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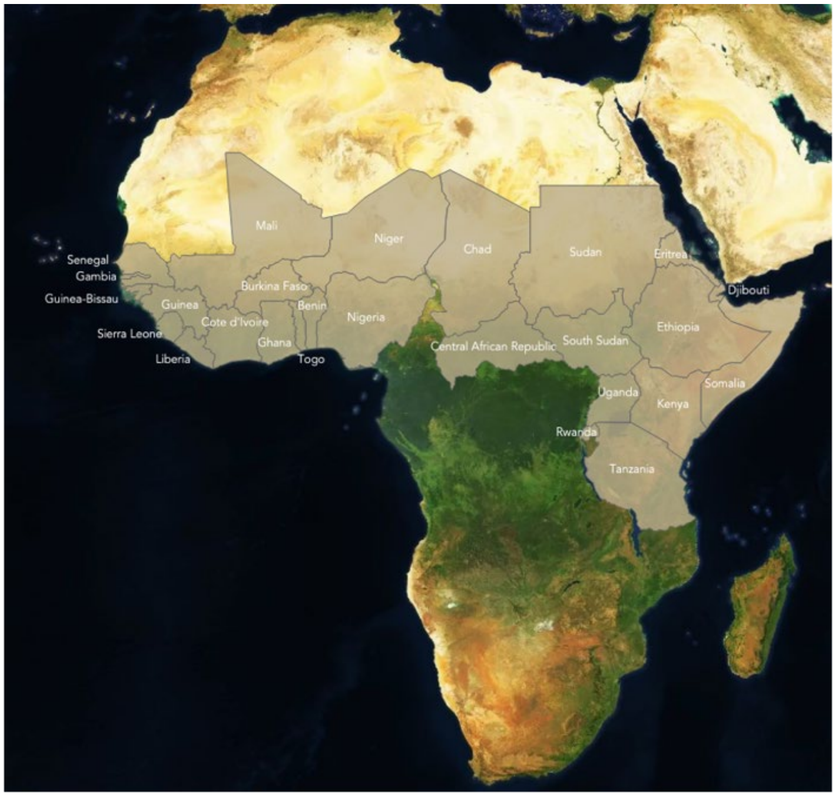
Anticipating the Future Operational Environment (AFOE) Sahelian Computational Models



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Produced in support of the Strategic Multilayer Assessment (SMA) Office (Joint Staff, J3)

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Cover image: African countries included in analysis

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Executive Summary

The physical, social, political, economic, and cultural systems comprise the operational environment and interact in complex ways. The Strategic Multilayer Assessment (SMA) *Anticipating the Future Operational Environment (AFOE)* project models this complexity with special relevance to US national security concerns. The AFOE team constructed a generic *Global Exploitable Conditions Model (GECM)* that captured this complexity as a system of nodes, or variables, and edges, which are the relationships between nodes. The generic GECM was then tailored to the specifics of the USAFRICOM AOR to produce the *AFRICOM Exploitable Conditions Model (AECM)*. A subsystem of the AECM was extracted to align with key USAFRICOM objectives in the greater Sahelian region: a part of the African continent encompassing 24 countries in the Western and Eastern African zones, and two countries from the Central African zone. These countries generally occupy the area between the Sahara Desert and the tropical forest regions of Africa and are the focus of a designated Sahelian system model.

The analytic approach, like the region itself, was multi-faceted. First, empirical data was collected to provide quantitative measures representing the ways that conditions of the operational environment impact USAFRICOM's key concerns. These data provided key inputs into two types of models: network analysis and system dynamics. Analyses of network models evaluate the potential of a node to influence a system by virtue of its position in the system. System dynamics models simulate the flow of influence throughout a system by virtue of positioning, the functional relationship of the edges that connect nodes, and most important through feedbacks in the system.

It should be noted that the SMA team benefited significantly from close cooperation with its colleagues at USAFRICOM. This report describes how these conceptual models were used to provide insights into important conditions and dynamics that impact USAFRICOM's mission objectives.

Caveats

The models used in this analysis are still under construction and refinement. However, they are not notional; they are the product of extensive background research and analysis, all of which is based on empirical data. We believe they can be taken as a starting point for further analysis and to produce better validated and more completely specified models. Improvements are recommended as detailed in the Appendix: Lessons learned in creating a computational model of the Sahelian system.

Insights

Empirical analysis of the Sahelian system model showed that most relationships between nodes in the system are weak and linear; only a few relationships are non-linear and accelerating.[1] The relevance of this is that one could expect the Sahelian system as a whole to evolve slowly, and thus conditions antithetical to US interests to erode slowly as well. The slower pace of this deterioration gives the US time to take action to mitigate, or possibly change, the direction of negative trends. The few relationships that have the potential to accelerate are

- global warming accelerating epidemic crises,
- political violence and political polarization accelerating terrorist attacks, and

[1] Throughout this report, increase refers to a linear increase from one node to another, as in the slope of a line or in physics terms, velocity. Accelerate refers to an increasing increase, as in the second derivative of a function, or in physics terms, acceleration.

- infrastructure improvements dramatically accelerating internet access, which can accelerate the impact of disinformation.

Findings from the Sahelian network and system dynamics models were complimentary, but not entirely overlapping, thus reinforcing the value of employing multiple modeling approaches to USAFRICOM concerns in the region. Some of the key findings include the following:

- Governing effectiveness is positioned to be the prime driver of change in the Sahelian system, impacting many other key nodes and USAFRICOM concerns such as political stability, internal war (including civil wars between governments and non-state groups), corruption, epidemic crises, terrorism, and through feedback, good governance itself.
- Reinforcing relationships between government effectiveness, and the presence or lack of corruption control, and internal war are conjoined; there are numerous paths by which these nodes influence one another.
- The degree of undernourishment in a population is also most impacted by reinforcing relationships involving government effectiveness, corruption control, and internal war.
- Terrorism is embedded in multiple reinforcing loops, including political violence, political polarization, fragility of public services, factionalized elites, foreign disinformation, and political state terror. This suggests that seriously diminishing terrorism in the Sahel may require coordinated efforts to address at least six problems simultaneously.
- Infrastructure improvements lead to a sharp increase in the consumption of online media and foreign malign information. Foreign malign information fuels political polarization.
- Migration is impacted by the reinforcing loops that connect government effectiveness, corruption control, and internal war. Specifically, government effectiveness, reinforced by corruption control, can help buffer a state from the outbreak of civil war. However, outbreak of civil war can diminish government effectiveness and spur increased political violence. Internal warfare pushes people to emigrate.

A final caveat. George E.P. Box's admonition that "all models are wrong, but some are useful," should be well-remembered. Models systematically capture complex interactions that elude qualitative analyses and traditional statistics. However, models are imperfect abstractions of the complex world with which decision makers deal. All models, including those presented here, should be used wisely.

Introduction

This report is part of the multi-phase SMA *Anticipating the Future Operational Environment (AFOE)* project intended to inform Joint Staff and Combatant Command (CCMD) planners, analysts, and operations staff about challenges to US international influence (i.e., strategic competition). The original inspiration for this project was research conducted by the US Army TRADOC G-2, which identified twenty-four "exploitable" global conditions that could impact US-China-Russia strategic competition (Burns et al., 2019). Phase I of the AFOE project concentrated on decomposing the 24 conditions into subsystems of elements, called nodes, and exploring the connections between the nodes. This resulted in the *Global Exploitable Conditions Model (GECM)*, which is a conceptual model of the interrelationships among the nodes within and between these subsystems. Phase II of the AFOE project involved tailoring the generalizable GECM to the concerns of specific Geographical Combatant Command (GCCs). Details on GECM tailoring to the African continent and the generation of the *AFRICOM Exploitable Conditions Model (AECM)* can be found in the User's Guide (Lindquist, 2023).

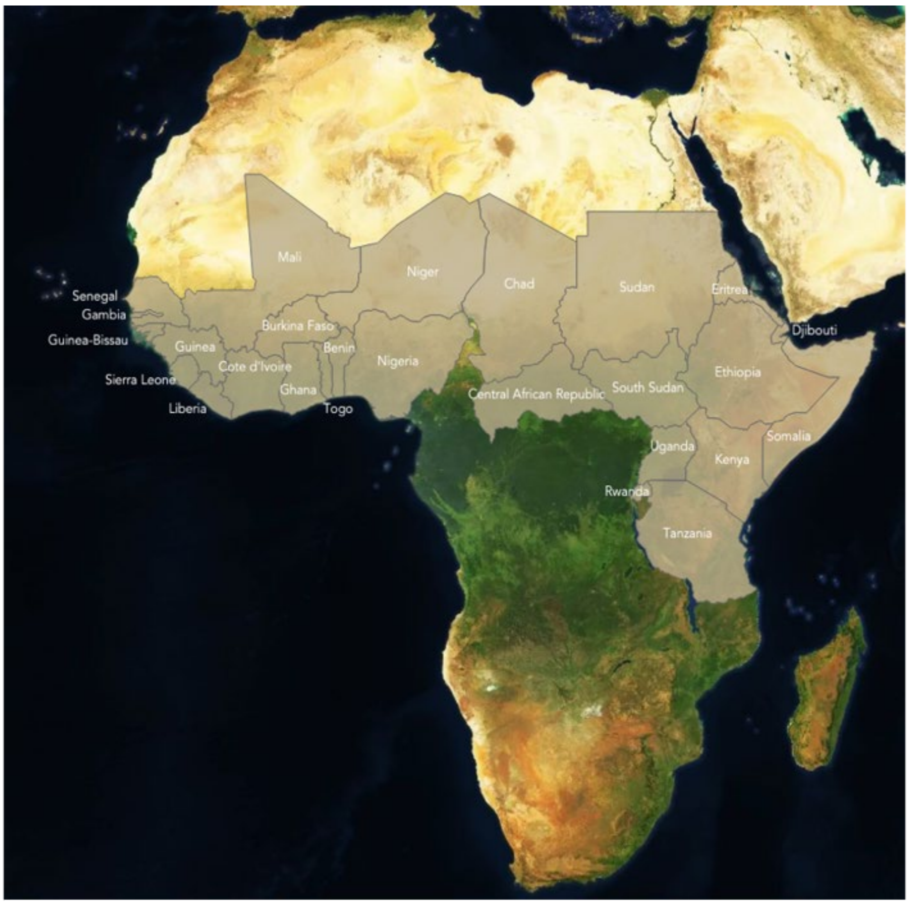

Figure 1. "Sahel" countries used in computational models

USAFRICOM's enduring objectives (Townsend, 2022) are frequently challenged by violent extremist organizations (Kuznar & Day, 2021b; Lobban & Dalton, 2017), political instability (Fluckiger & Ludwig, 2018; Schumetie & Watabagi, 2019), migration (Giménez-Gómez, Walle, & Zergawu, 2019), and Russian and Chinese military and political activity (Adunbi & Stein, 2019; Folarin, Ibietan, & Chidozie, 2016). The models and analyses described in this report are focused on the Sahel (Figure 1), a region in which each of these challenges is particularly acute. Two modeling approaches were used to analyze the system of exploitable conditions in this region—network analysis and system dynamics modeling—which are briefly introduced in the following section. Next the key findings of the research are presented, followed by detailed descriptions of the methodology used to render the Africa-wide AECM to computational models representing the Sahel. While the Sahel technically refers to the arid grassland region between the Sahara and the tropical forests of central Africa, countries included in this analysis include USAFRICOM's designated East African region, plus Chad and the Central African Republic (Central African region) that also contain tropical grasslands. The computational models reviewed in this report will be referred to as the Sahelian models as a shorthand. The following section provides a summary of the key findings of the analyses.

Summary of the Analytic Approach and Findings

As shown in Figure 2, the analytic approach, like the Sahelian region itself, was multi-faceted. First, to ensure that the modeling efforts were evidence-based, empirical data was collected to operationalize nodes in the AECM and provide quantitative measures representing the ways that conditions of the operational environment impact USAFRICOM's key concerns. Next, regression analyses were conducted to test the strength and direction of the relationships between nodes in the AECM (for a detailed discussion of this portion of the analysis, see section Operationalizing AECM to generate the Sahelian system).

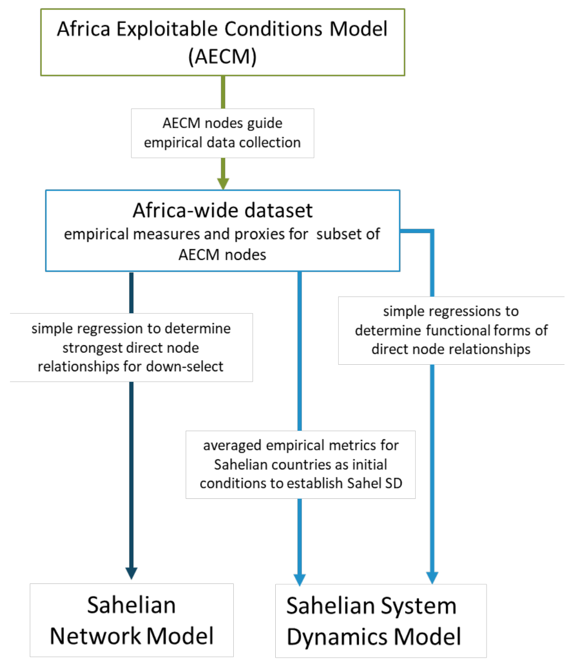

Figure 2. Analytical approaches used for Sahelian computational modeling

These data provided key inputs into two types of models: network and system dynamics. The network analyses modeled relations between the nodes as a system of network influences. Analyses of the centrality of nodes in the network provided insights into how well positioned different nodes were to influence the Sahelian system (for a detailed discussion of this portion of the analysis, see section Analysis of the Sahelian network model). The system dynamics model tracked the actual flow of influence throughout the system by virtue of positioning, the functional relationship of the edges that connect nodes, and most important through feedbacks in the system (for a detailed discussion of this portion of the analysis, see section Analysis of the Sahelian system dynamics model).

