable to potential shocks. With the climate change exacerbating fragility, people gradually begin to focus on the importance of measuring and dealing with the fragility. In order to solve these problems, we first **establish an evaluation model** to measure the **fragility under climate change**. Then it is applied to **Afghanistan and Egypt** to show their fragility situation. At last, a set of **optimal interventions** are given and the model is modified in order to apply to smaller and bigger states.

To begin with, **37 inferior factors** are considered into our model and we figure out the normalization method and measurement for each inferior factor. After that, **eight superior indicators** are summarized from inferior factors include **food, water, shelter, security, stability, economics, governance and demography**. The analytic hierarchy process method is used to weigh these indicators. At last, the impacts of climate change are characterized by **precipitation, arable land, temperature and natural disasters**.

Next, the evaluation model is applied to Afghanistan and Egypt. **Afghanistan** is in the top ten fragile states list and **Egypt** is not in the top ten list. **Fragility indicator** is used to measure the fragility. It is a **benefit-type indicator** normalized to the range of [0,1]. Using the collected data, we find that with the climate change, the fragility indicator is **0.280 for Afghanistan and 0.407 for Egypt**. Without the climate change, it is **0.310** for Afghanistan and **0.428** for Egypt. The percentage change is **10.7%** and **5.2%**, respectively. Among the eight superior indicators, **economics** is mostly affected. At last, we use the **K-Means Clustering Algorithm** to determine the **tipping point** and **stable point**. Results show the tipping point is **0.428** and the stable point is **0.711**.

In order to help Afghanistan and Egypt escape from the fragility, an **optimization model** is developed to maximize the fragility indicator under the **limitation of the budget**. To prevent fragility, Afghanistan needs to spend **285% of its GDP (57.2 billion dollars)** and **Egypt 1% (3.32 billion dollars)**. We figure out the optimal distribution of money using our optimization model. Results show that money for **food and water** should account for **30%** and **25%**, respectively. **Sensitivity analysis** is made at the end. Our model is a little more sensitive to precipitation.

At last, our model is modified to fit for smaller and bigger states. For smaller states, the **factors and weights** are reconsidered and the **cost of intervention is lower** because of the synergy effect; for bigger states, the **sphere of influence** is restrained, and the **cost is higher** because of the difficulty in managing the bigger states. Still using the data of Afghanistan and Egypt, we find that other things equal, **smaller states** can develop **more quickly** while **bigger states** develop much more **slowly**.

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1 Introduction

Backgroud

People used to think that climate change just affects the environment business. However, Frank Walter, the foreign minister in Germany, claimed that climate change is a growing threat to peace and stability[1]. It will aggravate the fragility of countries.

When the climate change is combined with the poverty and resource scarcity, the state might be more fragile because of the violent conflicts caused by the combination. We have to study on the relationship between climate change and fragility of countries, in order to halt the exacerbation of fragility and offer the reasonable intervention plans to the fragile states.

Literature Review

States can be divided into fragile states and resilient states. Fragility and resilience are defined in the report of *New Climate for Peace*. Fragility is the inability (whether whole or partial) of a state to fulfil its responsibilities as a sovereign entity, including a lack of legitimacy, authority, and capacity to provide basic services and protect its citizens[2]. Resilience is the opposite. Climate change alone cannot make significant effects on the state, but it can so when it interacts other pressures. There are seven risks that will emerge: local resource competition, livelihood insecurity and migration, extreme weather events and disasters, volatile food prices and provision, transboundary water management, sea-level rise and coastal degradation, and unintended effects of climate policies. These possible consequence offers the base of thinking for our study.

The essay of *Department for International Development* indicated that, the governance efficiency, state function and international support need to be improved, in order to relieve the fragility problem[3]. In another essay, the writer pointed out that the rebuilding of Afghanistan includes the economic, politics, security and society area[4]. These facets should be included in our fragility model to make it more comprehensive.

The previous researches have contributed a lot to the solution of fragility problems, but there are still some limitations of their work for solving our problem. For instance, the factors of the physiological need are ignored in the rank of fragility, and the cost of the intervention has not been considered. Furthermore, they provide little statistics and models to measure the fragility, which are taken into account in our study, these factors are involved to build a more complete and useful model.

Our Work

Because of the weaknesses of the previous work, we should further study this issue in detail. The mind map of our study is shown in Figure 1 in detail. Firstly, a new **evaluation model** should be established considering more factors. **Climate change** impacts should also be taken into account. In our study, the climate change is regarded as an influential factor added into the fragility evaluation model. After that, Afghanistan and Egypt are analyzed and the fragility situations are discussed. Afghanistan is in the top ten fragile states list while Egypt is not.

In order to fight against fragility, interventions are needed. **Optimization model** is used to figure out the best intervention plan under the limitation of budget. The main purpose is to maximize the fragility indicator. At last, **modification** is made to smaller and bigger states according to their natural features. The factors and costs of intervention for smaller and bigger states are reconsidered.

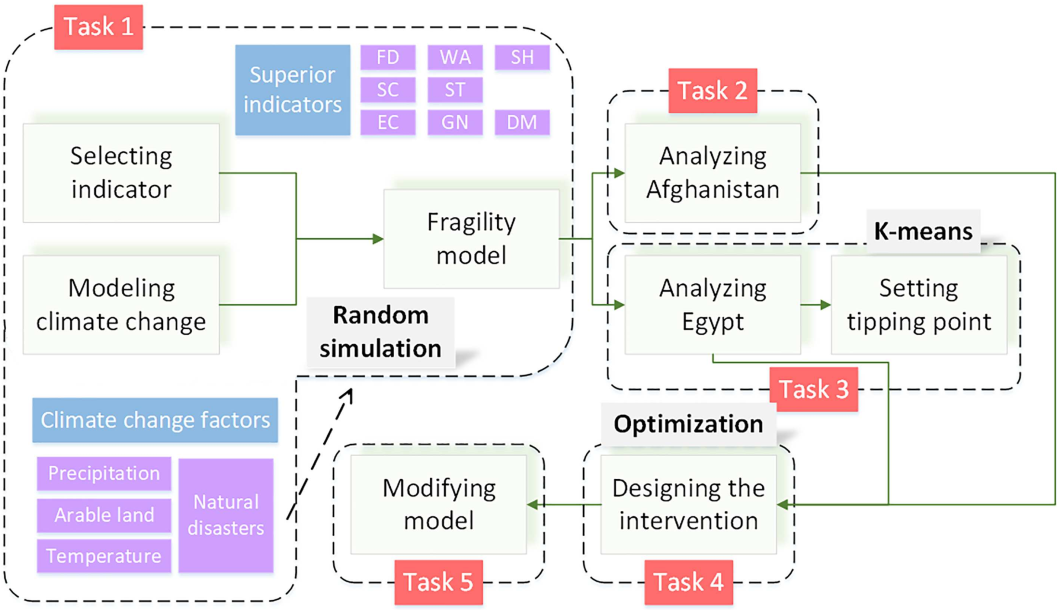


Figure 1: Flowchart of our study

2 Assumptions

- The fragile states are not able to adapt to the climate change in the short run.
  - If a state can adapt to that change well, climate change can even benefit that state[5]. Considering that most fragile states are developing states, we assume that they are not able to adapt to the climate change in the short run.
- The long run impacts of natural disasters are neglected.
  - The impacts of natural disasters are always direct, like economic loss. In the long run, the disasters will be solved and their impact will not last as long as other climate changes like temperature increase.
- The marginal cost of intervention increases linearly.
  - This is a reasonable simplification of increasing marginal cost[6]. In reality, the increase of marginal cost depends on the specific situation.
- The physiological need is the most important need of human.
  - Physiological need is the most basic need. It should be given more attention.

3 Measurement of Fragility and Climate Change

The fragility model includes two parts: the **indicators** used to describe fragility and the **impacts of climate change** on indicators. The fragility of a state is actually measured by the indicators and the impacts of climate change is built into the indicators. Therefore, We will first establish an indicator system to evaluate the fragility. Climate change is regarded as influential factors to the indicators.

3.1 Establishment of the Fragility Model

According to the problem, a fragile state is one where the state government is not able to, or chooses not to provide the basic essentials to its people. This implies that the theory of needs can be applied to measure the fragility. The most popular theory of needs is Maslow's hierarchy of needs. From the most basic needs to the most superior, the needs are physiology, safety, society, self-esteem and self-actualization[7].

