A RISK REDUCTION APPROACH TO TSETSE AND AFRICAN TRYPANOSOMIASIS CONTROL: CASE STUDY THE CANVAS METHOD

By

Demetrice R. Jordan

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ABSTRACT

A RISK REDUCTION APPROACH TO TSETSE AND AFRICAN TRYPANOSOMIASIS CONTROL:
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African trypanosomiasis is an inherently multiscale human-animal-environment problem, with a spatially and environmentally constrained vector, a transnational disease distribution, two distinct disease strains (East and West African), innumerable human and animal reservoirs, and entrenched socio-cultural barriers and policy challenges. Colloquially known as 'sleeping sickness' and 'Nagana' in animals, African trypanosomiasis is a parasitic infection caused by pathogenic protozoa of the genus Trypanosoma.

The parasite is transmitted through the salivary glands of tsetse fly during a blood meal. African trypanosomiasis is a major neglected tropical disease endemic to 36 countries in sub-Saharan Africa. Neglected tropical diseases are communicable, viral, parasitic, and bacterial infections that mainly affect poor people. Worldwide, neglected tropical diseases are not allotted the resources necessary to control and eradicate them. As a neglected tropical disease, African trypanosomiasis is given a lower global health priority which hinders control program effectiveness.

Despite decades of research to control tsetse, trypanosomiasis continues to threaten the health and well-being of people and animals across sub-Saharan Africa. Compounded by resource

constraints for control efforts, African trypanosomiasis is also poorly understood, severely underreported, often misdiagnosed, and fatal. The disease has a case fatality rate of nearly 100%, if untreated. While treatment is available, they are often expensive and toxic. Annual deaths attributed to African trypanosomiasis have a compounding impact across human and animal populations and the landscape. An estimated 60 million Africans and countless livestock are at risk of the infection, illuminating the need for risk reduction approaches to mitigate exposure.

This dissertation examines tsetse and African trypanosomiasis control from an interdisciplinary perspective, combining health geography, disease ecology, diffusion of disease epidemiology, development economics, and global health policy. As a more general contribution, this dissertation presents a framework for addressing vector-host problems, using a multifaceted risk reduction and control strategy, innovative methodologies, and community participation to increase long-term success.

For my beloved Uncle, Roosevelt Jordan, who nurtured my love of reading and gifted me the book that introduced me to the tsetse fly and African sleeping sickness.
To my son Ashton Jordan, for being my North Star.

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KEY TO ABBREVIATIONS

AAT	AFRICAN ANIMAL TRYPANOSOMIASIS
HAT	HUMAN AFRICAN TRYPANOSOMIASIS
WHO	WORLD HEALTH ORGANIZATION
CDC	CENTERS FOR DISEASE CONTROL AND PREVENTION
IAEA	INTERNATIONAL ATOMIC ENERGY AGENCY
CANVAS	CONTROL APPLICATIONS TO NEUTRALIZE VECTORS ACROSS SPACE
SMART	SIMULATED MODEL FOR AREAS AT RISK FOR TRYPANOSOMIASIS
GETED	GOOGLE EARTH ENGINE TSETSE ECOLOGICAL DISTRIBUTION MODEL
PEST	POLITICAL ECONOMIC SOCIO-CULTURAL TECHNOLOGICAL ANALYSIS
FAO	FOOD AND AGRICULTURE ORGANIZATION
PATTEC	PAN AFRICAN TSETSE AND TRYPANOSOMIASIS ERADICATION CAMPAIGN
SAT	SEQUENTIAL AEROSOL TECHNIQUE
SIT	STERILE INSECT TECHNIQUE
TB	TRYPANOSOMA BRUCEI
MODIS	MODERATE RESOLUTION IMAGING SPECTRORADIOMETER
NDVI	NORMALIZED DIFFERENCE VEGETATION INDEX
LULC	LAND USE LAND COVER
LST	LAND SURFACE TEMPERATURE
TPR	TSETSE PRESENCE RISK
HPR	HOST PRESENCE RISK
ITC	INSECTICIDE TREATED CATTLE
AB	ARTIFICIAL BAIT
SSA	SUB-SAHARAN AFRICA