Each step in the analytic process provided both unique and complementary insights into the drivers of change and the leverage points in the Sahelian system that impact nodes of interest to USAFRICOM. The following subsections discuss some of the key insights about the Sahelian system that emerge when combining the findings from the empirical, network, and system dynamics analyses.

Change in the Sahel is Slow; Strategic Patience is Required

Note: **Bold font** is used to indicate a node in the Sahelian models.

Regression analyses indicate that most changes in the African system are linear and gradual.[2] Only a few relationships in the system have the potential for non-linear accelerating effects. For example, there is an accelerating relationship between **global warming**[3] and the numbers of people dying from epidemic diseases on the continent per year.[4] **Factionalized elites**[5] and **political violence**[6] have accelerating relationships with **terrorism**.[7] Not surprisingly, improvements in **infrastructure**[8] are associated with a dramatic increase in the **percent of the population that uses the internet**. This relationship has implications for the spread of accurate information as well as disinformation and its disruptive effects. However, despite these few non-linear direct relationships, most relationships were linear and weak indicating gradual change in the system.

Government Effectiveness is a Critical Driver of Negative and Positive Change in the Sahel

The network analysis showed that constituents' perception of **government effectiveness** [9] is positioned in the network to be a prime driver of changes in many other nodes in the Sahelian system because it directly influences other influential nodes and it is positioned to influence other nodes through many indirect pathways (1st through 3rd order).[10] Several other nodes are positioned to be drivers in the Sahelian network model—**terrorism**, **political polarization**,[11] and **political violence**—are involved in reinforcing relationships with **government effectiveness** and with each other. They are positioned to fall into vicious, accelerating cycles when they trend in undesirable directions. The system dynamics model confirms these results: **government effectiveness** decreases and **terrorism** increases at exponential rates due to reinforcing feedback from other nodes in that model.

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[2] Note that since the statistical analyses were done with data from the entire continent, this result generalizes to the continent. Since the Sahelian countries represent a restricted range of these data, it is all the more true of the Sahel.

[3] Global warming was measures as deviation from the average temperature between 1951 and 1980.

[4] The regressions represent associations between nodes that in some cases are direct and, in other cases, are the result of indirect relationships through intervening nodes.

[5] The term "factionalized elites" is defined in the Fund for Peace Fragile States Index database as "fragmentation along ethnic, racial, religious lines, brinksmanship and gridlock among elites, nationalistic rhetoric."

[6] Political violence is scored in the Varieties of Democracy database as "How often have non-state actors used political violence against persons this year?"

[7] The metric used in the models to track terrorism is the Global Terror Index (GTI) from the Institute for Economics and Peace.

[8] Infrastructure quality was measured with the World Bank Logistics Performance Index Infrastructure Score – "The quality of trade and transport infrastructure."

[9] The measure of government effectiveness used here is a composite measure from the World Bank and refers to *popular perceptions* of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. There AECM includes each of these factors plus others associated with the concept of effective governance as separate nodes in the model.

[10] An n^{th} order effect passes through *n* connections from one node to another.

[11] Political polarization is scored in the Varieties of Democracy database with the question "Is society polarized into antagonistic, political camps?"

Other nodes in the analyses had important effects but were not as pervasive as **government effectiveness**, **internal war**,[12] and **terrorism**. For example, the actual extent to which a government provides public services like sanitation, healthcare, and education (node = **fragility of public services**[13]) and the extent to which there is internal division among the country's elite (**factionalized elites**) are also positioned to influence conditions in the Sahel. However, the system dynamics analysis indicates that their impact on the entire system is moderate, indicating that they can exacerbate issues like **terrorism** and **government effectiveness,** but are not themselves major system drivers.

The Government Effectiveness – Corruption[14] – Civil War Nexus is Powerful

There is a nexus between **government effectiveness**, **corruption**, and **internal war** in the Sahelian models such that **corruption control**[15] and **internal war** are linked through reinforcing relationships each has with **government effectiveness** (Figure 3). Furthermore, the strongest relationship in the entire system is between **government effectiveness** and **corruption control**, and most important, this relationship is reciprocal. These nodes are bound in a reinforcing loop with one another, which enables them to have accelerating effects on one another. Increased **government effectiveness** increases the state's abilities for **corruption control** and vice versa, creating a virtuous cycle between these two desirable conditions or a vicious one if either is decreased.

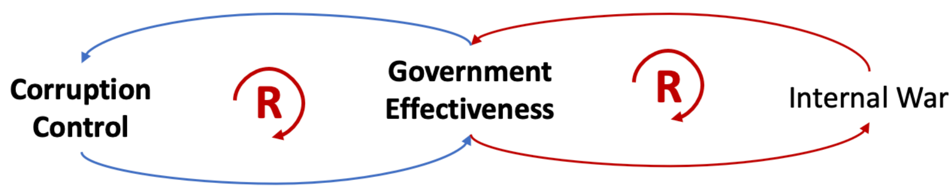

Figure 3. Government effectiveness - corruption - internal war nexus. Blue arrows = positive influence, red arrows = negative influence

Similarly, **government effectiveness** is in a reinforcing loop with **internal war**. **Government effectiveness** decreases the likelihood of **internal war**, but **internal war** decreases **government effectiveness**. Therefore, increasing **government effectiveness** can lead to a virtuous cycle in which the states' ability to quell internal violence, and thus the likelihood of

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[12] The Correlates of War (COW) Non State Actors database records the presence/absence of internal war excluding Islamic terrorism; internal wars are defined as "intra-state wars have been subdivided into three general types, based upon the status of the combatants: civil wars involve the government of the state against a non-state entity; regional internal wars involve the government of a regional subunit against a non-state entity; and intercommunal wars involve combat between/among two or more non-state entities within the state." The COW data were supplemented with additional personal research.

[13] Fragile public services is a metric from the Fund for Peace Fragile States Index database and is defined as fragility in a state's ability to "provision of essential services, such as health, education, water and sanitation, transport infrastructure, electricity and power, and internet and connectivity. On the other hand, it may include the state's ability to protect its citizens."

[14] Not all corruption is alike. In this report "corruption" refers to "grand corruption" rather than "petty corruption." Grand corruption refers to abuses of elite power at the expense of most of the population, and cause serious and widespread harm to individuals and society who may see it as the few stealing from the many. It includes activities like state capture, political corruption, and administrative corruption. "Petty corruption" on the other hand, refers to the abuse of entrusted power by public officials in their interactions with ordinary citizens, who often are trying to access basic goods or services in places like hospitals, schools, police departments and other agencies. This includes activities like petty bribery.

[15] World Bank database, "Control of Corruption - perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests."

internal war, is decreased, which in turn can increase **government effectiveness**. However, low or decreasing government effectiveness can generate a vicious cycle in which **internal war** further decreases **government effectiveness**, which in turn increases the likelihood of further **internal war**. **Government effectiveness** is not the only node that **influences internal war**. In addition, **political polarization**, **political violence**, and **factionalized elites** contribute to the likelihood of **internal war** in the system dynamics model. **Political polarization** increases the most through time in the system dynamics model, enabling it to have the greatest direct, one-way effect on **internal war**. Therefore, the two most important drivers of **internal war** appear to be political polarization and its reinforcing relationship with **government effectiveness**.

In the system dynamics model, **internal war** and **corruption control** experienced non-linear changes through time as a result of their reinforcing relationships with **government effectiveness**. There is a nexus of two conjoined reinforcing loops, united by **government effectiveness** whose reinforcing effects impact other nodes in the system. The example of undernourishment illustrates this effect.

Simply Providing Food Cannot Cure Undernourishment

Government effectiveness and **corruption control** each are positioned in the network model to decrease the **percent undernourished**, (e.g., by efficient distribution of foreign aid, or government provision of health and food aid) while **internal wa**r is positioned to increase the **percent undernourished** (e.g., by destroying food production and distribution in conflict zones or causing population displacement). However, their effects alone are not very strong. What is likely to drive the *extent* to which **internal war**, **government effectiveness**, or **corruption control** impact **percent undernourished** is the reciprocal dynamics of the relationships between the nodes with reinforcing relationships, not their direct relationships to undernourishment. The operational implication of this is that addressing undernourishment requires breaking vicious cycles or enhancing virtuous cycles in the **government effectiveness** – **corruption** – **internal war** nexus. Otherwise, a lack of **government effectiveness** or **internal war** may easily overwhelm the effect of direct food aid.

Terrorism Begets Terrorism

Terrorism is involved in six simultaneously reinforcing loops in the Sahelian network model. It is positioned to reciprocally increase **political polarization**, **political state terror**,[16] **foreign malign information (disinformation)**,[17] **factionalized elites**, **political violence**, and **fragility of public services**. In other words, in the model there are six different ways that **terrorism** directly creates conditions that foster its own acceleration; once **terrorism** begins, it is positioned to beget more **terrorism** in multiple ways. In the system dynamics model, terrorism increases exponentially through time. This effect is driven primarily by reinforcing loops with **factionalized elites** and **foreign malign information**, and by one-way effects from **political polarization**, **fragility of public services**, **political violence**, and **political state terror** in the system

[16] Political state terror is measured with the US Department of State Political Terror Scale, which “measures ‘state terror’: violations of physical or personal integrity rights carried out by a state (or its agents) (Wood & Gibney, 2010).”

[17] Foreign disinformation was measured with the Varieties of Democracy Digital Society Project score with the question, “How routinely do foreign governments and their agents use social media to disseminate misleading viewpoints or false information to influence domestic politics in this country?”

dynamics model. The only buffer that decreases the likelihood of terrorism is **government effectiveness**. The system dynamics model indicates that these factors, however, have vastly different potential to impact terrorism. **Political polarization** and **foreign malign information** increase **terrorism** the most, and in an exponential fashion due to their reinforcing relationships with each other. An exponential increase in **internet users** also fuels the consumption of **foreign malign information**. Therefore, according to the Sahelian system dynamics analysis, these are primary drivers of, and those most influenced by, terrorism in the system. **Political state terror**, **government effectiveness**, and **factionalized elites** are also reciprocally related to **terrorism**, but they change more slowly and in a linear fashion, indicating that they are less dramatic drivers.

The relative effects of these loops are sufficiently similar that mitigating terrorism requires attacking at least six problems at the same time and using multiple DIMEFIL[18] levers to do so. For example, the model suggests that effectively breaking the network of multiple vicious cycles that fuel terrorism in the Sahel might involve coordinated support to a government's provision of public services, using military security cooperation and diplomatic pressure to professionalize host nation security forces to minimize political state terror, offering military support in suppressing political violence, and diplomatic efforts to minimize **political polarization** and **factionalized elites** (see section Conclusion: Operational implications of Sahelian computational modeling for suggested operational implications).

Increasing Use of Online Media Could Spur Political Polarization and Instability in the Sahel

As Africa modernizes, popular consumption of **online media**[19] is increasing rapidly (Chin, Callaghan, & Ben Allouch, 2019; Kuznar, 2023). The Sahelian system dynamics model indicates that consumption of this information is a major enabler of **foreign malign information**, which in turn drives **political polarization**. Moreover, the analysis showed that an increase in **political polarization** can spur a dramatic and exponential increase in **terrorism.** The implication is that increasing political instability could follow growing consumption of **online media** across the region and ultimately contribute to increased incidence of **internal war** and **terrorism** (see Piazza, 2022 for a statisical analysis of foreign disinformmation and terrorism).

Ineffective and Violent Governments Increase Emigration

Migration, and especially irregular **emigration** (i.e., migration outside of legal controls), is also a major concern for USAFRICOM. The analyses indicate a complex interaction of push factors (violence, corruption) and enablers (income) that combine to drive **emigration**.[20] In the system dynamics model, **emigration** from the Sahel countries was driven by a devastating combination of conditions: decreasing **government effectiveness** compounded by failures of **corruption control** and violent government

[18] DIMEFIL stands for Diplomatic, Information, Military, Economic, Financial, Intelligence and Law Enforcement
[19] Consumption of domestic online media is a measure taken from the V-dem Digital Society Project.
[20] This aligns with other empirical studies of irregular migration (see Olson & Olson, 2021; Van Hear, Bakewell, & Long, 2018; von Uexkull & Buhaug, 2021 for empirical research on push and pull factors in irregular migration).

repression (**political state terror)** against civilians create the impetus, while rising **income per capita** gives more people means to emigrate. Interestingly, in both the network model and the system dynamics model, the effects of **climate change**[21] had virtually no impact on **emigration**. This may be due to the small changes in temperature compared to larger changes other nodes in the system that impact migration. Nonetheless, the models indicate that dramatic cascading effects from climate change have not yet occurred, corroborating recent empirical studies (Gemenne, 2011; Hoffman, Dimitrova, Muttarak, Cuaresma, & Peisker, 2020; Kaczan & Orgill-Meyer, 2020; Kuznar & Day, 2021a; Kuznar, Kuznar, & Aviles, 2019; Nawrotzki & DeWaard, 2018).

The positive correlation between **emigration** and income may seem counter-intuitive, but actually mirrors widespread findings, especially for the African continent; migration requires resources, and it is actually people of middle income that are more likely to move away from threats such as violence and undesirable conditions, such as ineffective government and corruption, and toward greater economic opportunities (Cummings, Pacitto, Lauro, & Foresti, 2015; Nawrotzki & DeWaard, 2018). The Sahel system dynamics model also indicates that **internal war** leads to **emigration**, although this is a well-known phenomenon in civil wars as it is people who have resources who can flee conflict (Abel, Brottrager, Cuaresma, & Muttarak, 2019). Research on African irregular immigration identifies key push and pull drivers. The primary pull is economic opportunity. However, violence, both political and non-political, are key push factors (Cummings et al., 2015; Giménez-Gómez et al., 2019; Kuznar et al., 2019). Poverty itself is not a driver because, as noted, it takes resources to uproot one's life for escape or opportunity. The Sahelian system dynamics model captures the dynamics of the push factors (**internal warfare** especially) and the enabling effect increased income has on **emigration**, possibly accounting for irregular emigration dynamics currently observed in the Sahelian countries.