We only take into account the three most basic needs, considering that fragile states are often characterized by low income and weak government[8]. The framework of the fragility model is shown in Figure 2. Several specific factors are considered under each type of need in Figure 2. The physiology is consisted with food, water and shelter. The safety is consisted with security and stability. The society is consisted with economics, governance and demography. We set an indicator for each detailed need, so we get eight superior indicators describing the fragility. A specific assemblage $\boldsymbol{I}$ is given for them:

$$\boldsymbol{I} = \{FD, WA, SH, SC, ST, EC, GN, DM\}$$

where FD, WA, SH, SC, ST, EC, GN, DM represent food, water, shelter, security, stability, economics, governance and demography, respectively.

There are many inferior indicators under each superior indicator. As shown in Figure 2, 37 inferior indicators are considered in our fragility model. The superior indicators are determined by the linear combination of these inferior indicators. The determination of the weights will be discussed later. Those eight superior indicators measure the fragility of a state. We set the fragility indicator F as the linear combination of them:

$$F = \sum_{i \in \boldsymbol{I}} \omega_i i \tag{1}$$

where ω_i is the weight of each superior indicator.

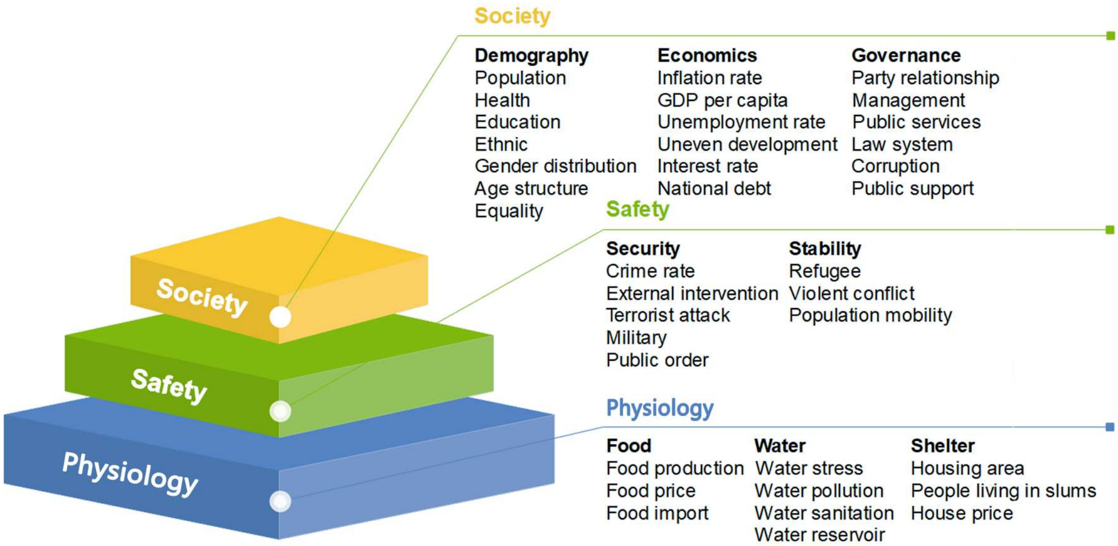


Figure 2: Framework of fragility model

We are going to introduce the inferior indicators and normalize each of them into the same pattern. After that, the weights of each superior and inferior indicator will be determined using the Analytic Hierarchy Process (AHP).

3.1.1 Discussion of the Superior and Inferior Indicators

The fragility indicator is calculated by eight superior indicators and the superior indicators are determined by the inferior indicators. We are going to discuss about them in detail.

- **Physiology**

Food is a basic precondition for living, so it is also a critical factor related to the fragility. When a country is lack of food, citizens will not satisfy and they may rob others or even attack the government. Therefore, the more food people can get, the less fragile the country is. The **food indicator** (FD) is based on the following inferior indicators: **food production per capita, average food price and food import quantity**.

Similarly, people need usable water to maintain their subsistence. A state may become less fragile because of the insufficient usable water. Therefore, the **water indicator** (WA) is also used to reflect the fragility. The specific inferior indicators are: **water quantity per capita, sewage discharge rate, improved water rate and total water reservoir**.

Shelter is an important factor affecting fragility. In the fragile countries, people generally do not have a stable shelter, especially when the violent conflicts exist. This situation can exacerbate the fragility[9]. The inferior indicators for **shelter indicator** (SH) are: **housing area per capita, slum population portion and house price**.

- **Safety**

The **security indicator** (SC) is important for the safety. the specific inferior indicators for the factors listed in Figure 2 are: **crime rate, external intervention level, number of terrorist attacks, army power and police density**.

The **stability indicator** (ST) refers to the stability of the migration of population, so it is affected by the population mobility. In some states, refugee is a serious problem. Their migration and mobility can disturb the society severely. The society is also suffered from the violent conflicts. The inferior indicator for these factors are **refugee index, number of violent conflicts and migration rate**.

- **Society**

The **economic indicator** (EC) is rather important. It is influenced by many aspects, like GDP, inflation, etc. The inferior indicators are chosen as: **GDP per capita, inflation rate, unemployment rate, the Gini coefficient, debt to GDP ratio and interest rate**.

The **governance indicator** (GN) mainly refers to the ability to manage the society. It measures whether the government can manage the state well. The inferior indicators for it are **law system completeness, management efficiency, corruption rate, public service quality, party relationship and the government support rate**.

Demography indicator (DM) describes the features related to people, like population and age structure. Similarly, the inferior indicators are: **population density, amount of the ethnics, literacy rate over 15 years old, epidemic rate, sex ratio, average age and equity level**.

3.1.2 Normalization of Inferior Indicators

The inferior indicators need to be normalized into the range of [0,1]. Meanwhile, the inferior indicators need to be transformed to the **benefit-type indicators** which means that the larger the better. We use different normalization method to normalize different kinds of indicators according to their characteristics. These methods include the logistic function, the maximum normalization method, the moderate normalization method, the minimum normalization method and the subordinate function of fuzzy mathematics. We are going to show the applications of each method we use.

- **Logistic function**

This normalization method is applied to indicators which do not have a specific upper limitation, such as the food production per capita. There are some rules of normalization for this kind of indicators. When the original indicator is close to 0, the normalized indicator should be 0; when the original indicator approaches infinity, the normalized indicator should be close to 1. Meanwhile, the normalized indicators should rise sharply when it is close to 0. For these reasons, we choose logistic function to be the normalization function:

$$x' = \frac{1}{1 + e^{-b(x-x_0)}} \tag{2}$$

where x' is the normalized indicator; x is the original indicator; x_0 is the minimum standard of the indicator; b is a parameter to control the climbing speed of the normalization function. The value of b will be determined in the solution of model.

- **Maximum normalization method**

This method is used to normalize the benefit-type indicators, like the improved water rate. The greater the indicator is, the better the situation is. The way to normalize the indicators is

$$x' = \frac{x}{x_{max}} \tag{3}$$

where x_{max} is the maximum of the indicator.

- **Minimum normalization method**

This method is similar to the maximum normalization method. It is used to normalize the cost-type indicators, such as the crime rate. The way to normalize the indicators is

$$x' = 1 - \frac{x}{x_{max}} \tag{4}$$

- **Moderate normalization method**

This method is used to normalize the moderate-type indicators. When the indicator is close to the optimal value, the state can have better resilience. The example of this kind of indicators includes the inflation rate. The way to normalize is

$$x' = \frac{|x - x_{op}|}{\max\{|x_{max} - x_{op}|, |x_{min} - x_{op}|\}} \tag{5}$$

where x_{op} is the optimal value of the indicator.

- **Subordinate function**

This method is used to normalize the discrete indicators. These indicators can be divided into several intervals with a discrete grade, like GDP per capita. According to the theory of fuzzy mathematics, we choose the correspondence of the value set and the comment set as:

$$\{Awful, Bad, Normal, Good, Excellent\} = \{1, 2, 3, 4, 5\} \tag{6}$$

The partial large Cauchy distribution membership function is determined as:

$$f(x) = \begin{cases} \dfrac{1}{1 + \frac{a}{(x-b)^2}}, 1 \leq x < 3 \\ c \ln x + d, 3 \leq x \leq 5 \end{cases} \tag{7}$$

We set that when the grade value is 1, the membership grade should be 0.01; when the grade value is 3, the membership grade should be 0.8; when the grade value is 5, the membership grade should be 1. Hence, the parameters of the partial large Cauchy distribution membership function can be determined as:

$$\begin{cases} a = 1.1086, \quad b = 0.8942 \\ c = 0.3915, \quad d = 0.3699 \end{cases} \tag{8}$$

Using these normalization method, all the inferior indicators can be normalized. Here we omit the detailed methods for each inferior indicator.