INTRODUCTION

Tsetse and African trypanosomiasis are organisms of antiquity that continue to threaten the lives and livelihoods of humans and animals across sub-Saharan Africa. African trypanosomiasis is a vector born, parasitic illness that can be transmitted by the bite of the tsetse fly during a blood meal. The tsetse fly is a biting fly of genus Glossina and the vector of both human and animal African trypanosomiasis. The entire history of the region has been complicated by the presence of tsetse fly and trypanosomiasis infections (Ford 1971; Mahamat 2015a; Alsan 2015a). Tsetse and trypanosomiasis have been a source of economic distress, impacting animal husbandry, beef and dairy production, and posing a barrier to development in sub-Saharan Africa (Grant 2014; Grant, Anderson, and Machila 2015a; Alsan 2015a). Both the fly and the disease exacerbate poverty in rural areas that remain undeveloped due to their presence (Ilemobade 2009; Namangala and Odongo 2013). Chronic underdevelopment, premature mortality, and the failure of many villages to thrive can be attributed to the presence of the tsetse fly and African trypanosomiasis (Berrang-Ford 2007; Lachenal 2017; Fiedler 1950).

Tsetse and trypanosomiasis in sub-Saharan Africa are a complicated puzzle of interconnected factors and drivers. The conceptual diagram in Figure 1.1 demonstrates the interplay of these relationships on the trypanosomiasis landscape. Many underlying factors contribute to the complexity of controlling the vector and eradicating the disease (Yaro et al. 2016; Preston, Daszak, and Colwell 2013; Mata 1982). The science and empirical knowledge about the geographic distribution of tsetse presence, habitat suitability, and the microbiology of the fly have improved over the past five decades (V Doudoumis and Tsiamis 2012; A. H. Dicko et al. 2014) Epidemiological understanding of the disease distribution, sleeping sickness regions or

foci, and disease symptoms have improved surveillance and control efforts over the past 100 years (Uba et al. 2016; Kagbadouno et al. 2009). However, there are many questions that remain unanswered surrounding tsetse and trypanosomiasis such as: How effective are tsetse control programs? Does efficacy vary across different regions in sub-Saharan Africa? What drives the differences across space? What would a global policy for tsetse and trypanosomiasis risk reduction and control require to be successful? Who would be the major stakeholders and what agencies will need to be involved? Such questions serve as opportunities and justification for reimagining tsetse and trypanosomiasis control and will be explored in this dissertation.

1.1 The environment of tsetse and trypanosomiasis in sub-Saharan Africa

Research in health geography and public health maintains that place affects health (Cutchin 2007; Macintyre, Ellaway, and Cummins 2002) and that there are links between environmental conditions and human welfare (Cutter, Boruff, and Shirley 2003). Similarly, animal health science research argues that place can have deleterious effects on the health and well-being of animals when there is an outbreak of infection or disease (Teresa Capucchio et al. 2019), with consequent impact to public health, regional and national production systems, and global trade (Cartn-Rojas 2012). The interdependence of the human-animal-environment systems is magnified by issues such as tsetse and African trypanosomiasis and warrant joint examinations to achieve a comprehensive understanding.