The Sahelian Ecosystems of Ecosystems

When interrelated variables are seen as systems, each has its own ecosystem of direct effects that expands as variables connected at 2nd and 3rd orders are added. However, as the results of the network and system dynamics models demonstrate, in a sufficiently dense system of connections these separate ecosystems inevitably overlap, creating a larger ecosystem of ecosystems. In the three ecosystems examined in this report, **government effectiveness**, **terrorism**, and **emigration**, the same nodes have been mentioned repeatedly, demonstrating their interconnections. None of these problems occurs in a vacuum; what happens in one impacts the others. For instance, a lack of **government effectiveness,** particularly in the provision of security**,** is an important antecedent to **terrorism**. At the same time, nodes impacting political instability, such as **internal war** and **corruption,** can diminish **government effectiveness**. In this way, the indirect effects of as **internal war** and **corruption** are felt though diminished **government effectiveness**, explaining how they indirectly fuel **terrorism** in the Sahel. Similarly, as **internal war** increases, **government effectiveness** decreases and a rise in **emigration** is expected. A state's resort to use of **political state terror** drives **terrorism** in the model as well. **Political polarization** can spur **internal war** and **terrorism**. **Factionalized elites** drive **terrorism** and **political violence**, which in turn drive **internal war** and so on. The Sahel, and certainly the African continent, constitutes a complex ecosystem of

[21] Climate change was measured as temperature change from the 1951 to 1980 average baseline.

ecosystems. Understanding the dynamics of this system-of-systems can aid operational planning, which is explored in the concluding section.

These findings are only a few of the insights that could be drawn from this effort and were selected to reflect the strongest relationships in the Sahelian models of interest to USAFRICOM. Many more are possible with the models in their current state of development, although the models should be further developed and refined before being fully exploited. The following sections provide detailed descriptions of each of the approaches, empirical analysis, and network and system dynamics modeling used in this effort.

Operationalizing AECM to Generate the Sahelian System

The first step in tailoring the AECM to conditions in the Sahel involved three steps that began with deriving a subsystem of nodes from the AECM associated with USAFRICOM's enduring mission objectives and key concerns in the Sahelian region. This step created a subsystem of thirty-five nodes and the relationships among them. The second step was to represent the nodes of the Sahelian subsystem with empirical measures, and the third was conducting regression analysis with those measures to determine the functional relationships between nodes in the model. Three subsets, or ecosystems, in the Sahelian models will be examined: **government effectiveness**, **terrorism**, and **emigration**. Nodes common to these three systems are indicated in bold in the Figures to facilitate comparisons of where these smaller sub-systems interconnect.

Representing the Sahelian Subsystem Nodes in Data

The relationships between nodes in the AECM are based on theoretical or empirical relationships proposed in academic research for the African continent as a whole (Astorino-Courtois et al., 2022). However, the extent to which these relationships hold in a specific region of the continent should be tested. To do so, the SMA team assembled empirical metrics from publicly available sources. Data metrics were chosen to reflect the concepts in the AECM as closely as possible. However, in some instances the limitations of using available empirical data to operationalize AECM nodes required use of measures that were conceptually related, but not defined in precisely same way as is in the AECM. For example, **education access** is defined in the AECM as "access to education and training" whereas the proxy data measure used in the Sahelian models was **tertiary education** defined as "the percent of the population that receives post-secondary education." The constructs overlap but are not identical, as for example the AECM and Sahelian model operationalizations of **global warming** as changes in land temperature relative to a baseline period. Where multiple proxy measures were available to represent an AECM node, regression analyses were compared to determine which metrics performed best.

The 53 countries that make up the USAFRICOM AOR are basic units of analysis for the Command are often basic units for academic empirical analyses, and data are most often aggregated and reported at the country and year level. One hundred and seventy-two metrics were chosen from 25 different datasets, including the World Bank, the International Monetary Fund, US government sources, Fund for Peace, Varieties of Democracy, Correlates of War, Polity V, EM-DAT, and GDELT. A full accounting of metrics, their definitions, their relationships to the GECM node definitions, and sources is found in the Computational Model Data Catalogue.[22]

Regression Analyses to Determine Edge Relationships

Regressions were run on the first-order relationships posited in the AECM. Africa is a diverse continent environmentally, demographically, economically, culturally, and politically. Because the Sahelian countries are very similar on many of the metrics, they represent a restricted range of data points. Therefore, regression analyses were performed on data from the entire continent in order to capture the full functional relationships between nodes represented in the Sahelian models. Panel regressions were used, correcting for the idiosyncrasies of time and country.

The direct (first-order) relationships between nodes in the AECM can be represented by either linear or non-linear regressions. There were 190 relationships, or edges, between the 38 nodes in the Sahelian model. Simple linear regressions indicated that 79% of the relationships between nodes were linear and in the expected direction or statistically significant. Twenty-one percent of the relationships in the system were non-linear and in the expected direction or statistically significant. Quadratic relationships (low and high levels on a node produce extreme values on another) were present in 12% of the relationships. Logarithmic relationships accounted for 5%, power relations (one node in a pair raised to a power) accounted for 2.6%, and exponential relationships (*e* raised to the power of a node) accounted for 1% of the relationships (Table 1).

Table 1. Functional relationships between nodes in the Sahelian model

Function Type	Number	Type Percent	Statistically Significant	Statistically Significant Percent	Expected Direction	Expected Direction Percent	Significant or Expected	Significant or Expected Percent	Refuted	Refuted Percent
Linear	152	80%	71	73%	55	87%	126	79%	26	87%
Quadratic	22	12%	16	16%	4	6%	20	13%	2	7%
Logarithmic	9	5%	7	7%	2	3%	9	6%	0	0%
Power	5	3%	2	2%	1	2%	3	2%	2	7%
Exponential	2	1%	1	1%	1	2%	2	1%	0	0%
Total	190	100%	97	100%	63	100%	160	100%	30	100%
Percent Total	100%		51%		33%		84%		16%	

Linear relationships were by far the most common, and the analyses showed that 126 (79%) were statistically significant and these were generally weak. Non-linear relationships accounted for 21% of the relationships that were at least in the direction expected. Although in most cases, the direction of the non-linear relationships actually had a buffering effect (i.e., negative coefficients for quadratic, power, and exponential relationships) that would inhibit change. Only five non-linear relationships would directly accelerate change as follows. Of the 16 statistically significant quadratic relationships, four had positive coefficients (Figure 4); only one exponential relationship has a positive coefficient, indicating a potential for accelerating effects. **Inequality** (measured by the Gini coefficient)[23] technically has a non-linear

[22] Data sources and use rights are found in the Computational Model Data Catalogue. To receive a copy of the data catalogue, please contact Dr. Allison Astorino-Courtois at aastorino@nsiteam.com or Dr. Katy Lindquist at klindquist@nsiteam.com.

[23] From World Bank database: "The Gini index measures the extent to which the distribution of income or consumption among individuals or households within an economy deviates from a perfectly equal distribution. A Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality."

relationship to the **unemployment rate**. However, it had a very small coefficient rendering this relationship practically linear.

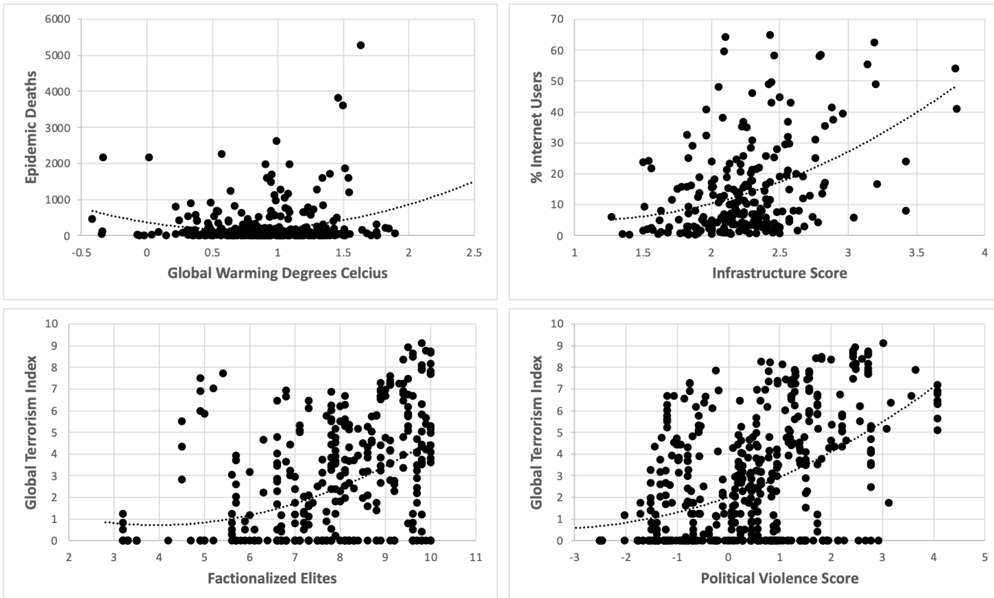

Figure 4. Quadratic accelerating relationships between AECM nodes

In terms of validating the AECM relationships included in the Sahelian models, most were in the expected direction and statistically significant (51%). Another third was not statistically significant but was in the expected direction. Given the proxy nature of the data and the uniqueness of Africa compared to the rest of the world, we think that 84% of the hypothesized relationships meeting expectations validates the generalizability of the GECM and AECM conceptual models. The coefficients from these regressions will form the empirical basis for the subsequent network and system dynamics models.

Analysis of the Sahelian Network Model

Only statistically significant relationships uncovered in the regression analyses were used to build the Sahel network model to ensure that the model had the soundest empirical footing. Furthermore, several metrics (e.g., Fragile States Index, World Bank Political Stability Index) were aggregates of other metrics and were excluded because they redundantly represented other nodes already in the model. Because of this down selection, the final Sahel network model contained 32 nodes and 77 edges. Standardized coefficients[24] from the regressions were used as weights for the relationships, or edges, in the graph representing the Sahel network model (Figure 5). Edges in the graph are proportional to their edge weights and depict the generally weak connections between nodes in the system.

[24] Standardized coefficients render coefficients from different regressions comparable in scale and therefore a reasonable weight for the edges in a network graph.

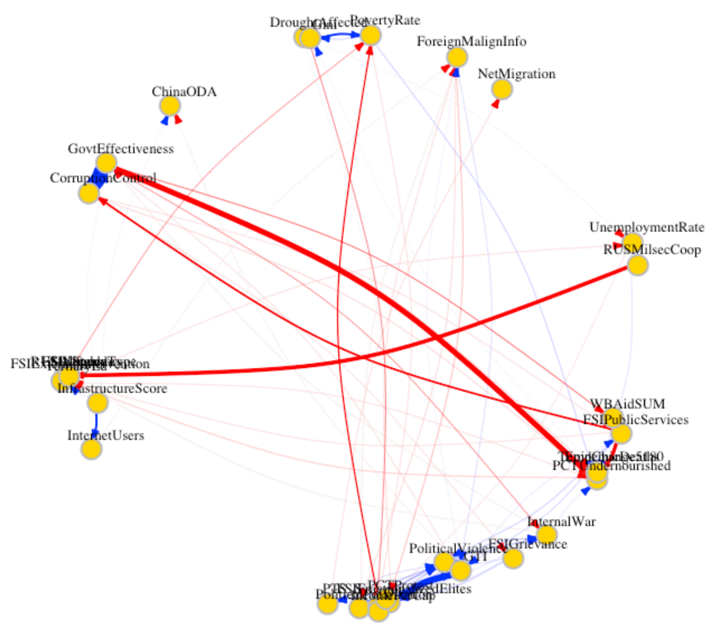

Figure 5. Sahel network graph. Line width proportional to strength of relationship
Blue arrows = positive influence, red arrows = negative influence

It is important to note that network analysis assesses the structural properties of a network and therefore identifies nodes that are *positioned* to influence the system. Actual influence depends on the flows of influence between nodes and how those flows percolate through the system. For instance, information operations are positioned to influence political stability, but only if they are conducted effectively. System dynamics models are suited to assess flows of influence on a system (Forrester, 1968; Meadows, 2008) as described in Analysis of the Sahelian system dynamics model section. The network analyses presented here are assessments of potential impact based on positioning in the system, not actual flows of influence. However, an important first step in the analysis of a system is to identify nodes that have potential leverage in a system, and network analysis identifies those potentials. A node's "connectedness" is a measure of its potential impact in the system. A node that is poorly connected has fewer opportunities to impact or be impacted by the system, whereas a node that is highly connected has many opportunities to impact the system.

Centrality Analysis of the Sahelian Network Model

The density of the graph, the probability that two nodes are connected, is 0.08 and its mean distance is 2.64 (i.e., nodes were, on average, 2.64 degrees, or steps, apart from one another). These figures indicate that the Sahelian network is fairly sparse—that is, there are not many connections between all of the nodes—and that a node has, on average, an effect at about three degrees of separation.

Ten network analysis centrality measures were used to assess a node's connectedness within the Sahelian model.[25] Overall, centrality is important to establish a node's potential to impact and to be impacted by the system. Impacts *on* the system measure downstream effects and therefore identify potential drivers in the system. This analysis identifies the relative strength of potentially causal relationships, but the precise mechanisms require further exploration. If these nodes can be influenced, then they represent key leverage points, or places to intervene to affect changes in the system. The precise ways and means for interventions require a closer analysis but the centrality helps to narrow the search space and by identifying the nodes with greatest potential influence. If they cannot be influenced, then they represent

[25] Centrality metrics were also used to assess the relative connectivity of each node in the full GECM model. A description of this analysis can be found in Appendix: Full GECM Centrality metrics.

drivers that must be monitored. If a node is indicated as highly impacted *by* the system and it is of national security concern, then decision makers should consider whether the nodes impacting it can be influenced or if not and how that impact might be achieved.