3.1.3 Determination of the Weights for Indicators

The **Analytic Hierarchy Process** (AHP) is a well-developed method which is used to analyze the weights. The hierarchy structure of the indicators need to be determined. It consists eight superior indicators and 37 inferior indicators.

The weights of normalized superior and inferior indicators is calculated using AHP method. Specifically, the superior indicators are divided into three groups based on the three kinds of need. The weight of the superior indicators in the same group is regarded as the same. The results are listed in Table 1.

Table 1: The weights of indicators

<table>
<tr><td colspan="6">Physiological need</td></tr>
<tr><td colspan="2">Food 18%</td><td colspan="2">Water 18%</td><td colspan="2">Shelter 18%</td></tr>
<tr><td colspan="2">Price 26%, Import 10%
Production 64%</td><td colspan="2">Stress 46%, Sanitation 26%
Pollution 14%, Reservoir 14%</td><td colspan="2">House price 14%, Slums 24%
Housing area 62%</td></tr>
<tr><td colspan="6">Safety need</td></tr>
<tr><td colspan="3">Security 15%</td><td colspan="3">Stability 15%</td></tr>
<tr><td colspan="3">External intervention 11%
Military 6%, Public order 21%
Terrorist attack 42%, Crimes 20%</td><td colspan="3">Refugee 29%, Violent conflict 62%
Population mobility 9%</td></tr>
<tr><td colspan="6">Society need</td></tr>
<tr><td colspan="2">Economics 5.33%</td><td colspan="2">Governance 5.33%</td><td colspan="2">Demography 5.33%</td></tr>
<tr><td colspan="2">GDP 40%, National debt 6%
Inflation 16%, Interest 5%
Unemployment 10%
Uneven development 23%</td><td colspan="2">Law 5%, Corruption 18%
Management 34%
Party 22%
Public support 9%
Public services 12%</td><td colspan="2">Population 47%
Education 6%, Health 10%
Gender distribution 10%
Equality 4%, Ethnic 18%
Age structure 5%</td></tr>
</table>

We assume the physiology is the most important factor. Therefore, the food, water and shelter indicator occupy the largest weights. Among the inferior indicators, the food production, the water stress and the housing area indicators are most important. As for safety and society, the management, GDP, terrorism and violent conflict seem to be more significant. These indicators do have huge impact on the fragility of a country in reality.

3.2 Modeling the Climate Change Impacts

Next, we will measure the impacts of climate change. The climate change includes many kinds of forms, such as shrinking glaciers and unpredictable weather. We should describe them using typical parameters so that it can be made clear.

3.2.1 Characterizing the Climate Change

We extract three important factors as they run through nearly all of the climate changes. These three factors are: percentage change of the **precipitation, arable land and temperature**. Besides, another category called **natural disaster** is also set to include those climate changes which are not reflected by the three factors.

We will define the direct and indirect impacts of climate change. The **direct impacts of climate change** are defined as impacts which are **simply caused by climate change** and do not necessarily relate to other factors. They are always the impacts to food, water and shelter. The **indirect impacts of climate change** are impacts which are caused by **climate change combined with other factors**. They are always the impacts to factors under safety and society in Figure 2.

The climate impacts report has analyzed the impacts in detail. They gave out seven ways in which climate change may exacerbate the fragility[2]. We list them out as follows: 1. local resource competition; 2. livelihood insecurity and migration; 3. extreme weather events and disasters; 4. volatile food prices and provision; 5. transboundary water management; 6. sea-level rise and coastal degradation; 7. unintended effects of climate policies.

We can categorize them into some groups according to the their general features. These seven impacts can be concluded into three general features: **water and food scarcity** (WFS), **potential insecurity and instability** (PII)and **extreme weather and disasters** (EWD). Local resource competition, volatile food prices and provision and transboundary water management are categorized into WFS. They are all impacts related to water and food. Livelihood insecurity and migration, sea-level rise and coastal degradation and unintended effects of climate policies belong to PII. As for the natural disasters, it will be discussed in EWD.

Up to now, we summarize the climate change impacts into three categories, which is shown in Figure 3. The impacts caused by the change of climate factors except disasters have long run impacts. EWD refers to the sudden impacts because of disasters. We can express the superior indicators after taking each kind of impacts into account as

$$i_c = f_i \times i - \delta_i, i \in \boldsymbol{I} \tag{9}$$

where i_c is the indicator after the impacts of climate change; f_i is the **influential coefficients** of different indicators, which characterize the long run impacts; δ_i is the **sudden impacts** caused by the natural disasters.

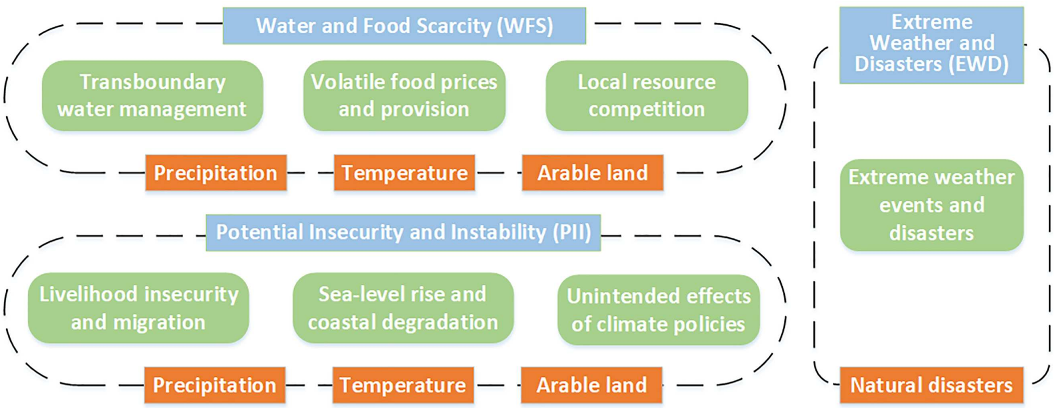


Figure 3: Categories of Climate Change Impacts

The four climate factors we refined can describe most of the impacts. We will next determine the influential coefficients and the sudden impacts based on the three categories.

3.2.2 Water and Food Scarcity Impacts

Water and food scarcity (WFS) includes water scarcity and food scarcity. Climate change can make both direct and indirect impacts related with WFS, as defined before. We will discuss these two types of impacts, respectively.

- **Direct impacts**

The direct impacts of WFS are the water scarcity and food scarcity caused by precipitation decrease, arable land decrease and temperature increase. Specifically, water scarcity is only related to the precipitation, and food scarcity is related to precipitation, temperature and arable land.

Food may be affected by all of the climate factors. We assume that food will change proportionally with each climate factor, so the influential coefficient of food can be obtained as:

$$f_{FD} = (1 - \lambda_{pr})(1 - \lambda_{te})(1 - \lambda_{ar}) \tag{10}$$

where $\lambda_{pr}, \lambda_{te}, \lambda_{ar}$ are the percentage change of precipitation, temperature and arable land, respectively.

Water is mainly relevant to the precipitation. The same proportional assumption is made so that the influential coefficient of water f_{WA} is

$$f_{WA} = 1 - \lambda_{pr} \tag{11}$$

- **Indirect impacts**

The indirect impacts mainly refer to impacts on security and some social factors (Figure 2). They are caused by the combination of climate change and WFS. This is in line with the fact that resources scarcity and poor governance can combine to affect fragility, as illustrated in the reference [2].

First we concern the indirect impacts on security. Poor governance can further exacerbate the side effects like violent conflicts according to the report of G7 in 2015[2]. This can worsen the security of a state. Thus, the influential coefficient $f_{SC,1}$ for security indicator is defined as

$$f_{SC,1} = f_{WA} f_{FD} GN^{\alpha_{SC,1}\lambda_{pr} + \beta_{SC,1}\lambda_{ar} + \gamma_{SC,1}\lambda_{te}} \tag{12}$$

where GN is the governance indicator; α, β, γ reflect the importance of governance to cope with climate change. As we can see from Equation 12, it involves both the climate change and governance. The greater the climate change factors λ_i are, the smaller the influential coefficient for security indicator is.