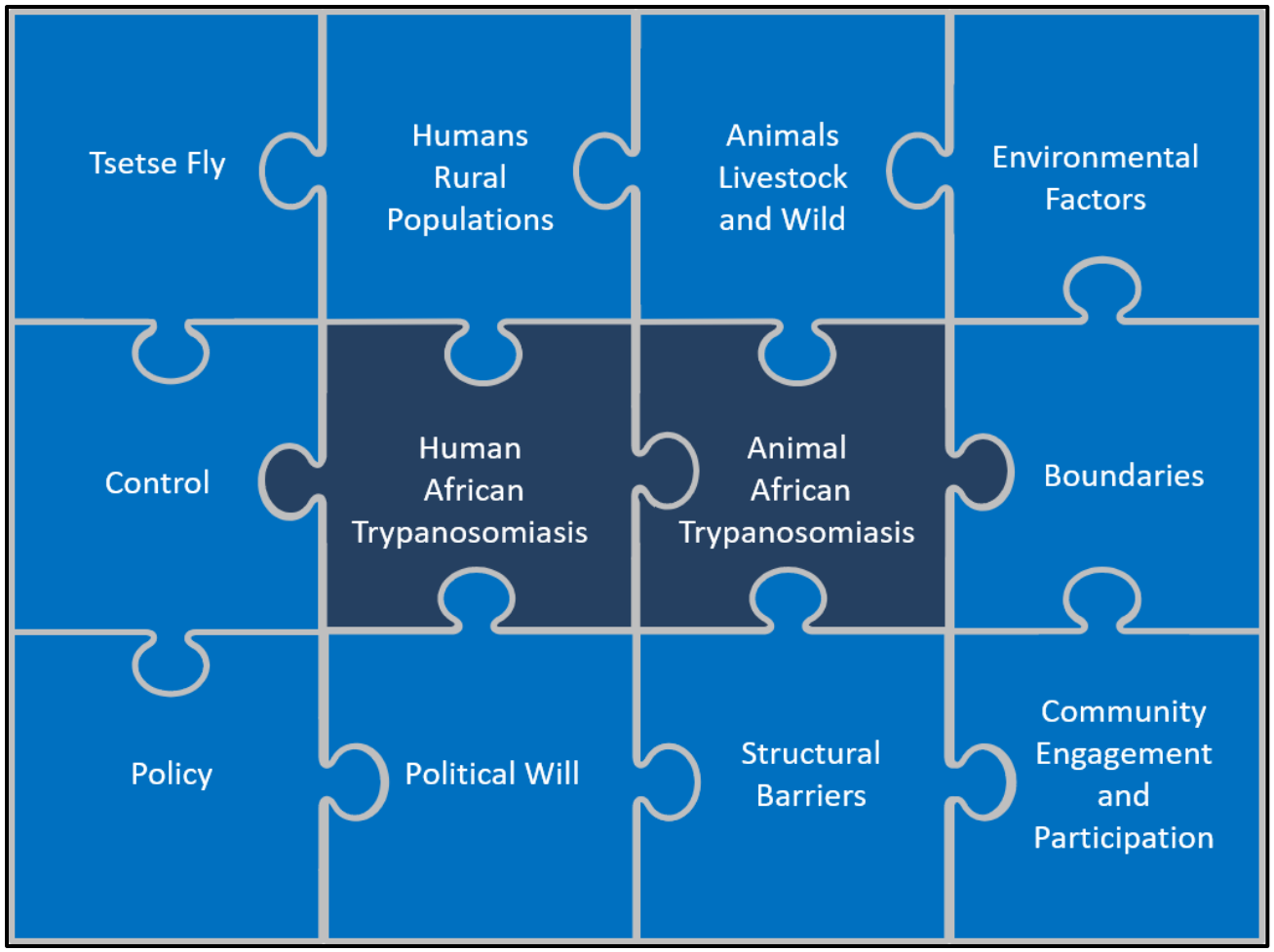


Figure 1. 1 Conceptual diagram of the interconnected relationships between the factors and drivers of human and animal trypanosomiasis.[1]

[1] Diagram format adapted from www.presentationmagazine.com

Tsetse flies are an environmentally dependent vector that persist and thrive in certain ecological niches (S. G. A. Leak 2009; Glass 2006). In Africa, tsetse flies are geographically constrained to the sub-Saharan region. The internal limits of tsetse habitats are south of the Sahel (15°N) and north of the Kalahari (20° S) with coastal limits along the eastern perimeter of the continent (FAO 1982; Jose R. Franco, Simarro, Diarra, and Jannin 2014; Mahamat 2015a). There are three groups or biological clades of tsetse: (1) the fusca group, (2) the morsitans group, and (3) the palpalis group. Each of the three tsetse groups occupies a specific ecological niche which forms the basis of their primary habitat: (1) the fusca group are forest tsetse, (2) the morsitans group are savanna tsetse, and (3) the palpalis group are riverine tsetse (Carpenter 1920; Ford 1971). Environmental and microclimatic conditions – specifically temperature, vegetation type, and soil moisture – drive habitat suitability, tsetse presence and absence.

Due to the ecological limitations of tsetse, African trypanosomiasis is endemic to sub-Saharan Africa (Bouteille and Dumas 2003; Ian Maudlin, Eisler, and Welburn 2009). African trypanosomiasis is an inherently geographic disease which manifests in three forms: (1) west African trypanosomiasis (human), (2) east African trypanosomiasis (human), and (3) African animal trypanosomiasis. The human forms of African trypanosomiasis are predominantly a disease of adolescence and adulthood as these groups are most involved in household activities that engage the environment and habitats of tsetse during times when the fly is active (Steverding 2008a; Brun et al. 2010). The commodification of the environment and commercial pressures from the colonial agricultural production system, drastically altered the African landscape (Headrick 2014). Over time, these actions served as catalysts that exacerbated

trypanosomiasis epidemics among human and cattle (Endfield, Ryves, and Mills 2009; I. Maudlin 2006; Isenberg and Nash 2014).