The centrality metrics were binned in terms of outward (i.e., downstream effects) influence[26] and inward (i.e., are affected by the system) influence[27] to analyze the network. The result of this analysis indicated that there are six nodes positioned to exert disproportionate influence on the system (Figure 6), and six nodes positioned to receive disproportionate influence from the system (Figure 7). By far, **government effectiveness** is positioned to have the greatest effect on the Sahel system; it scored two standard deviations above the mean for outdegree and three standard deviations above the mean for Kleinberg hub centrality[28] and 1st – 3rd degree effects. In other words, **government effectiveness** is directly connected to many nodes, is connected to other nodes that likewise have strong outward effects, and is connected to other nodes through many 1st to 3rd order pathways. The other nodes that scored high on outward effect were **terrorism**, **political polarization**, **political violence**, f**ragile public services**, and **factionalized elites**.

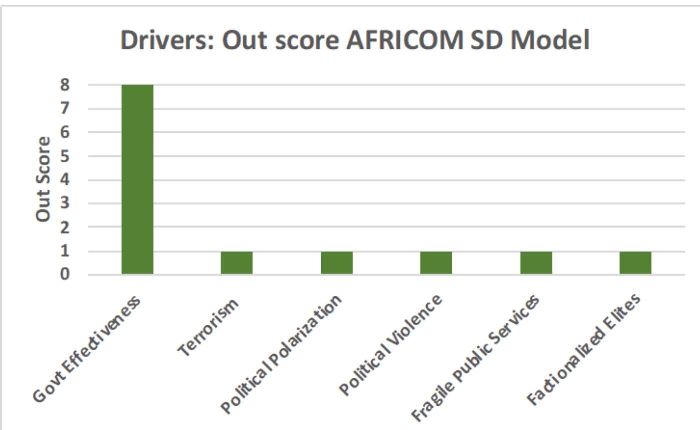

Figure 6. Network drivers in the AECM Sahel system

In terms of nodes positioned to receive disproportionate influence, **corruption control** scored highest. This was because its Kleinberg authority centrality score is three standard deviations above the mean. This indicates that **corruption control** is indirectly affected through other, highly connected nodes and that controlling corruption would require influencing many indirect effects and may therefore be challenging. The rest of the nodes with high inward scores were **terrorism**, **percent of population undernourished**, **political polarization**, **political violence**, and **income per capita**, and they all scored highly due to having a large number of direct connections from other nodes (high indegree). Their high indegree scores indicate that they may be impacted more directly, although the multiple nodes that impact them would have to be influenced simultaneously, again making attempts to affect them challenging.

[26] The network metrics used to measure outward influence were outdegree, Kleinberg's hub centrality, and the sum of 1st – 3rd order effects, see Appendix: Centrality metrics.

[27] The network metrics used to measure inward influence were indegree and Kleinberg's authority centrality, see Appendix: Centrality metrics.

[28] Kleinberg hub centrality is a measure of how much influence a node has on other nodes by virtue of being connected to other highly centralized nodes. See Appendix: Centrality metrics for a fuller description.

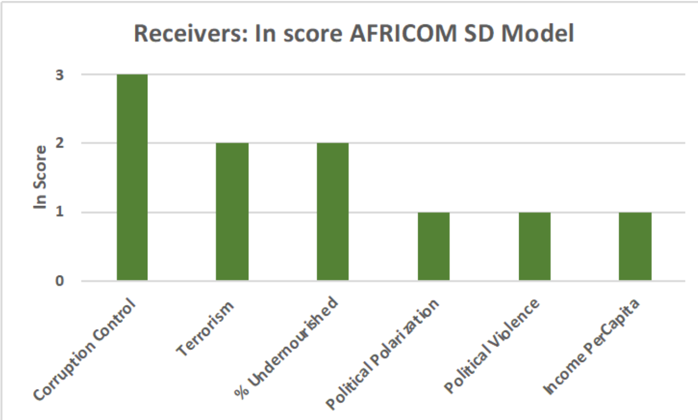

Figure 7. Network receivers in the AECM Sahel system

The high scores on both outward and inward centrality metrics for **terrorism**, **political polarization**, and **political violence** indicate a reinforcing effect of these nodes on themselves. **Reinforcing loops** create snowballing effects in which a node's influence recursively affects itself, thereby setting in motion a cycle of acceleration (Meadows, 2008). When these cycles are desirable, they are often referred to as virtuous, and when they are undesirable, they are referred to as vicious cycles creating negative runaway effects. Vicious cycles have the potential to increase rapidly, if not exponentially (see Analysis of the Sahelian system dynamics model section). These reinforcing effects can create flare-ups or, in extreme cases, transformations of the whole system (Meadows, 2008). Further analysis of how this system of connections positions nodes for these effects is explored below.

Drivers and Impacted Conditions in the Sahelian Operational Environment

The network analysis indicates that **government effectiveness** is positioned to have significant impact on the Sahel system. Its proximate ecosystem is represented by its direct and 2nd order effects.[29] It impacts five nodes directly, with indirect influences between them (Figure 8). There are two reinforcing loops in the system.

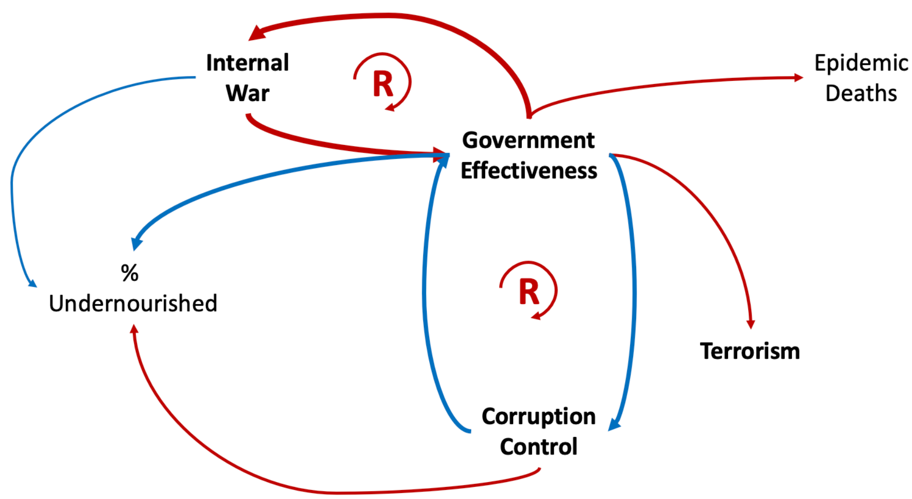

Figure 8. Government effectiveness network. Edges roughly proportionate to relative strength of connection. Blue arrows = positive influence, red arrows = negative influence. Nodes in bold are common to the subsystems described in this report.

The **percent of population undernourished** presents an interesting case where three nodes have a combined effect but where the reinforcing loops between these

[29] Only second order effects are examined here because a myriad of 3rd order effects complicates the analysis. Third order effects are treated separately below.

nodes can profoundly impact population undernourishment.

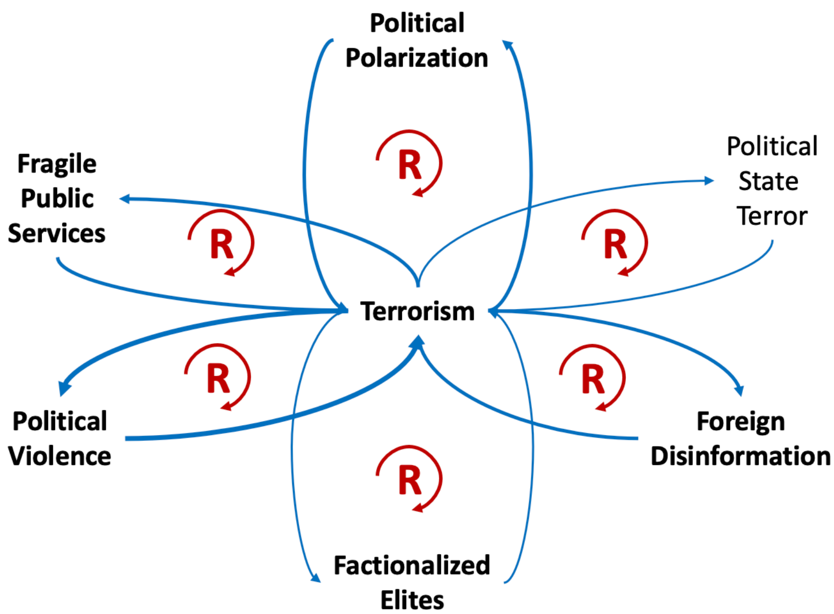

Figure 9. Terrorism network. Edges roughly proportionate to relative strength of connection. Blue arrows = positive influence, red arrows = negative influence. Nodes in bold are common to the subsystems described in this report.

As noted, **terrorism**, **political polarization**, and **political unrest** are both drivers and receivers of influence in the Sahelian system. The example of **terrorism** illustrates how the reciprocal effects of multiple reinforcing loops reinforce these phenomena (Figure 9).

Terrorism is involved in six simultaneously reinforcing loops. It is positioned to reciprocally increase **political polarization**, **political state terror**, **foreign malign information (disinformation)**, **factionalized elites**, **political violence**, and **fragility of public services**.

First Through Third Order Effects

Examining ***n*th order effects** provides a means of measuring the potential magnitude and sign of effects of one node upon another. First through third-order effects are examined here for three reasons. First, little empirical information is gained by going beyond the third order effects; in the AECM the correlation between first and second order effects is 0.700, between second and third order effects, is 0.747, and between third and fourth order effects is 0.975. The correlation asymptotically reaches 1.000 after fourth order effects. Second, the mean distance of 2.64 degrees of separation between nodes in the Sahelian model indicates that third order effects capture the average connectedness between nodes. Third, research on complex systems indicates that the influence of a node on a system diminishes rapidly beyond second order effects (Williams et. al., 2002) indicating that third order effects are most likely sufficient to capture meaningful downstream effects of one node upon another in most systems. Using network analysis to examine some of the strongest 1^{st} – 3^{rd} order effects in the system helps to illustrate how some individual nodes can drive others. The number of possible 1^{st} – 3^{rd} order pathways between two nodes is a measure of these potential downstream effects. In this analysis the 1^{st} – 3^{rd} order effects were normed to permit easy comparison of nodes' potential downstream effects *relative to one another*.[30] For example, a normed 1st – 3rd order effect of 0.33 has 1/3 as many 1st – 3rd order pathways than one with a value of 1.0.

Government Effectiveness, Public Services, and Corruption

The network analysis indicates that the strongest first through third order effects involve **government effectiveness**, the **fragility of public services**, and **corruption control**. The strongest 1st – 3rd order node in the Sahelian model is the potential effect of **government effectiveness** on **corruption**; therefore, its relative effect is normed to 1.0. **Government effectiveness** also has strong potential impacts on **percent undernourished** (-0.303) and is positioned to have positive 1st – 3rd order effects on **tertiary education** and, reciprocally, on itself (0.044). **Government effectiveness** is also positioned to have negative 1st – 3rd order effects on **internal war** (-0.032), the **fragility of public services** (-0.016), population **grievances** (-0.014), **terrorism** (-0.013), and **epidemic deaths** (-0.011). The **fragility of public services** is positioned to have a strong reciprocal effect on **government effectiveness** (-0.130). **Corruption control** is positioned to have a strong positive 1st – 3rd order effect on **government effectiveness** (0.027), a reciprocal effect on itself (0.046), and a strong negative effect on the **fragility of public services** (-0.010) and **percent undernourished** (-0.025). These results illustrate that investments in **government effectiveness** have downstream potential to impact a number of issues of concern to USAFRICOM positively by controlling corruption; reducing undernourishment; improving public services; reducing epidemic deaths; reducing grievance, terrorism, and the likelihood of internal war; and recursively improving government services, which can accelerate these positive results.

The findings from the Sahel network analysis suggests what key levers in the system may need to be targeted to support USAFRICOM's enduring objectives, but the analysis is based on the positioning of these nodes with respect to one another. To use an American football analogy, the network is the field formation, necessary for successful competition but not sufficient. At some point, the ball has to be snapped and the play has to begin. System dynamics modeling provides analysis of how the competition will unfold once that ball is snapped.

Analysis of the Sahelian System Dynamics Model

System dynamics modeling permits tracking influences throughout a system. It was developed by engineer Jay Forrester in the mid 1950s to model complex systems such as ecosystems and economies and was famously advanced by his student Donella Meadows and her colleagues through their Limits to Growth model, which simulated the sustainability of the global ecosystem and economy (Forrester, 1968, 1991; Meadows, Meadows, Randers, & Behrens III, 1972). System dynamics models are deterministic—they are based on modeling a system as a set of simultaneous differential equations that presumably have a solution. Because of their deterministic nature, new structures of the system cannot emerge from the

[30] The absolute number of pathways is a function of the size of the network and in itself is not informative. The 1st – 3rd order effects are normed by dividing the number of pathways between two nodes by the maximum number of pathways that exists between two nodes in the network, yielding a measure of relative potential influence.

system's interactions, as in other modeling approaches such as agent-based modeling (Holland, 1998; Kuznar & Sedlmeyer, 2005; Kuznar, Toole, & Kobelja, 2006; Lansing & Kremer, 1987). However, their strength is in their ability to track the dynamic flow of a currency (or influence) through a system. Therefore, they provide another way to identify a system's key drivers. Because they track dynamic flows, they can also be used for course of action analyses by altering the initial conditions of nodes or the rates of flow between them to gain insight into how impacts on levers may influence other nodes in the system.