Now we are going to talk about the impacts on economics. Food scarcity will cause volatile food prices. The increase of food price will inevitably cause the price level to rise, because food is a kind of necessity for subsistence. This is known as inflation. Therefore, climate change will have indirect impacts on economics. Furthermore, this will cause the whole economy to be affected more significantly than the initial impact because of the **multiplier effect**[10]. The multiplier effect is the reality that people have their marginal propensity to consume (MPC) and will not spend all the money. Therefore, the whole economy would lose more from an economic perspective than the initial impact. Based on the above analysis, the influential coefficient f_{EC} is

$$f_{EC} = 1 - \frac{1}{1 - MPC}(1 - f_{FD}) \tag{13}$$

3.2.3 Potential Insecurity and Instability Impacts

Climate change makes impacts related with potential insecurity and instability (PII). For direct impacts, climate change can significantly affect the environment. Once the environment is not suitable to live, people will have to migrate to other places. This might increase the risks of insecurity and instability. What's more, temperature increase will also affect human health and further exacerbate the demographical situation. For indirect impacts, the security, stability and governance should be taken into account.

- **Direct impacts**

The direct impacts on PII mainly refers to the impacts on the shelter and demography.

Shelter is mainly affected by the sea-level rise and coastal degradation. Sea-level rise is caused by the melting of glaciers, so we can assume that the rate of sea-level rise is proportional to the temperature increase[11]. We can get the rate of sea-level rise is

$$\frac{dH}{dt} = a\lambda_{te}(t)T_0 \tag{14}$$

where a is proportionality constant; $\lambda_{te}(t)T_0$ is the temperature increase. Besides, the lower the elevation of a region is, the more susceptible the region is to the sea-level rise. Thus, we use the ratio of the elevation and sea-level rise rate to measure the impact of sea-level rise to the shelter. Considering that people may also migrate to other places because of the lack of precipitation and arable land, we take the influential coefficient of shelter indicator as

$$f_{SH} = (1-\lambda_{pr})(1-\lambda_{ar})(1-e^{-\frac{E}{dH/dt}}) \tag{15}$$

where E is the elevator; dH/dt is the rate of sea-level rise. According to Equation 15, if the elevation is relatively high, the shelter indicator will almost not be influenced.

Demography would be affected by temperature because of health. Germs may become more active in high-temperature areas. For simplicity, we approximately take the influential coefficient of demography as

$$f_{DM} = 1 - \lambda_{te} \tag{16}$$

- **Indirect impacts**

Large amount of people might surge into the city or other regions because of the climate change. This is a threat to the security and stability of a region. Besides, the public services in the region may be insufficient if there are too many people. Therefore, the security, stability and the governance quality will be affected.

The threat to the security mainly comes from migration and disease, and the sound quality of governance can alleviate it to some extent. If migration is banned or limited, this kind of security threat will decrease. Therefore, the influential coefficient of security should take migration, disease and governance indicator into consideration. It is determined as

$$f_{SC,2} = f_{SH} f_{DM} GN^{\alpha_{SC,2}\lambda_{pr}+\beta_{SC,2}\lambda_{ar}+\gamma_{SC,2}\lambda_{te}} \tag{17}$$

where α, β, λ reflect the importance of law to cope with climate change. Combine two influential coefficients of security indicator, and we can get the complete influential coefficient for security f_{SC} as

$$f_{SC} = f_{SC,1} f_{SC,2} \tag{18}$$

The stability only relates to the migration of people and completeness of the law, which is similar to what we have discussed for the security. Therefore, the influential coefficient of stability indicator is

$$f_{ST} = f_{SH} GN^{\alpha_{ST}\lambda_{pr}+\beta_{ST}\lambda_{ar}+\gamma_{ST}\lambda_{te}} \tag{19}$$

On the contrary, governance quality can also deteriorate because of the migration, such as public service and management. Governance quality can be influenced by the demographic indicators, like population and education. Therefore, the influential coefficient of governance indicator f_{GN} is

$$f_{GN} = f_{SH} DM^{\alpha_{GN}\lambda_{pr}+\beta_{GN}\lambda_{ar}+\gamma_{GN}\lambda_{te}} \tag{20}$$

3.2.4 Extreme Weather and Disasters Impacts

Extreme weather and disasters (EWD) is a special form of climate change impacts which is different from (WFS) and (PII). WFS and PII are caused by the change of precipitation, arable land and temperature, which belong to the long-run impacts. On the contrary, EWD does not have significant long-run indirect impacts, but it does great harm directly in the short run. For example, droughts, flood or hurricane will not maintain for a long time, but they will cause destroyable damage to assets and lives[12]. Therefore, we only focus on the direct impacts of EWD in this part.

Natural disasters are somewhat random. Therefore, we use the random simulation to simulate natural disasters and measure its possible influence. The Poisson distribution is often used to measure the frequency of natural disasters in a given period[13], so we suggest that the number of disasters in a year follows the **Poisson distribution**:

$$N \sim P(\mu) = \frac{\mu^k e^{-\mu}}{k!}, k = 0, 1, 2, \cdots \tag{21}$$

where μ is the parameter of Poisson distribution, also known as the mean value of N. μ describes whether the natural disasters occur frequently or not in this region and it can be determined by the history data.

The natural disaster will affect our fragility indicators when it occurs. The general significance of its impacts is measured by the **exponential distribution**. We assume the general significance is 0.001 each time in average, so we get

$$Sig \sim f(x) = \begin{cases} 1000e^{-1000x}, & x > 0 \\ 0, & x \leq 0 \end{cases} \tag{22}$$

The mean value is chosen as the general significance Sig. The decrease in each fragility indicator is still simulated using exponential distribution, based on the general significance of the disaster. Therefore, the impacts of the disasters are expressed as:

$$\delta \sim f(x) = \begin{cases} \frac{1}{Sig} e^{-\frac{x}{Sig}}, & x > 0 \\ 0, & x \leq 0 \end{cases} \tag{23}$$

Up to now, the influential coefficients f_i and sudden impacts δ_i are determined. The superior indicators after taking into account the climate change i_c is calculated using Equation 9.

4 Analysis of Fragility in Afghanistan and Egypt

We choose Afghanistan and Egypt as our study objects. **Afghanistan** is in the top ten fragile states list, while **Egypt** is not. Afghanistan is fragile with dry climate and water scarcity. Egypt is a state whose fragility level is at the boundary of fragility. We will calculate the fragility with and without impacts of climate change for Afghanistan and Egypt. Meanwhile, the differences between the two states will be compared.

4.1 Fragility Situation in Afghanistan and Egypt

The original fragility of Afghanistan and Egypt can be obtained based on our model and the data of inferior indicators. Other parameters will be set according to references and reality. At last, we will do sensitivity analysis of the critical variables: the percentage change of precipitation, arable land and temperature.

In order to calculate the fragility indicator, the weights and data of each inferior and superior indicators must be obtained. In subsection 3.1, the weights have been determined using AHP. In this part, some parameters and data will be decided and collected. In order to calculate the fragility indicator after climate change, the parameters in subsection 3.2 should be determined.

We can get some information about precipitation, arable land and temperature change from references [14] and [15]. The climate change is estimated as 0.1% for temperature increase, 0.2% for precipitation decrease and 2.7% for arable land decrease. The parameters of the importance of governance to cope with climate change α, β, γ are set to 1 for simplicity. According to economic textbook[16], the marginal propensity to consume MPC is estimated as 0.6 in average. The proportionality constant a in the expression of sea-level rise rate is determined by the relative research as 0.34mm/year per centigrade[11]. μ which measures the average number of disasters is set as 10. The average temperature is estimated as 20°C for Afghanistan and 25°C for Egypt.