Systems dynamics modeling has its own terminology. Fundamentally, the system is modeled as the **flow** of a currency between **stocks**. **Auxiliary variables** may be exogenous to the system or simply artifices required to transform one unit of influence to another (e.g., how much an increase in income changes the number of people who migrate). Stocks are things that can accumulate or deplete, for example, the number of people who migrate can rise or fall based on migration rates. Flows describe how a stock flows into or out of another stock or auxiliary variable and take the form of a function; for example, an emigration rate is a simple function that describes the flow of people out of a country. The nodes in the Sahelian model are generally modeled as stocks and the flows are represented as edges between nodes. The regression analyses that provided coefficients for the Sahel network model are used as the basis for the functional relationships that describe the flows in the Sahelian system dynamics model. Initially, only nodes with statistically significant relationships to other nodes were used in the Sahelian system dynamics model in order to base the model and subsequent analysis on relationships that had the soundest empirical footing. A few non-statistically significant relationships were added to complete necessary connections between nodes in the model. The resulting Sahelian system dynamics model has 23 nodes modeled as stocks, with 80 flows connecting them and closely resembles the network model although they are not a one-to-one match. The list of nodes and their connections are presented in Appendix: Sahelian system dynamics model nodes.

The model was constructed and then calibrated on data averaged for the African continent, since the original regressions were based on that data set. The regression equations describe the relationship between two nodes. As a first step in validating the model, the outputs were compared to continent averages through time. Because of averaging effects and scaling issues, a precise match was not expected. Instead, the coefficients from the regressions were used to establish the direction of the influence (positive or negative), as a first approximation of the magnitude of effect in the flow, and the functional form of the flow (linear vs. non-linear). The magnitudes of the coefficients were adjusted to bring model outputs within a reasonable range of historical data from 2000 to 2020. Once the model was calibrated, the initial values of the stocks and auxiliary variables were set for the average of the 26 Sahelian countries to yield a model representative of this region.

Findings From the Sahel System Dynamics Model

The utility of a system dynamics approach will be illustrated by examining nodes found to be central in the network model, as well as what the system dynamics model says about other USAFRICOM concerns such as migration. The model's findings are illustrated by comparing model predictions with historical data for the continent and projecting model results to 2025. Projections beyond 2025 are possible, but the farther beyond established historical baselines, the less reliable the results are likely to be.

The Government Effectiveness/Corruption Nexus

The Africa-wide baseline data indicate that the continent will see a slowly accelerating decrease in **government effectiveness** through time, closely matching historical data in which **government**

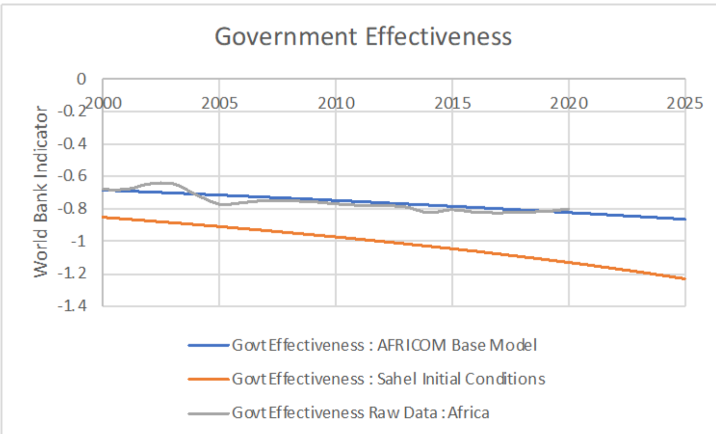

Figure 10. AECM Sahel model results: Government effectiveness

effectiveness decreased by 18% from 2000-2020 (Figure 10). The model parameterized with Sahelian initial values shows a similar gradually accelerating decline. Of more interest is what drives the decreasing government effectiveness in the model.

The subsystem surrounding **government effectiveness** in the model illustrates the nodes that directly increase it (**infrastructure score** and **corruption control**) and those that decrease it (**internal war**) (Figure 11).

Infrastructure score did not change over the time scale of the simulation and therefore is not causing any change in **government effectiveness** and not depicted in Figure 11. As shown in Figure 12, **internal war** and **corruption control** did show non-linear changes through the time frame: **internal war** increases by 68% and **corruption control** decreases by 27%. Note also that the two nodes that most influence **government effectiveness** have reciprocal relationships, or in systems terminology, are part of reinforcing loops.

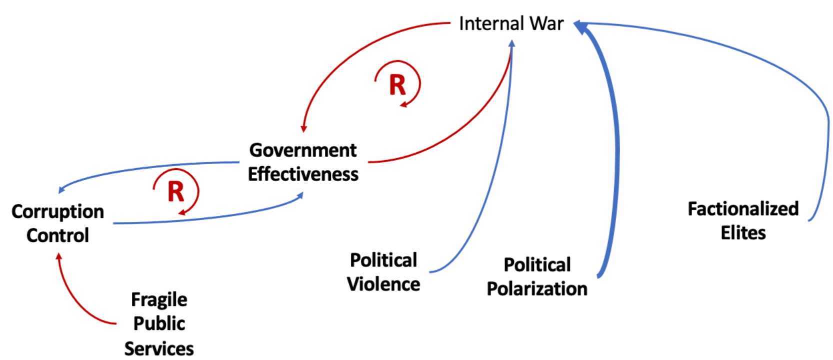

Figure 11. Sahelian system dynamics ecosystem. Blue arrows = positive influence, red arrows = negative influence. Flows roughly proportionate to influence in the system. Nodes in bold are common to the subsystems described in this report.

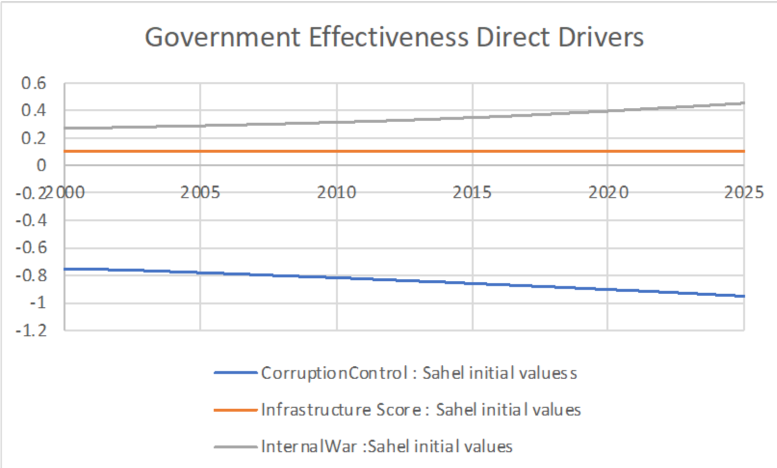

Figure 12. Sahelian system dynamics government effectiveness drivers

Indirect effects can be key to driving changes in nodes, and a system dynamics model enables examination of what indirect drivers might be, or what nodes are feeding these reinforcing loops. **Internal war** increases 68% in the model. **Government effectiveness** decreases by 44% and **factionalized elites** increases by 38%, contributing to the likelihood of **internal war**. However, the primary drivers of **internal war** are **political violence** (increases by 161%) and even more so **political polarization**, which increases by 1096% in the model. In the case of **corruption control**, **government effectiveness** decreases by 44% over time and the **fragility of public services** increases by 9% over time, indicating that **government effectiveness** is the primary driver of **corruption control** with a secondary effect of public services. Note that the effect of **government effectiveness** on **corruption control** is a reinforcing effect in the system.

The Pernicious Reinforcing Effects of Terrorism

Countering non-state terrorist violence is a key USAFRICOM objective. The Sahelian system dynamics model provides a number of insights into the dynamics that drive terrorism and why it is so pernicious and intractable.

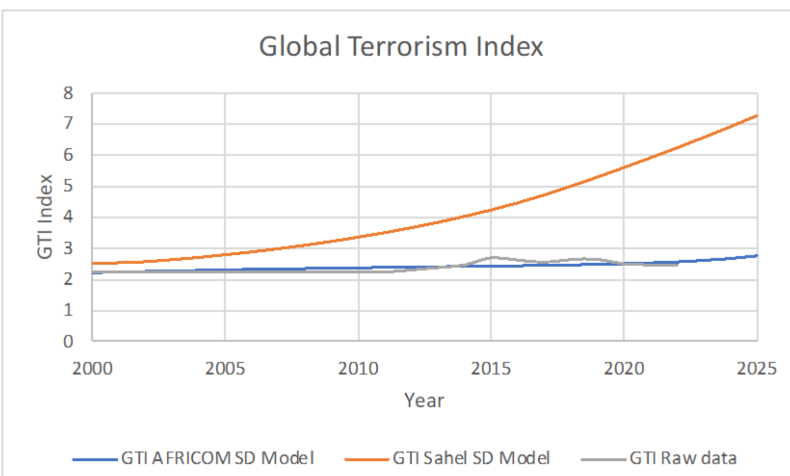

Figure 13. AECM Sahel system dynamics model results: Terrorism

The calibrated Africa-wide base model predictions for **terrorism** are extremely close to the historical data for the continent. When initialized for the Sahel, terrorism increases 191% in an exponential trend (Figure 13). This effect is driven primarily by increasing **factionalized elites**, **political polarization**, **fragility of public services**, **foreign malign information**, **political violence**, and **political state terror** (Figure 14). The only buffer that decreases the likelihood of terrorism is **government effectiveness**. **Government effectiveness** is likely to buffer against terrorism because it provides for effective security, provides government revenues that can be turned into public services that can limit grievances, and probably most important, limits corruption, which is strongly associated with terrorism (Brooks, 2012; Coggins, 2015; Kuznar & Day, 2021b; Pelletier, Lundmark, Gardner, Ligon, & Kilinc, 2016; Plummer, 2012). The model indicates that these factors, however, have vastly different potential to impact terrorism. **Political polarization** and **foreign malign information** increase the most rapidly, 1096% and 718% respectively, and in an exponential fashion. Therefore, according to the Sahelian system analysis, these are primary drivers of, and those most influenced by, terrorism in the system. However, **political violence** increases by 162% in the system, making it a candidate driver as well. **Political state terror** (47% increase), **government effectiveness** (44% decrease), and **factionalized elites** (38%) are also reciprocally related to terrorism, but they change more slowly and in a linear fashion.

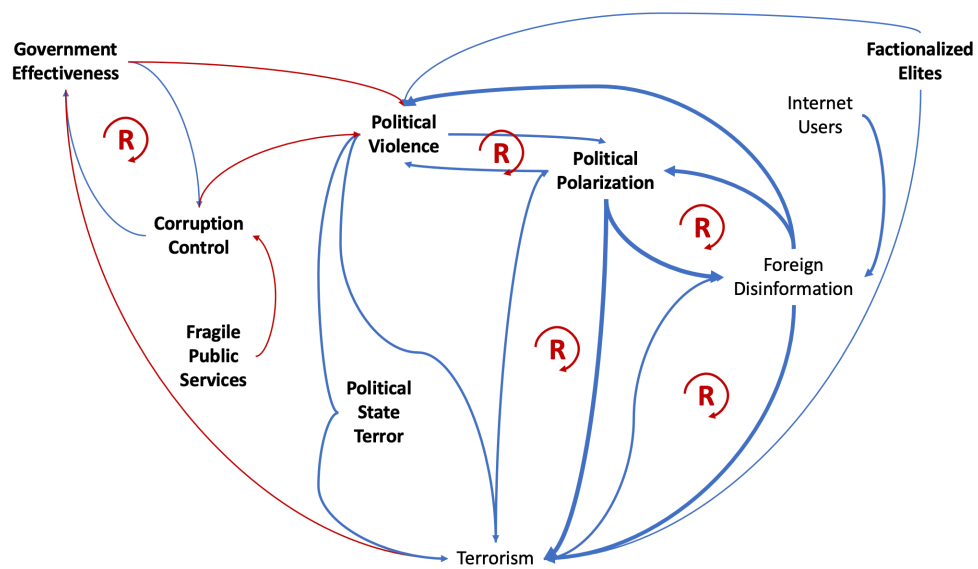

Figure 14. Sahelian system dynamics terrorism ecosystem. Blue arrows = positive influence, red arrows = negative influence. Flows roughly proportionate to influence in the system. Nodes in bold are common to the subsystems described in this report.

The drivers of **political polarization** are familiar characters in the Sahel ecosystem of political instability and include **foreign malign information**, **terrorism**, and **political violence**, each of which increases substantially and exponentially in the model as already described.

A fourth driver, population **grievance**,[31] changes very little (increases only 0.3%) and is therefore unable to account for the change in **political polarization**. **Foreign malign influence** is driven by several factors that increase dramatically in the model. The dramatic increases in **political polarization** and **terrorism** have already been described. **Factionalized elites** increase a more modest, but still significant, 38%. However, the exponential rise in **internet users**, increasing 144-fold, clearly emerges as the primary driver of **foreign malign influence**. **Political violence** is driven by a familiar set of factors, including **political polarization**, **foreign malign information**, **political terror**, **government effectiveness** (lack thereof), **factionalized elites**, and corruption. **Corruption control** changes the least of these factors (decreases 26%) in the model.

[31] Grievance is measured with the Fund for Peace Fragile States Index grievances index.

The Migration Ecosystem

The Sahelian system dynamics model indicates that **emigration**[32] from Sahelian countries will increase linearly and rapidly by nearly ten-fold through 2025 (Figure 15). This prediction does not track with the World Bank net migration statistics used for the model. However, the World Bank notes that estimates of migration are unreliable, and they use a variety of methods that do not necessarily account for irregular migration.[33] For instance, many African irregular migrants[34] come from the countries upon which the Sahel model is based (Giménez-Gómez et al., 2019; Mueller, Sheriff, Dou, & Gray, 2020). Therefore, the model may well be capturing a dynamic not recorded in official statistics. Exploring the model dynamics as to why this might be the case may shed light on these drivers.

Emigration is driven in the model by decreases in **government effectiveness**, **corruption control**, and increases in **income per capita** and **political state** (Figure 16). **Income per capita** increases linearly by 97% in the model, more than any factor and is therefore a candidate for the prime driver of **emigration** in the Sahel system. Other lesser drivers include **political state terror** and decreases in **government effectiveness** and **corruption control**.