Table 2: Superior indicators before and after climate change

Indicators	Afghanistan		Egypt	
	Without climate change	With climate change	Without climate change	With climate change
FD	0.271	0.307	0.409	0.429
WA	0.336	0.363	0.547	0.557
SH	0.324	0.341	0.520	0.543
SC	0.070	0.105	0.161	0.183
ST	0.149	0.174	0.215	0.240
EC	0.305	0.379	0.538	0.596
GN	0.437	0.471	0.429	0.454
DM	0.729	0.749	0.598	0.602
F	0.280	0.310	0.428	0.407

The values of superior indicators and fragility indicator (F) of Afghanistan and Egypt without and with climate change are listed in Table 2. The fragility indicators are calculated using Equation 1. From Table 2, the fragility of Afghanistan increases from 0.28 to 0.31 without the impacts of climate change. The percentage change is 10.7%. This is a relatively significant change for Afghanistan. As for Egypt, the fragility indicator decreases from 0.428 to 0.407 after the impact of climate change. The percentage change is 4.9%. This is a smaller change but is still significant. Compare Afghanistan and Egypt and we find Afghanistan is more vulnerable. This indicates that states with lower fragility indicator will be more vulnerable.

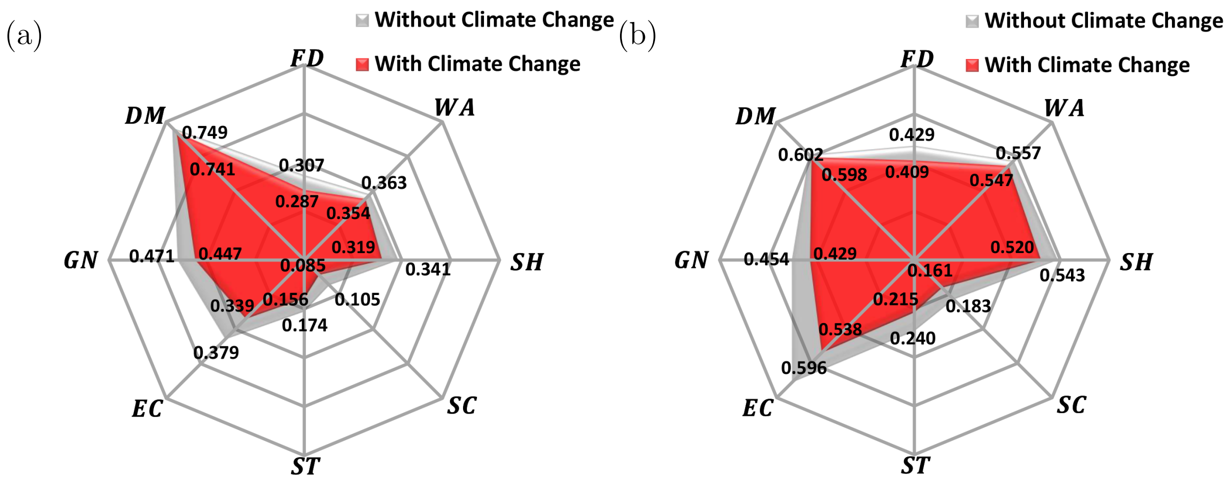


Figure 4: Superior indicators with and without climate change:
(a) Afghanistan; (b) Egypt.

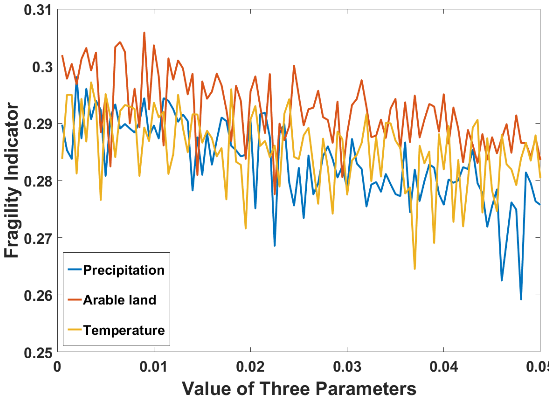
The significance of climate change impacts can be demonstrated more intuitively by the radar graph shown in Figure 4. From Figure 4(a), the economic indicator, shelter indicator and governance indicator are more vulnerable. The demography indicator is the least vulnerable in Afghanistan. The similar impacts also fit for Egypt, as shown in Figure 4(b). Specifically, the economic indicator is very vulnerable in Egypt. This is a result of the huge population in Egypt and that each person has a marginal propensity to spend money.

4.2 Sensitivity analysis

Next, we will do the sensibility analysis for the important variables: **percentage change of precipitation, arable land and temperature**. We will discuss the influence of these three parameters on the fragility indicator. The initial value of these three parameters are set as 0.2%, 2.7% and 0.1%, respectively. When discussing one of them, the other two parameters are set as the initial values.

We change the three parameters from 0.05% to 5% with the footstep of 0.05%. The variation of the fragility indicator of Afghanistan and Egypt is shown in Figure 5. From Figure 5, we can conclude that the fragility indicator keeps a decreasing trend with the rise of the three parameters. It is obvious that the influence of the percentage change of precipitation decrease λ_{pr} is more significant than the other two parameters. The influence of the percentage change of temperature increase λ_{te} performs differently in different countries. For Afghanistan (Figure 5(a)), the influence caused by temperature increase seems to be not significant. For Egypt (Figure 5(b)), the influence is more obvious, so Egypt is more sensitive to temperature increase. Besides, the influence of the natural disasters is shown by the fluctuation of the fragility indicators. The drastic fluctuation shows that the influence of natural disasters is very crucial to the fragility indicator. In conclusion, the decrease in precipitation and the natural disasters are the two main reasons which make the two states more fragile.

(a)



(b)

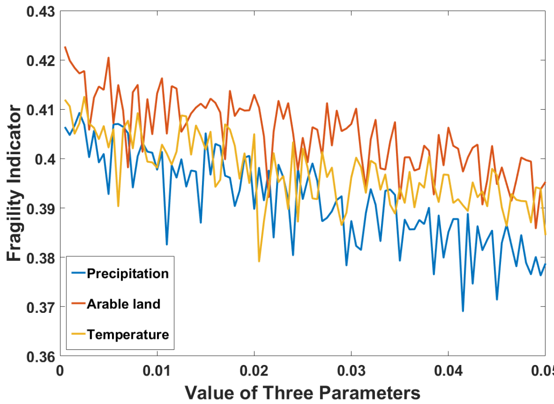


Figure 5: Sensitivity analysis of the percentage change of climate factors: (a) Afghanistan; (b) Egypt.

4.3 Determination of Tipping Point

There are 193 countries all over the world and about 35 to 50 of them are listed as fragile states[8]. This means that about a quarter of countries in the world are fragile states. Our tipping point should be determined as the boundary between these fragile states and other states. What's more, we will additionally define a stable point which divide the vulnerable country and stable country.

We classify the countries in the world into four categories according to the fragility indicator. The boundary of the most fragile states is the tipping point and the boundary of the stablest group is the stable point. The method we use is the **K-means Clustering Algorithm**. K-means Clustering Algorithm aims to partition n observations into k clusters[17]. Its purpose is to minimize the sum of the distances from the sort center $D(\mu_k)$:

$$D(\mu_k) = \sum_{x_i \in C_k} (x_i - \mu_k)^2 \tag{24}$$

where x_i is an observation in the k^{th} cluster C_k.

However, it is so difficult to calculate the fragility indicator of each country in the world so that the K-means Clustering Algorithm is hard to apply. Therefore, we will first use FSI (Fragile States Index) to find the tipping point based on the official indexes. Then we will find the country whose FSI is the closest to the tipping point. At last, we calculate the fragility indicator of that country using our model and set it as our tipping point.

The tipping point is calculated as 91.3 and the stable point is 47.4 based on FSI, as shown in Figure 6(a). The FSI of Egypt is 89.8, which is close to the FSI tipping point. The FSI of Argentina is 48.2, which is the closest to the FSI stable point. We approximately use the fragility indicator of Egypt as the tipping point and that of Argentina as the stable point.

The fragility indicator of Egypt and Argentina are **0.428** and **0.711**, respectively. Therefore, the tipping point is determined as 0.428 and the stable point is 0.711. As shown in Figure 6(b), when the fragility indicator is lower than 0.428, the state is fragile; when the fragility indicator is greater than 0.711, the state is stable, otherwise the state is vulnerable.

(a) (b)

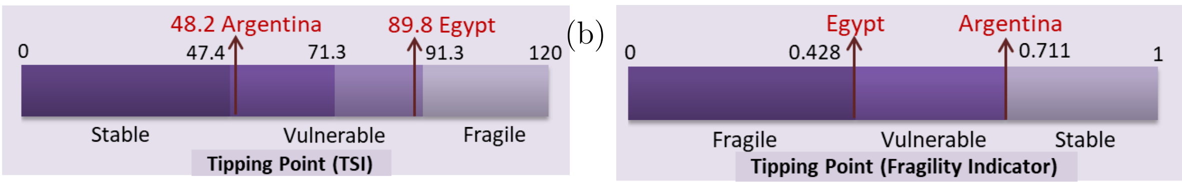


Figure 6: Tipping point and stable point in different calculation systems: (a) FSI; (b) fragility indicator.

5 Designation of Intervention Plan

Intervention plans for Afghanistan and Egypt are necessary. Fragility is harmful for a state to develop. We will **establish an optimization model** under the **budget limit** for fighting against fragility. Then we move on to decide the values of related parameters. After solving the model, a set of intervention plans and its impacts will be given. At last, we will analyze the sensitivity of the climate change factors.

5.1 Establishment of the Optimization Model

Our optimization model is a single objective model. The objective of the optimization model is maximizing the fragility indicator. The main constraint is the total budget for improving fragility indicator. That means we should maximize the fragility indicator with a certain amount of budge.

Better management of budgets can benefit the fragility to the best extent. This decides that the constraints of the model mainly come from the **budget** B. Therefore, total cost of the interventions should not exceed the total budget:

$$\sum_i B_i \leq B, i \in \boldsymbol{I} \tag{25}$$

where B_i is the money spending on each superior indicator.

When an indicator increases by 0.01, the certain amount of money is needed. We call the amount of money as B_k^0. According to the economic **law of increasing marginal cost**[6], the marginal money B_k^0 needed for the additional improvement increases progressively. For simplification, we approximately take it as

$$B_i^0 = \alpha_i(i - f_i i_0 - \delta_i), i \in \boldsymbol{I} \tag{26}$$

where α_i is the linear coefficient; i_0 is the original value of indicators before taking into account the impacts of climate change. In this way, the budget used to improve a certain fragility indicator can be written as

$$B_i = \int_{i_0}^{i} \frac{B_i^0(\zeta)}{0.01} d\zeta, i \in \boldsymbol{I} \tag{27}$$

Taking into account the relationships between those superior indicators established in subsection 3.1, and we can finally obtain the optimization model:

$$\max \quad F$$
$$s.t. \begin{cases} F = \sum\limits_i \omega_i i \\ \sum\limits_i B_i \le B \\ i = f_i i_0 - \delta_i + 0.1\sqrt{\dfrac{2B_i}{\alpha_i}} \\ B_i \ge 0 \\ 0 \le i \le 1 \end{cases} \tag{28}$$

There are also other constraints which relate the indicators together. These constraints include Equation 9-13, 15-20 and 23.

5.2 Formulation of a Intervention Project

In order to reflect the amount of money needed intuitively, **the proportion of budget in GDP** r is used to describe the money needed, so the budget for fragility dealing is

$$B = r\mathrm{GDP} \tag{29}$$

The GDP of Afghanistan and Egypt in 2016 are 21.06 and 332.3 billion dollars, respectively. We assume that the percentage of precipitation decrease, arable land decrease and temperature increase are 0.2%, 2.7% and 0.1%, respectively, which is in accordance with the former part. Further analysis of the percentage changes will be shown in the sensitivity analysis.

Figure 7 shows the relationship between fragility indicator and the budget. For both Afghanistan and Egypt, intervention plans are effective. However, Figure 7(a) illustrates that 285% of Afghanistan GDP is needed to prevent Afghanistan from being a fragile country. That is, the total cost of intervention is about 57.2 billion dollars. It is hard for Afghanistan to escape from fragility without the external help. As for Egypt, its fragility indicator is 0.428 without the impacts of climate change, which is set as our tipping point. After taking into account the climate change impacts, the fragility indicator of Egypt decreases to about 0.38, which means that Egypt becomes a fragile state. Egypt must spend 1% of its GDP (about 3.32 billion dollars) to deal with fragility problems in order to prevent itself from turning into a fragile state. The fiscal pressure for Egypt is much lower than that of Afghanistan. There are two reasons account for this result. On the one hand, Egypt is not far away from the tipping point at the very beginning while Afghanistan is in the top ten fragile states list. On the other hand, the GDP of Afghanistan is much lower than Egypt. This means Afghanistan must spend a larger portion of its GDP.

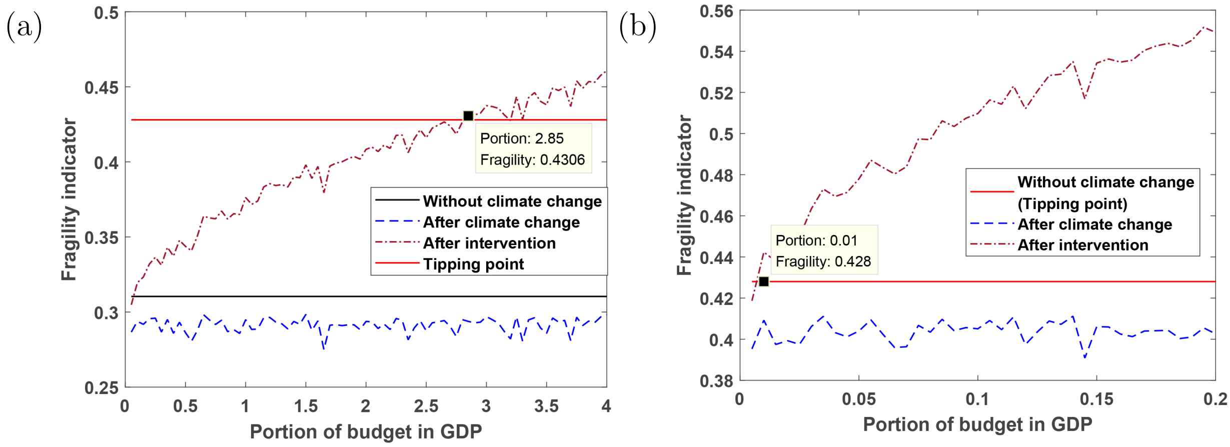


Figure 7: Fragility situation with/without climate change and intervention: (a) Afghanistan; (b) Egypt.

We will give the optimal intervention plan under the budget of each country. As analyzed above, the total cost for Afghanistan to escape from fragility is **57.2 billion dollars** and for Egypt, **3.32 billion dollars**, so we discuss the intervention plan under these budgets. We get the optimal plan from the optimization model and show it in Figure 8. As we can see from Figure 8, the allocation of the budget is similar for Afghanistan and Egypt. What's more, the indicators of the physiological need should be invested more because they are given more weights in our fragility model. They are the most basic factors to prevent fragility.

Based on these results, we suggest that both Afghanistan and Egypt should spend about one-third of their budget on the facet of food. Following that, nearly one-fourth of the budget should be spent to improve water situation, such as water pollution, water sanitation and water stress. Food and water are two basic requirements of people. Shelter and security should be regarded as equally important according to the optimization results, where Afghanistan and Egypt should spend about 6.5 billion and 0.4 billion respectively. As for facets of other superior indicators:stability, economics, governance and demography, Afghanistan should spend 4.51, 2.62, 1.61 and 2.23 billion dollars and Egypt 0.27, 0.15, 0.09 and 0.13 billion dollars.

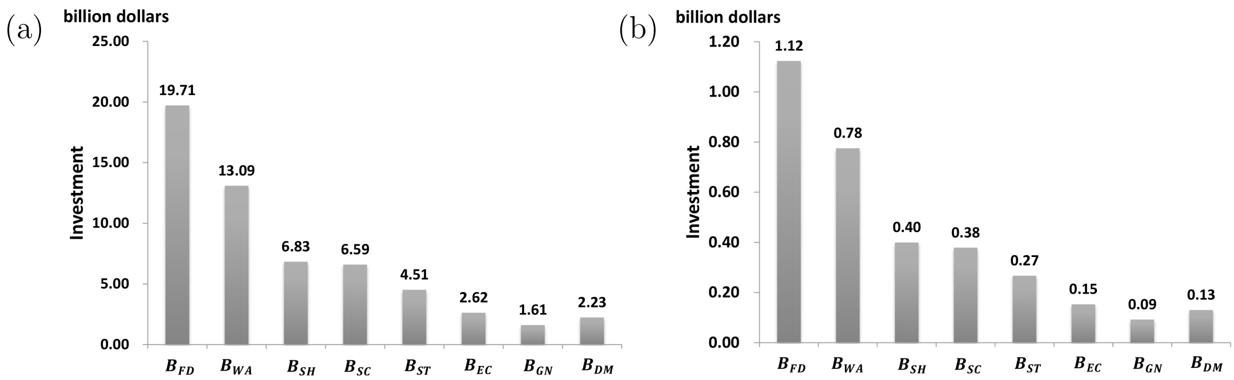


Figure 8: Optimal allocation of budget: (a) Afghanistan; (b) Egypt.