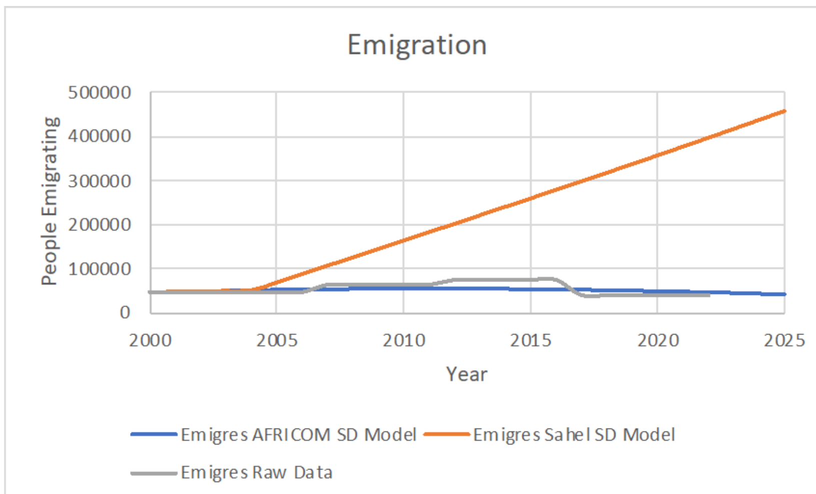

Figure 15. AECM Sahel system dynamics model results: Emigration

[32] Emigration figures are from World Bank net migration statistics.
[33] Please refer to the World Bank Metadata Glossary https://databank.worldbank.org/metadataglossary/population-estimates-and-projections/series/SM.POP.NETM
[34] The UN International Organization for Migration defines irregular migration as the "movement of persons that takes place outside the laws, regulations, or international agreements governing the entry or exit from the state of origin, transit or destination."

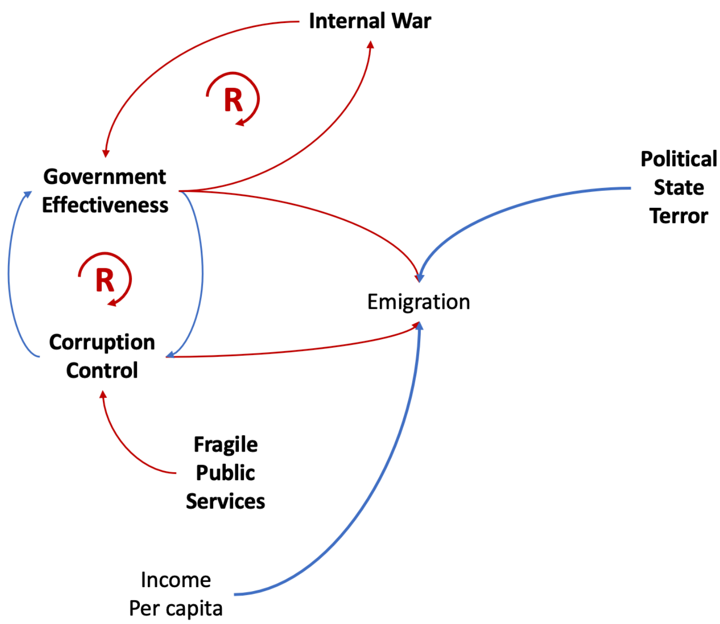

Figure 16. Sahelian system dynamics model emigration ecosystem. Blue arrows = positive influence, red arrows = negative influence. Flows roughly proportionate to influence in the system. Nodes in bold are common to the subsystems described in this report.

In terms of the indirect effects of **emigration**'s drivers, we have already described how **government effectiveness** is driven by two reinforcing loops between **internal war** and **corruption control** and how **corruption control** is driven in part by a government's ability to provide services.

Conclusion: Operational Implications of Sahelian Computational Modeling

SMA research does not suggest policy but is intended to inform policy choices and aid planning and operations. The analyses presented in this paper cover only a few of USAFRICOM's concerns and a fraction of the dynamics that exist in the Sahelian system. This section reviews operational implications implied by these modeling exercises.

Strategic Patience. The empirical analysis of relationships between nodes in the Sahelian system indicate that the majority are linear or have non-linear dampening effects, both of which indicate that change in the Sahel will be slow and that effecting change will be difficult. Therefore, strategic patience will be necessary when operating in the region.

Government Effectiveness and Corruption Control. Empirical analysis and both computational models repeatedly demonstrated that **government effectiveness**, coupled in a reinforcing loop with **corruption control**, is a prime driver in the Sahelian system. This is because it is directly connected to many nodes and many of those connections are reinforcing loops that accelerate their effects, creating accelerating non-linear relationships in an otherwise linear and slowly changing system. Improving **government effectiveness** improves well-being (decreasing **undernourishment**, **epidemic deaths**, and the **fragility of public services**) and political stability (decreased corruption, likelihood of civil war, and terrorism). Furthermore, the models demonstrate that increases in **government effectiveness** recursively increase itself. It appears that controlling corruption and improving government effectiveness are better suited to the missions and authorities of interagency partners like USAID and the State Department. However, USAFRICOM can play a key role as mediator of these relationships though connections to the military of Sahelian countries, which are often keys to host nation political support and often implementers of on-the-ground actions to effect these changes or to protect actions as they are implemented.

The Danger of Polarization. **Political polarization** and **factionalized elites**, fueled by **grievances** (3rd order effect in the models not shown) have been identified in the models as drivers of **political violence**. **Grievances** can be material (conflict over resources, frustrations over economic inequality), political (lack of influence over governance or representation), or social (conflicts between ethnic or social identities) (Basedau, Fox, Pierskalla, Struver, & Vullers, 2017; Bormann, Cederman, & Vogt, 2016; Collier & Hoeffler, 2004; Klaus & Mitchell, 2015; Kuznar, 2007; Østby, 2008). The nature of grievances in a country needs to be assessed, and the extent to which they may be addressed through economic, diplomatic, or informational means needs to be evaluated. Once assessed, a variety of means for addressing them seem available.

The system dynamics model demonstrated a strong influence on **political polarization** and **political violence** from **foreign malign information**. Material grievances may be addressed through economic aid (USAID), political grievances may be addressed through diplomacy (Department of State, military attaches), and social grievances through combinations of economic development, diplomacy, and the enforcement of security through military security cooperation (USAFRICOM). Information operations, executed through Department of Defense resources and/or the Department of State's Global Engagement Center can play a role in mitigating the pernicious effects of foreign malign influence. However, the generally weak influences between **grievance** and other nodes in the model indicate that any means of addressing grievances are likely to have slow and marginal influences on the violence and factionalism they are meant to address. Once again, the models indicate the need for strategic patience in the Sahel.

Careful Attention to Possible Acceleration Points. Non-linear, accelerating direct (1st order) relationships existed in four cases. **Global warming** accelerates **epidemic deaths,** and improvements in **infrastructure** accelerate the numbers of **internet users**. These two relationships are potentially significant to USAFRICOM objectives since **epidemic deaths** are a measure of the severity of crises and the growth in **internet users** has a strong impact on the influence of **foreign malign information as discussed above**. Also, the presence of f**actionalized elites** and **political violence** have accelerating relationships with **terrorism**, in addition to their reciprocal reinforcing relationships. Unfortunately, among the 48 direct non-linear relationships tested, none could accelerate conditions favorable to US interests.

Non-state and State Political Violence. Because of the mutually accelerating effects of **terrorism**, **political violence**, and **factionalized elites**, attempts to break their effects may be particularly challenging. USAFRICOM is directly engaged in counterterrorism efforts. If these are successful, they could have important follow-on effects on several other USAFRICOM concerns. State-conducted p**olitical violence** can be more difficult to counter than operations by non-state actors (at least those operating in the territories of willing US partners). For instance, authoritarian regimes with high governing capacity can effectively repress dissent (Asal & Brown, 2022). North Korea, China, Russia, and Iran have successfully repressed dissent, and the authoritarian regime Zimbabwe's Robert Mugabe maintained control through repression for decades. However, government repression typically backfires for democracies and states with weak capacity (Kornblith, 2005). US policy precludes encouraging state-conducted political violence but efforts to curb non-state political violence, combined with efforts to train or otherwise encourage states to avoid state-conducted political violence, have the potential to break cycles that fuel terrorism.

Migration. Based on the modeling results, mitigating **emigration** should involve preventing push factors, such as **internal war** and **political state terror**, and increasing **government effectiveness** and **corruption control** to foster conditions that make staying more attractive. Diplomatic and military security cooperation could be instrumental in preventing internal war and military security cooperation, especially professionalizing security forces and instilling a respect for the rule of law, can potentially reduce **political state terror**. The means for increasing **government effectiveness** and **corruption control** have already been addressed. Ironically, USAID and other economic aid provided to Sahelian countries will have the unintended effect of enabling emigration, and development efforts should anticipate this unintended effect.

Because of the complex interrelatedness of nodes in the Sahelian system, exploring operational implications necessarily forces summarizing the findings from the empirical analysis and computational modeling efforts. These implications reinforce the genuinely complex nature of the Sahelian operational environment. Evidence is crucial for operational planning, especially since Sahelian dynamics are likely to differ from dynamics in other parts of the world. The empirical data gathered for this effort is an example of how to ground evidence-based planning. The complexities of the Sahelian operational environment become readily apparent in the modeling approaches, even though these models are simple relative to the complexity of factors in operation in the environment. Evidence-based computational modeling provides a means for understanding and operating in USAFRICOM's complex and difficult AOR.

Appendix: Data Sources and Use Rights

Metric Source	Name	Official citation (if any)	URL	Use Rights
AidData William and Mary	AidData	Custer, S., Dreher, A., Elston, T.B., Fuchs, A., Ghose, S., Lin, J., Malik, A., Parks, B.C., Russell, B., Solomon, K., Strange, A., Tierney, M.J., Walsh, K., Zaleski, L., and Zhang, S. 2021. *Tracking Chinese Development Finance: An Application of AidData's TUFF 2.0 Methodology*. Williamsburg, VA: AidData at William & Mary.	https://www.aiddata.org/data/aiddatas-global-chinese-development-finance-dataset-version-2-0	standard open data commons use
ATOP	Correlates of War Alliance Treaty Obligation and Provisions (ATOP) Project.	Leeds, Brett Ashley, Jeffrey M. Ritter, Sara McLaughlin Mitchell, and Andrew G. Long. 2002. Alliance Treaty Obligations and Provisions, 1815-1944. International Interactions 28: 237-260.	http://www.atopdata.org/data.html	can share with permission
COW Military Cooperation	Correlates of War	Kinne, Brandon J. 2020. "The Defense Cooperation Agreement Dataset (DCAD)." *Journal of Conflict Resolution* 64(4): 729-755.	https://correlatesofwar.org/data-sets/	can share with permission
COW War Data Set	Correlates of War	*Sarkees, Meredith Reid and Frank Wayman (2010). Resort to War: 1816 – 2007. Washington DC: CQ Press.*	https://correlatesofwar.org/data-sets/	
EM-DAT	Centre for research on the Epidemiology of Disasters		https://www.emdat.be	Registration required for use
FAO	Food and Agriculture Organization		https://www.fao.org/faostat/en/#home	Free access
Freedomhouse	Freedom House		https://freedomhouse.org/report/freedom-world	declared "open data"
FSI	Fund for Peace FFP Fragile States Index		https://fragilestatesindex.org	no apparent restrictions
GDELT	Global Database of Events, Language, and Tone		https://www.gdeltproject.org/data.html	declared "open data"

Global Hunger Index	Global Hunger Index		https://www.globalhungerindex.org/download/all.html	no apparent restrictions
Historical Index of Ethnic Fractionalization Dataset (HIEF)	Historical Index of Ethnic Fractionalization Dataset (HIEF)	Drazanova, Lenka, 2019, "Historical Index of Ethnic Fractionalization Dataset (HIEF)", https://doi.org/10.7910/DVN/4JQRCL, Harvard Dataverse, V2, UNF:6:z4J/b/PKbUpNdIoeEFPvaw== [fileUNF]	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/4JQRCL	standard open data commons use
IMF	International Monetary Fund		https://data.imf.org/?sk=9D6028D4-F14A-464C-A2F2-59B2CD424B85	
IMF bilateral trade data	International Monetary Fund		https://data.imf.org/?sk=9D6028D4-F14A-464C-A2F2-59B2CD424B85	
Institute for Economics and Peace	Global Terrorism Index		https://www.visionofhumanity.org/maps/global-terrorism-index/#/	IEP grants each recipient authorised by IEP a license to use this data only for its own internal non-commercial purposes." "the data may **not be distributed in excel format** to any person without IEP's consent"
Johns Hopkins SAIS China-Africa Research Initiative	Chinese Loans to Africa Database	China Africa Research Initiative and Boston University Global Development Policy Center. 2021. Chinese Loans to Africa Database, Version 2.0. Retrieved from chinaafricaloandata.bu.edu/.	http://www.sais-cari.org/data	
ND-GAIN	Notre Dame - Global Adaptation Initiative		https://gain.nd.edu/our-work/country-index/download-data/	
Political Terror Scale	Political Terror Scale	Gibney, Mark, Linda Cornett, Reed Wood, Peter Haschke, Daniel Arnon, Attilio Pisanò, Gray Barrett, and Baekkwan Park. 2022. The Political Terror Scale 1976-2021. Date Retrieved, from the Political Terror Scale website: http://www.politicalterrorscale.org/.	http://www.politicalterrorscale.org/	

Polity V	Polity V		https://www.systemicpeace.org/inscrdata.html	can share with permission
SIPRI	Stockholm International Peace research Institute	Fair use is freely authorized as long as due reference is given to the specific SIPRI source(s).”	https://www.sipri.org/databases	Fair use policy, defined as the excerption of SIPRI copyrighted material for such purposes as criticism, comment, news reporting, teaching, scholarship or research in which the use is for non-commercial purposes and the reproduction of less than 10 per cent of a published data set.
Transparency.org	Corruption Perceptions Index	*CPI (2022) by Transparency International is licensed under CC BY 4.0*	https://www.transparency.org/en/cpi/2021	no apparent restrictions
UN	United Nations		https://data.un.org	
USGS	United States Geological Services		https://www.usgs.gov/programs/mineral-resources-program/science/critical-mineral-resources	