5.3 Impacts of the Intervention Project

We compare the superior indicators before and after intervention in order to know the impacts of the intervention. The impact of interventions on superior indicators can be obtained according to the third constraint in the optimization model. Figure 9 shows the radar graphs of the eight superior indicators before and after the intervention. As shown in Figure 9, the food and water situation are improved significantly after intervention both in Afghanistan and Egypt. The improvement of food indicator is about 0.183 in Afghanistan which is especially significant. These are excellent achievements because physiological needs account for the most part of the fragility. At the same time, other superior indicators like shelter, security and stability also improve a lot in Afghanistan and Egypt. These will help them deal with the fragility.

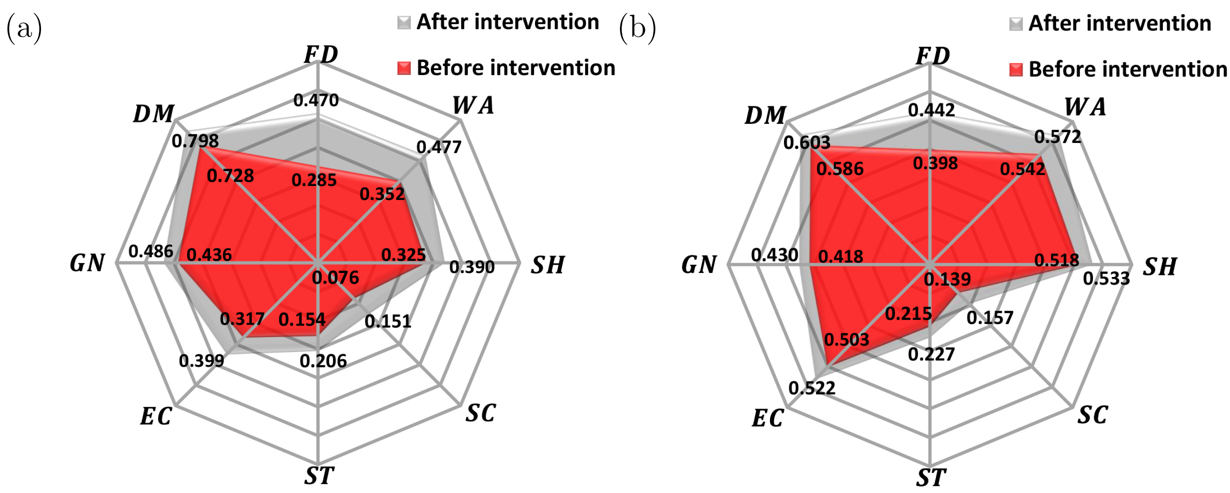


Figure 9: Superior indicators before and after the intervention: (a) Afghanistan; (b) Egypt.

After these interventions, the fragility indicator of Afghanistan is 0.385, and its fragility indicator before intervention is 0.288. The fragility indicator increases by 33.7%, but it is still smaller than the tipping point. Afghanistan is still a fragile country after the intervention. This is may be caused by the random natural disasters. Natural disasters would do significant harm to the region at many facets. Besides, the total cost of this improvement is about 57.2 billion dollars, which is three times of Afghanistan GDP. This is a big challenge for the state. As for Egypt, our intervention can effectively prevent Egypt from becoming a fragile state with only 1% of its GDP. The fragility indicator of Egypt increases from 0.397 to 0.42. This is very close to the tipping point.

5.4 Sensitivity Analysis

Next, we will analyze the sensitivity of the climate change factors: percentage change of precipitation, arable land and temperature. The initial values of them are 0.2%, 2.7% and 0.1%. We change the value of each factor from 0.005 to 0.2 with the step of 0.005. When one of the parameters is changing, other two parameters are still set as the initial value. The proportion of budget in GDP is set as 57.2 billion dollars for Afghanistan and 3.32 for Egypt.

Figure 10 shows the trend of optimal fragility indicator of Afghanistan and Egypt. The trends are similar in the two states. We can see that fragility decreases mostly rapidly with the change of precipitation. This means that our optimization model is most sensitive to precipitation. The fluctuation of the line represents the random natural disasters.

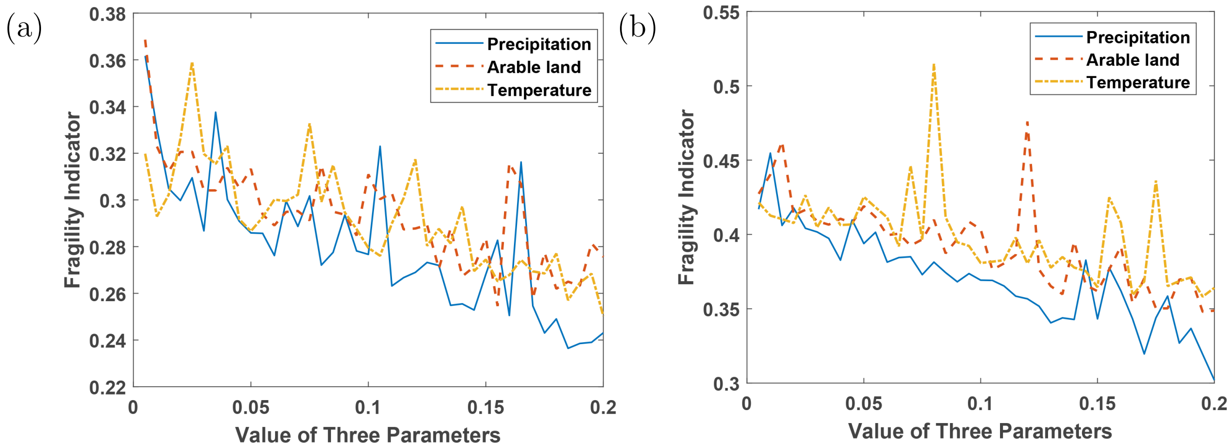


Figure 10: Sensitivity analysis of percentage change of climate factor using the optimization model: (a)Afghanistan; (b) Egypt.

5.5 Suggestions

From the results of our optimization model, we conclude that **Afghanistan** should spend **285%** of its GDP to prevent fragility and **Egypt 1%**. The difference is significant. For Afghanistan, it is almost impossible to prevent fragility in the short run. Therefore, we suggest the related organizations should help those countries whose fragility indicator is far lower than the tipping point, like Afghanistan. Otherwise they can hardly escape from fragility. Specifically, fragile states should use about one-third of the budget to deal with food issues and about one-fourth to deal with water issues. As for other aspects, the specific investment can be obtained through our optimization model. This model can give out the optimal intervention to eliminate fragility within a limited budget.

6 Modification of Fragility Model

It is worth noted that our model aims to solve the fragility in small or middle countries like Afghanistan and Egypt. That is because when we consider the possible factors, we regard the country as a whole and provide factors for sovereign states. However, some factors need to be modified when our model is applied to smaller region like cities or bigger state like continents. Specifically, there are three problems for smaller states:

- Factors like parties and ethnic is not suitable to smaller states.
- Factors like city environment and development indicator should be considered.
- The cost of interventions will be lower because of synergy[18].

Similarly, there are two problems for bigger states like continents:

- Climate change impacts will not affect the state as a whole;
- The cost of interventions should be related to the scale of intervention it implements to;

We will modify our model based on these problems in this section in order to make our model available to smaller and bigger states.

6.1 Modification for Smaller States

Modification for smaller states includes two general aspects: factor reconsideration and cost modification.

For superior indicators of physiological need, most of the original factors are still suitable except food import. Food import is a general factor for a sovereign state, so it should be deleted. For superior indicators of safety need, the external intervention and military factors should be deleted, because they are not meaningful for cities. Meanwhile, sustainability and flexibility should be added to measure smaller states. For superior indicators of society need, ethnic, uneven development, national debt and party relationship should be deleted. Economic structure, economic efficiency, subsidy and public green space should be taken into account. We still use the AHP method and get weights of the factors for smaller state, which are shown in Table 3.

From Table 3 we can see that the main body of our model is unchanged. The weights are still similar to Table 1. This guarantees that our model is consistent for smaller states and normal states.

Table 3: The weights of indicators

Physiological need		
Food 18%	Water 18%	Shelter 18%
Price 26%, Production 74%	Stress 46%, Sanitation 26% Pollution 14%, Reservoir 14%	House price 14%, Slums 24% Housing area 62%

Safety need	
Security 15%	Stability 15%
Public order 11% Terrorist attack 58%, Crimes 31%	Refugee 25%, Violent conflict 48% Population mobility 9% Sustainalibity 13%, flexibility 6%

Society need		
Economics 5.33%	Governance 5.33%	Demography 5.33%
GDP40%, Unemployment11% Inflation 20%, Interest 5% Economic structure 17% Uneven development 11% Economic efficiency 7%	Law 5%, Corruption 18% Management 34% Subsidy 21% Public support 9% Public services 12%	Public green space 17% Education 6%, Health 10% Gender distribution 10% Equality 5%, Population 47% Age structure 5%

The cost of intervention in smaller states such as cities will be smaller because of the synergy effect. High population density can improve communication ability and knowledge sharing so that the cost of intervention will decrease. We use ξ to measure the synergy effect and the linear coefficient for smaller states in intervention cost α_s can be rewritten as

$$\alpha_s = \xi\alpha \tag{30}$$

6.2 Modification for Bigger States

The impact area of climate change and the complexity of governance should be considered for bigger states.

As for the impact of climate change, we mainly focus on natural disasters because it always occurs to a limited range. Other climate changes like greenhouse effect and sea-level rise are global climate change. Therefore, even bigger states like continents will suffer from it as a whole.

We define an influential range index ψ to measure how significantly the climate change impacts this bigger state. Most natural disasters will not too serious and extreme disaster only occurs accidentally, so we assume the probability function of the influential range index $f_\psi(x)$ as

$$f_\psi(x) = \begin{cases} -2x+2, & x \in [0,1] \\ 0, & \text{others} \end{cases} \tag{31}$$

In this way, the possibility of serious natural disasters is much lower. The impacts of disasters for bigger states is determined as

$$\delta_b = \psi\delta \tag{32}$$

where δ is the impacts of natural disasters in normal states.

The cost of interventions has nothing to do with the proportion of budget in GDP in the former model. However, it is impossible for the government to cope with the fragility of the whole state at a time in bigger states. The efficiency of large-scale investment coping with fragility will inevitably decrease because of the ability limitation. This is equivalent of increasing the unit cost of intervention. Generally, the higher the proportion of budget in GDP is, the bigger the scale of intervention is, and the higher the unit cost of intervention is. Therefore, the linear coefficient for bigger states in intervention cost α_b is determined as

$$\alpha_b = (1 + r)\alpha \tag{33}$$

where r is the proportion of budget in GDP.

6.3 Application to Afghanistan and Egypt

We still use the example of Afghanistan and Egypt to apply the modified model in order to compare the model before and after the modification. Figure 11 illustrates the differences of our three models. The horizontal axis represents the proportion of budget in GDP, and the vertical axis represents the best fragility level it can reach under the limitation of current budget.

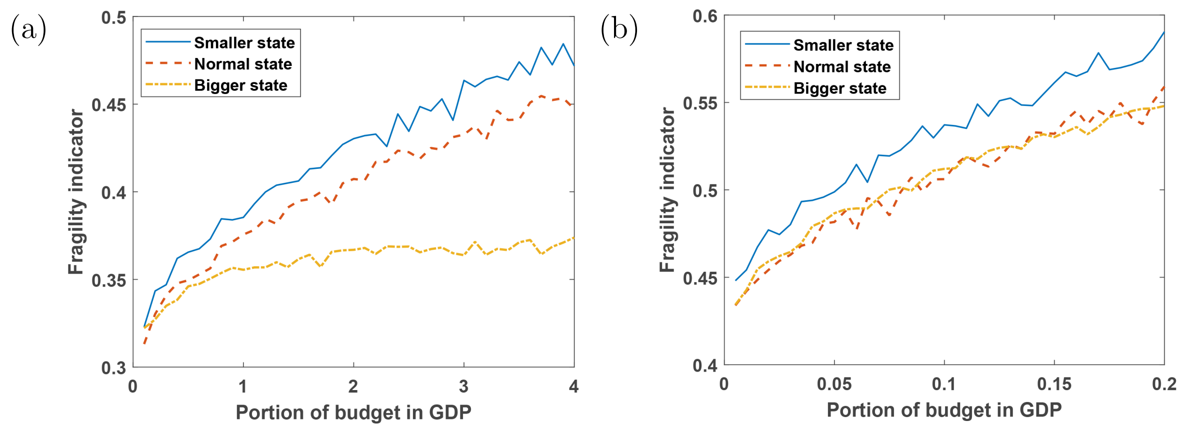


Figure 11: Comparison between the original fragility model and the modified one: (a) Afghanistan; (b) Egypt.

We can know from Figure 11 that the general trend of the fragility of smaller states increases more rapidly than bigger states because of the synergy effect. The fragility of bigger states increases very slowly when the budget increases. This is because continent is too large to manage in the short run. Therefore, trying to improve the fragility of bigger states in one time is impossible. Figure 11(a) shows that Afghanistan is more similar to a smaller state. This is in accordance to the reality. Afghanistan is a relatively small country with about twenty million people. This population is similar to that of Beijing. As for Egypt, it is a relatively large country with ninety million people. Therefore, it is more similar to the bigger state, as shown in Figure 11(b).

We suggest that the scale of the state should be considered when using our fragility model. For smaller state, the modification of factors and cost should be applied; for bigger state, the modification of the influential area and cost should be applied.

7 Conclusions

To sum up, we first establish an **evaluation model** to measure fragility, and then we take into account the climate change impacts. The **optimization model** is used to find the intervention to reach the fragile point. Besides, the modification of the evaluation model figures out suitable models for smaller and bigger states. **Afghanistan** is in the top ten fragile states list and **Egypt** is not fragile but vulnerable. They are analyzed using our model to decide the impacts of climate change on fragility.

The results of our model show that the fragility indicator with climate change is **0.280 for Afghanistan** and **0.407 for Egypt**. Without the climate change, the fragility indicator changes to **0.310 for Afghanistan** and **0.428 for Egypt**. Among the eight superior indicators, **economics** indicator will be mostly affected whose average percentage change is **14.6%**. The **tipping point** and **stable point** are determined as **0.428** and **0.711**, which divides the states into three kinds: fragile, vulnerable and stable.

According to the result of optimization, Afghanistan needs to spend **285%** of its GDP and Egypt **1%** to avoid fragility. The cost is mainly used to prove the **food and water** indicators. After intervention, both states will be less fragile. However, it is hard for Afghanistan to escape from fragility in the short run.

We **reconsider the factors and weights** for smaller states and **lower the cost** of intervention for them because of the synergy effect. For bigger states, the **influence range** is considered and the **cost is higher** because of the difficulty in managing. We find that smaller states can develop more quickly than bigger states.

8 Strengths and Weaknesses

Strengths

- Five different normalization methods are used to normalize the inferior indicators. According to the different features of different type of indicators, we choose the most suitable normalization method. This will improve the availability of our models.
- The influence of the natural disaster is generated by the random distribution. We use Poisson distribution to simulate it. This is a suitable method to measure the disasters. Compared with others who neglect the disasters, our model can be more useful.
- In the optimization model, the costs of the intervention are set as an increasing cost. This is more realistic. Because actually the marginal cost of everything is increasing, our model is more practicable.
- In the modification of the model, we apply our modified model to Afghanistan and Egypt to test its availability. Results show Afghanistan is similar to a smaller state and Egypt is similar to a bigger state. This can validate our modified model.

Weaknesses

- In the K-means Clustering Algorithm, the data from the FSI website is used to help us find the tipping point. This may cause some deviations, but this method can simply our calculation process and bring convenience.
- Some of the value of parameters are estimated such as the cost of unit intervention. This may cause the actual effect of the budget deviates from the reality, but more specific statistics can be collected when using our model to solve this problem.
- For bigger states, it is better to divide the states into different part according to their geological characteristics. In this way our model can be more accurate. The further work can be done to improve this aspect.

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