V-dem	Varieties of Democracy	Coppedge, Michael, John Gerring, Carl Henrik Knutsen, Staffan I. Lindberg, Jan Teorell, Naz- ifa Alizada, David Altman, Michael Bernhard, Agnes Cornell, M. Steven Fish, Lisa Gastaldi, Haakon Gjerløw, Adam Glynn, Sandra Grahn, Allen Hicken, Garry Hindle, Nina Ilchenko, Katrin Kinzelbach, Joshua Krusell, Kyle L. Marquardt, Kelly McMann, Valeriya Mechkova, Juraj Medzihorsky, Pamela Paxton, Daniel Pemstein, Josefine Pernes, Oskar Ryďen, Johannes von R˙omer, Brigitte Seim, Rachel Sigman, Svend-Erik Skaaning, Jeffrey Staton, Aksel Sund- str¨om, Eitan Tzelgov, Yi-ting Wang, Tore Wig, Steven Wilson and Daniel Ziblatt. 2022. ”V- Dem [Country–Year/Country–Date] Dataset v12” Varieties of Democracy (V-Dem) Project. https://doi.org/10.23696/vdemds22.	https://www.v-dem.net/data/the-v-dem-dataset/	no apparent restrictions
WB	World Bank		https://data.worldbank.org	
WBI	World Bank Governance Indicators		https://databank.worldbank.org/source/world wide-governance-indicators	

Appendix: Centrality Metrics

Ten centrality metrics were used to assess the relative connectivity of each node in the full GECM system (Table 2). Guides to these metrics and their underlying algorithms are found in Bonacich (1987), Kleinberg (1998), and Wasserman and Faust (1994). Outdegree and indegree measure the direct, first order effects between nodes. Betweenness measures the extent to which a node joins other nodes. Closeness measures a node's accessibility to all other nodes. Eigenvalue centrality is one of the most often used centrality metrics; it measures the degree to which a node is central based on its connection to well-connected nodes. For instance, if one has only a few friends, but they each have many friends, one would be well-connected in a network of friends. The next four metrics are variants of eigenvalue centrality designed to assess the directionality and strength of influence in a network. Kleinberg authority centrality measures the extent to which other nodes link to it and is therefore a measure of how other nodes can potentially influence it. Kleinberg hub centrality measures the extent to which a node points toward well-connected nodes and is, therefore, a measure of how much information (i.e., influence) it sends throughout a network. Bonacich's alpha centrality takes into account the extent to which nodes are exogenous (i.e., have influence on other nodes). Bonacich's power centrality is based on a node's connection to poorly connected nodes; the power centrality score is high if the node is connected to "weak" nodes with few connections because it dominates the weakly connected nodes. The Bonacich centrality metrics may not be capturing the directionality of influence in the GECM and AECM networks in a manner appropriate to the kinds of nodes in these networks, which are influences of an operational environment versus individuals influencing other individuals and so are treated as general centrality metrics. The final centrality metric considered is 5th order effect, or a measure of the number and sign (positive or negative) of effects a node has five steps away. This is another measure of a node's "downstream" or outdegree effect on other nodes.

Table 2. Centrality metrics used to analyze node importance

METRIC TYPE	CENTRALITY METRIC	DEFINITION
General centrality	Betweenness	The number of times a node acts as a bridge along the shortest path between two other nodes.
	Closeness	Average length of the shortest path between a vertex and all others; weights must be positive.
	Eigenvalue centrality	Measure of the influence of a vertex; measures a vertex's degree and those of its neighbors and so on.
	Bonacich's alpha centrality	Eigenvalue centrality plus external influence (i.e. authority imbued from outside) on nodes. The alpha weight was set to 1, and all nodes were considered potentially exogenous, as were the default values
	Bonacich's power centrality	Based on the notion that being connected to others that are not well-connected makes one powerful because these other actors are dependent on you. One begins by giving each actor an estimated centrality equal to their own degree, plus a weighted function of the degrees of the actors to whom they were connected. An "attenuation factor" indicates the effect of one's neighbor's connections on ego's power. Where the attenuation factor is positive (between zero and one), being connected to neighbors with more connections makes one

		powerful. This is a straightforward extension of the degree centrality idea. Bonacich also had a second idea about power, based on the notion of "dependency." If ego has neighbors who do not have many connections to others, those neighbors are likely to be dependent on ego, making ego more powerful. Negative values of the attenuation factor (between zero and negative one) compute power based on this idea.
Impact on the system	Outdegree	Number of direct links to other vertices.
	N^{th} order effects	N^{th} order effects are those n steps away from a node. A measure of the number of possible nth order effects of one node upon another is given by raising the adjacency matrix of 1^{st} order connections by the nth power. The 3^{rd} order was used to ensure that a thorough consideration of downstream effects of one node upon another were fully considered.
	Kleinberg's hub centrality	Authorities contain information, hubs point to information. It is measured by the Eigenvector of A*t(A) where A is the adjacency matrix.
Impacted by the system	Indegree	Number of nodes with a direct link to a node.
	Kleinberg's authority centrality	Authorities contain information; hubs point to information. It is measured by the Eigenvector of t(A)*A where A is the adjacency matrix.

These centrality metrics were binned into those that represent general centrality (betweenness, closeness, eigenvalue, Bonacich's alpha, Bonacich's power), those that represent impact *on* the system (outdegree, Kleinberg's hub centrality), and those being impacted *by* the system (indegree, Kleinberg's authority centrality).

Appendix: Sahelian System Dynamics Model Nodes

Table 3 lists the stocks and the corresponding stocks or auxiliary variables to which they are connected in the AECM Sahel system dynamics model. Full definitions of their underlying metrics are found in the AECM modeling data catalogue.[35]

Table 3. AECM Sahel system dynamics model nodes

Stock	Connected Stocks/auxiliary variables
Drought Affected	Fragility of public services Global warming Government effectiveness
Net Migration	Government effectiveness Income per capita Corruption control Political terror
Percent Protest	Factionalized elites Political polarization Government effectiveness Corruption control
Percent undernourished	Poverty rate Internal war Fragility of public services Corruption control
Political violence	Factionalized elites Grievance Political violence Political polarization Foreign malign information Corruption control Government effectiveness
Political polarization	Terrorism Grievance Political violence Foreign malign information
Foreign malign information	Terrorism Political polarization Factionalized elites Percent internet users
Military spending	Terrorism Russian military security cooperation Proxies US military security cooperation Drought affected

[35] To receive a copy of the data catalogue, please contact Dr. Allison Astorino-Courtois at aastorino@nsiteam.com or Ms. Mariah Yager at mariah.c.yager.ctr@mail.mil.

	Internal war
Terrorism	Factionalized elites Political polarization Fragility of public services Foreign malign information Political terror Political violence Government effectiveness
Epidemic deaths	Global warming Government effectiveness Fragility of public services
Government effectiveness	Infrastructure score Corruption control Internal war
Fragility of public services	Terrorism Corruption control
Factionalized elites	Terrorism Political violence Grievance Foreign malign information
Internal war	Political polarization Factionalized elites Political violence Government effectiveness
Grievance	Poverty rate Corruption control
Russian alliances	Military spending US military security cooperation
Political terror	Internal war Political violence Government effectiveness Corruption control Foreign malign information
Corruption control	Government effectiveness Fragility of public services Chinese loans Oil prices
State fragility of neighbors	Internal war Foreign malign information Government effectiveness
Global warming	(exogenous stock)
Income per capita	(exogenous stock)
Percent internet users	(exogenous stock)

Appendix: Lessons Learned in Creating a Computational Model of the Sahelian System

Empirical analyses are necessary for evidence-based decision making and computational modeling permits capturing the complexities of real-life systems. However, each methodology has its limitations as well as its strengths. This section reviews these limitations and provides suggestions for how the work presented in this report can be advanced to provide increasingly valid insights. The limitations include problems with evidence, limits of a network, and limits of systems dynamics modeling. The section concludes with suggestions for advancing the system dynamics modeling presented in this report.

Problems With Evidence

Evidence-based decision making is critical to overcome the preconceptions and biases of decision makers. However, evidence is imperfect, and the data never simply speak for themselves. Several limitations that should always be kept in mind include scale, accuracy, and the effect of proxy measures.

Scale & aggregation. The scale at which a phenomenon occurs and the extent to which data are aggregated can have profound effects on what data can represent. This is best illustrated by the ecological fallacy, or attributing what is true in the aggregate to smaller units. It is true that countries with higher fat consumption rates have higher rates of breast cancer. However, there is no statistical relationship between fat consumption and breast cancer in samples of individual women. Ecological fallacies commonly occur when there is inequality in data, as is common in income and food consumption. However, no obvious ecological fallacies were found when comparing aggregate data from the African continent and individual regions or countries. Nonetheless, the potential problems of aggregating data should always be born in mind.

Accuracy. Gathering data from different countries with differing levels of institutional support for data gathering, or differences in individual skill in data gathering, is a constant problem when gathering data and making comparisons across the world. The metrics used in this study were carefully chosen to be among the most accurate possible. However, the data sources are all candid about just how accurate and reliable the data are. The following excerpt from the World Bank Metadata Glossary[36] on its Migration data illustrate the point.

> The United Nations Population Division provides data on net migration and migrant stock. Because data on migrant stock is difficult for countries to collect, the United Nations Population Division takes into account the past migration history of a country or area, the migration policy of a country, and the influx of refugees in recent periods when deriving estimates of net migration. The data to calculate these estimates come from a variety of sources, including border statistics, administrative records, surveys, and censuses. When there is insufficient data, net migration is derived through the difference between the overall population growth rate and the rate of natural increase (the difference between the birth rate and the death rate) during the same period. Such calculations are usually made for intercensal periods. The estimates are also derived from the data on foreign-born population - people who have residence in one country but were born in another country. When data on the foreign-born population are not available, data on foreign population - that is, people who are citizens of a country other than the country in which they reside - are used as estimates.

[36] Please refer to the World Bank Metadata Glossary at https://databank.worldbank.org/metadataglossary/population-estimates-and-projections/series/SM.POP.NETM

Proxy measures. The original GECM and AECM conceptual models are based on theoretical abstractions, or concepts, drawn from research literature. These theoretical entities are not always measurable and some would argue are not measurable. A classic problem is the measurement of demand for goods and services. This is important because actual consumption is supposed to be a balance between supply and demand. However, economists almost always measure demand by measuring how much people consume. Therefore, studies of supply and demand are often tautological; economists infer that demand is high if consumption is high, even though their theory is that consumption is a function of supply and demand—assuming that consumption = demand creates an untestable theory because in analysis, one will always be right by definition. Demand is basically an unmeasurable phenomenon. Other problems with measuring concepts simply boil down to the fact that what one can measure is only an approximation to the concept. For instance, in the GECM/AECM conceptual models, "strength of governing institutions" is defined as the "extent to which a government's institutions, including legislative bodies, the bureaucracy, and the judiciary, exist and possess technical expertise and legal authority to pursue their intended missions or objectives (aka the human and institutional infrastructure of the state)." The proxy metric used for the computation models is the World Bank Governance indicator "Government effectiveness," which is defined as "perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies."[37] The concept focuses on institutions and their expertise whereas the metric is measuring perceptions of government services, their independence from political pressures, and government credibility. The concept and the metric definitions overlap but are clearly not identical. As this example indicates, concepts and metrics will not always overlap completely. A full accounting of conceptual and metric definitions is found in the AECM Data Catalogue.[38]

Limits of Network Modeling

Once a conceptual model is developed that establishes the connections between nodes, a network has been de facto created. Therefore, the next step in conducting a network analysis is a simple matter of rendering the network connections as an edgelist (a table of which nodes connect and the weights of their connections if any) or an adjacency matrix (an *n* X *n* matrix of connections between *n* nodes), which can be input to network analysis software (ORA, which is USG certified, USINET) or open source programming packages such as R or Python for more flexible analysis and outputs. The only requirement is background knowledge of network analysis, which is readily available (Borgatti, Everett, & Johnson, 2013; Cioffi-Revilla, 2014; Wasserman & Faust, 1994).

As already explained, a network analysis describes how the positioning of nodes in a network provides them with the potential to influence the network. As such, it provides assessments of what nodes have the most potential to influence a network by virtue of their position or, conversely, the extent to which they may be influenced by other nodes or the system overall. A network is a field formation that provides constraints on what could possibly happen as the network functions. It does not describe what will

[37] Please refer to the World Bank Metadata Glossary at https://databank.worldbank.org/metadataglossary/population-estimates-and-projections/series/SM.POP.NETM

[38] To receive copies of the AECM Data Catalogue, please contact Dr. Allison Astorino-Courtois at aastorino@nsiteam.com or Ms. Mariah Yager at mariah.c.yager.ctr@mail.mil.

actually happen once the network is activated. System dynamics models enable analysis of the dynamics flows through a system.

Limits of System Dynamics Modeling

Once the background research is done on the connections in a system, network analysis is a relatively easy next step in analysis, as described. System dynamics modeling requires a new level of empirical knowledge and domain expertise. Empirically, system dynamics modeling requires historical data that can provide initial values and an historical timeline to which the model can be compared for validation. Initial values are particularly important because complex systems are sometimes very sensitive to small perturbations and therefore different initial conditions can put a complex system on very different pathways.

System dynamics models enable very specific modeling of the functional relationships between nodes in the system. This strength of the model requires much greater empirical knowledge of what those functional relationships might be. Therefore, much more must be known about the relationships between nodes in order to create a sound system dynamics model. Also, inaccuracies in this precise knowledge have the potential to skew model results, placing a premium on the quality of the knowledge that informs these relationships.

These heightened data requirements often restrict the nodes and connections one is able to incorporate into a model, as described above. Therefore, system dynamics models are likely to represent a subset of relationships that can be captured in network models.

Nonetheless, the ability to capture specific functional relationships, the sensitivity to initial conditions, the ability to track system behavior through time, and the ability to project future states are definite strengths of a system dynamics approach.

Building on the Sahel System Dynamics Model

The Sahel system dynamics model presented in this report represents an initial attempt. As such they are incomplete, although we think that they are complete enough to provide some useful insights. However, they do require fuller development, and this section contains suggestions for what is missing, what requires further investigation, and suggestions for the best use of a system dynamics model.

What's missing?

The project's time constraints mitigated against fully developing the model. There are several variables that we think the model should have in order to cover what to us are some obvious gaps.

The effects of global warming were not sufficiently modeled, primarily due to the fact that its potential effects are very indirect and work though long pathways of intervening variables. Only the direct effect of increasing epidemic deaths with increasing temperatures was included. However, increasing temperatures are definitely related to decreases in pasturage and animal production in the Sahel according to the country-year data we gathered. Given the agrarian nature of Sahelian countries, the implications of the climate-driven changes in pasturage and animal production should be incorporated into the model. However, that requires further research into what those complex pathways might be.

International trade is one source of influence the United States and its competitors have in African countries. IMF bilateral imports and exports were collected for the United States, Russia, China, and other major trade partners on the continent (Spain, Italy, France, UAE, Brazil). Again, because of time constraints, trade impacts were not included in the model. The data indicate that there are many strong correlations between Chinese exports and imports and other nodes in the AECM, quite a few with imports from the United States, and comparatively few with Russian imports or exports. The implications of trade should be explored further.

Another economic variable that we think is missing is the importance of the informal economy. The informal economy involves "*the production, purchasing, or selling goods and services that are* ***in themselves legal****, in a manner that is not regulated or protected by the government, and takes place without official recognition or record. Both individual workers and entire enterprises may be operating in the informal economy"* (Bragg & Popp, 2022). The ILO estimates that 85% of employment in sub-Saharan Africa is in the informal economy. While this figure may seem extremely high, recall that many African countries still have heavily agrarian economies, with 65% of sub-Saharan Africans estimated to be small farm holders and pastoralists. The informal economy represents an opportunity cost in lost taxes and a lack of control for governments, and potential exploitation for laborers. However, many development experts point out the vital importance the informal economy has for ensuring that families can meet their basic needs. Given the many economic, governance, and social nodes the informal economy can potentially impact, it should probably be incorporated into any complete model.

Rule of law is an important covariate of government effectiveness in our data, and one often referred to as a source of political stability. It was not incorporated into the current model simply out of expediency, and it should probably be included in future iterations of the model.

Internally displaced persons (IDPs) are often a collateral effect of war and internal wars. As with rule of law, IDPs were not incorporated into the current model, although the AECM accounts for them and they should be added, especially since they at times motivate US military relief actions.

Further investigation

Two types of further investigation are required: calibration and missing variables. Calibration refers to adjustment of flow equations in order to achieve a better fit to historical data. Currently, there are five nodes in the model for which we think a better fit to historical data are needed. Two, epidemic deaths and number of people affected by drought, are historically episodic, occurring approximately every five years. Their overall trends have been captured as continuous functions, but their historical spikes are not. A relatively straightforward way of capturing these spikes might be the use of a pulse function in the system dynamics model that would raise these figures to historical heights every five or so years. Three other variables—percent protest, percent undernourished, and political violence—require better fits to the historic data. This might be achieved by simply altering coefficients in flow functions. Alternatively, their lack of fit might be due to under-specification of the model or missing variables. Any of these alterations can be tricky. Because the Sahel system dynamics model is complex, even a small change in a coefficient can throw other variables off their fit with the data. Consequently, calibration can become labor intensive.

Incorporating missing variables is even more involved. The AECM conceptual model contains much of the background research required for incorporating a missing variable. However, empirical metrics for measuring those variables will need to be gathered, and their hypothesized relationships to other variables will need to be examined, and ultimately, based on that research, incorporated into the model if appropriate. Also, it was the SMA team's experience that tailoring a variable to the USAFRICOM AOR required more background research. We have already noted that global warming, international trade, informal economy, rule of law, and IDPs should be researched and added to the model. Additionally, we think that inequality should also be added.

Inequality, as measured by the Gini coefficient, was originally intended to be included in the model. However, it was not highly correlated with many other nodes in the AECM. For instance, we suspect that many researchers who invoke inequality as a causal force behind grievances and social unrest for instance are actually referring to poverty. However, inequality simply refers to the distribution of wealth in a society (Kuznar, 2007; Kuznar & Day, 2021a). A wealthy country can still have high degrees of inequality. For instance, in our database, the United States is currently in the top 10 countries for income per capita, yet is also in the top third of countries in terms of inequality. Inequality is a complex phenomenon and may require separate modeling as a complex system, which then is connected to the larger AECM.

Of course, there are any number of other variables that one could add to the model; the process could be endless. The point of the modeling process is to produce a model that is sufficiently grounded so as to allow nature to check our biases and preconceptions but not to produce a precise mirror of nature.

Best Use

Statistician George E.P. Box's admonition that "all models are wrong, but some are useful," should be born in mind. The point of a computational model of a complex system is not to provide precise predictions; the point is to reveal the dynamics of the system. Correspondence with empirical data grounds a model to prevent it from merely reflecting our preconceptions and prejudices. Empirical grounding provides an evidence base for the model and therefore increases confidence in the model's validity. However, it is possible to overfit a model by adding enough variables and relationships in order to agree with data, and therefore create a model that works only for that data set but whose results cannot be generalized. The goal is to provide a model that is useful for its purpose.

We propose that the system dynamics model be used to reveal underlying dynamics and not to provide point predictions of the future. For instance, the fact that there are several reinforcing loops within two degrees of terrorism explains how it is that terrorism can flare up and what those drivers are. Identifying these drivers then provides USAFRICOM with nodes to monitor and target for influence in an effort to prevent them from creating flare-ups in terrorism. The model should not be used to predict a future level of terrorism.

The model could be useful for course of action (COA) analysis. As an example, control of corruption is in a strong reinforcing loop with the system's most important driver, government effectiveness. Hypothetically, USAFRICOM could provide support to an USAID anti-corruption campaign to limit corruption and dramatically improve government effectiveness. Further, suppose the program is assumed to reduce corruption by 10% per year. The anti-corruption campaign can be modeled by introducing an auxiliary variable that impacts corruption by 10% a year, and the corresponding effects on government effectiveness and the variables it is connected to such as internal war or terrorism can be examined. If the values of those nodes change in the direction expected, then the model provides evidence that the anti-corruption campaign can be effective. If the campaign is very costly, however, and only a small change in the target nodes is achieved, the model may indicate that the campaign is not worth its cost. Furthermore, the model may indicate that the campaign is not effective, or worse, may have negative unintended effects on other nodes in the system. Once again, the point is not to provide precise point predictions of the future, but to reveal dynamic relationships and their potential effects in order to inform decision making.

Appendix: Sahel System Dynamics Graphics in VENSIM

The system dynamics software, Vensim™, was used for the system dynamics modeling. The Vensim model graphics for key nodes discussed in this report are presented here to illustrate how the model was represented and constructed.

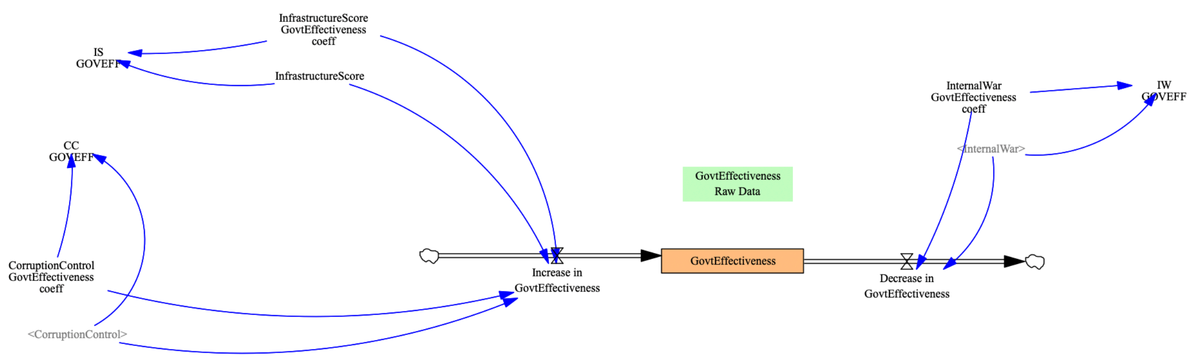

Figure 17. Vensim system dynamics government effectiveness graphic

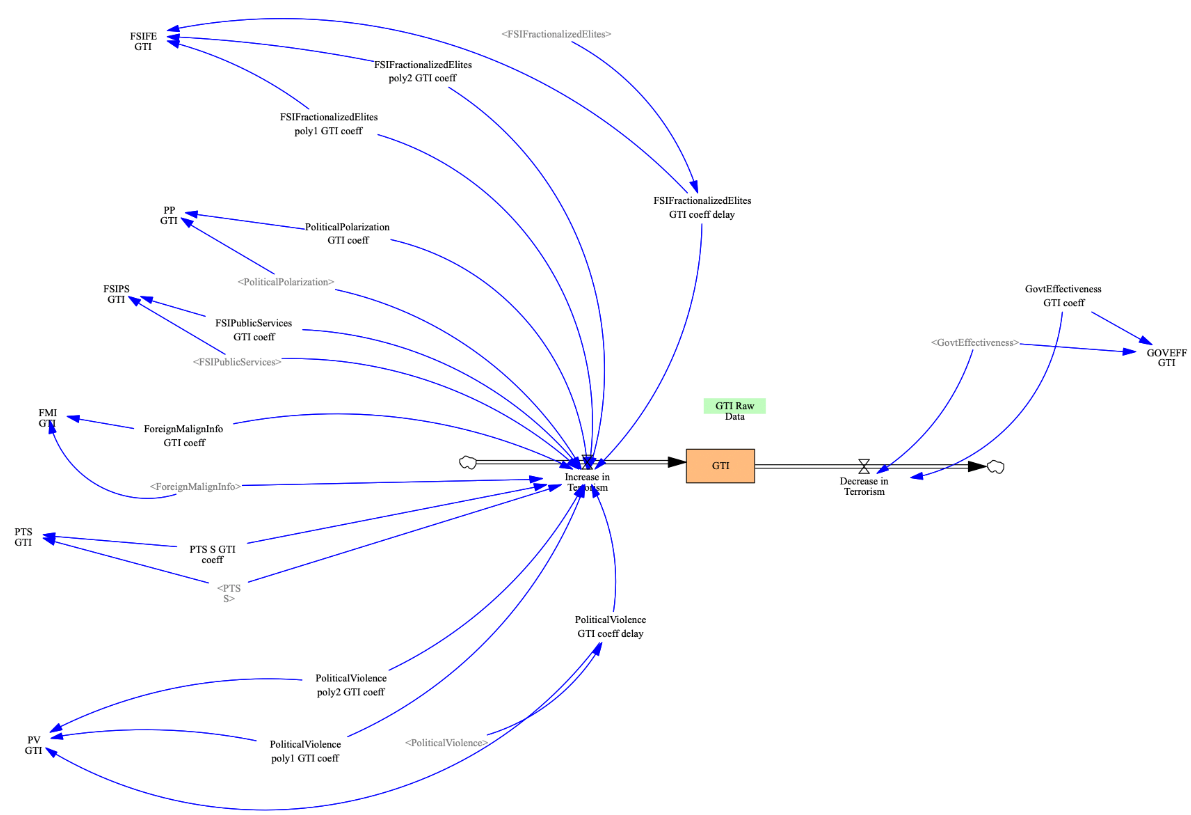

Figure 18. Vensim system dynamics terrorism graphic

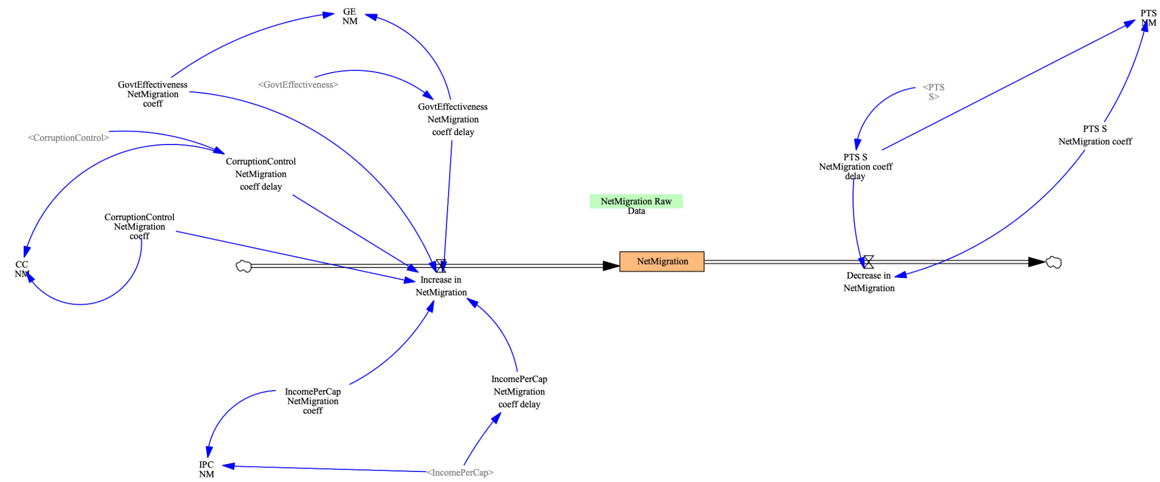

Figure 19. Vensim system dynamics net migration graphic

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