1.2 The science of the tsetse fly and trypanosomiasis: the vector and the disease

1. The Tsetse Vector

Tsetse flies are the vector of human and animal African trypanosomiasis. There are 33 species of tsetse fly of which all but two species are endemic to sub-Saharan Africa (Gooding and Krafsur 2005). Roughly the same size as a house fly (see Figure 1.2), tsetse are phylogenetically old and have several anatomically distinct characteristics that differentiate it from all other fly species (Jackson 1953; Bursell 1960). Tsetse are the only breed of fly in which the male and the female feed on blood (Rupert W. Jack 1941). The flies are tan and brown in color and morphologically the adult tsetse has distinctive features: (1) proboscis, (2) wing folding pattern, and (3) arista. The proboscis or feeding tube, is longer and thicker than regular flies and stays directly forward during non-feeding periods. The proboscis is composed of two long tubes enrobed in lip-like structures lined with teeth for piercing the skin of animal and human hosts (Wendy Gibson, Peacock, and Hutchinson 2017).

The bite of a tsetse is very painful, an abscess wound usually follows the bite (Baldacchino et al. 2014). Saliva is secreted at the site to prevent clotting during the blood meal; if the fly is infected with trypanosomes they are transmitted to the host at this time. Similarly, if the hosts have trypanosomes they are ingested by tsetse during feeding (Semayat and Maireg 2018). When resting, tsetse fold one wing completely on top of the other, which gives the appearance of a single wing (Kaba et al. 2017). The arista is a sensory appendage attached to the antenna.

In tsetse, the arista of all three antennas are covered with short stiff hairs, differentiating tsetse from all other flies (Enjin et al. 2016). Understanding the traits of tsetse aid in its identification in the field and can provide insights on vulnerabilities that could help control the fly.

2. Human African Trypanosomiasis

Human African trypanosomiasis (HAT), colloquially called sleeping sickness, is a neglected tropical disease that impacts the everyday life, subsistence, and prosperity of poor, rural people in sub-Saharan Africa. It is a parasitic infection caused by protozoa organisms of the species Trypanosoma brucei (T.b.) and transmitted by the bite of the tsetse fly. African sleeping sickness is one of several major neglected tropical diseases which mainly impact those in rural areas whose daily activities puts them in close proximity to tsetse habitats (Scoones 2014). Human African trypanosomiasis perpetuates the poverty cycle within endemic areas because it directly impacts people of productive household contributory ages (Welburn et al. 2017).

The disease manifests in two forms: (1) west African sleeping sickness – the chronic form of the infection with a life expectancy of up to three years after infection, and (2) east African sleeping sickness – an acute infection with a six-month life expectancy. The duration and severity of the disease depends on the trypanosome variant that causes the infection (CDC 2017). The case fatality rate of African sleeping sickness is near 100% if left untreated (Odiit, Kansiime, and Enyaru 1997). Throughout history many prevention and control methods have been attempted; however, eradication of human African trypanosomiasis has proven to be nearly impossible. Currently no vaccine exists and there is no cure for the disease (Mauldin 2006; Onyilagha et al. 2017). In the absence of prophylactic therapy or curative treatment, risk reduction through

minimizing direct contact between the vector and host become critical factors in controlling the disease.

3. African Animal Trypanosomiasis

Nagana is the most economically debilitating livestock disease in Africa (Odeniran and Ademola 2018). It has multiscalar implications: at the local scale, it perpetuates poverty cycles among rural households who derive their livelihoods from pastoralism, while at the national scale, disease outbreaks and herd losses impact national budgets, stifle dairy, beef production, and force countries to remain dependent on foreign imports of these products that costs of millions yearly (Odeniran et al. 2019; Fiedler 1950; A. P. M. Shaw et al. 2015). Disease manifestation in cattle includes emaciation, anemia, weakness, dull and rough coat appearance, discharge in the eyes, lack of engagement with the herd, fever, and swelling of the lymph nodes. Without treatment, death occurs in 1-3 months. Trypanocidal drug treatment is available for cattle. However, some cattle make it to market without receiving treatment, impacting the food chain and human African trypanosomiasis infections (Smith and Smith 2007).

1.3 The policy of tsetse and trypanosomiasis control: colonial concepts of fly control

Tsetse and trypanosomiasis control have been complicated by policies that have not favored the African people. One key issue is that policies governing control of the vector and disease have been dominated by a central theme: political economy, and the production of wealth for European nations by their colonies. The politics of tsetse and trypanosomiasis control have been a part of the story of Africa since the onset of colonialism, and in many regards the impacts still resonate across the continent today (Heldring and Robinson 2013; Neill 2012).

Particularly harmful were the inhumane social policies including segregation camps and harmful drugs administered through mandatory therapeutic "sanitization" programs, to vaccinate and treat trypanosomiasis infections. Moreover, colonial administrators enacted unethical control policies, which required Africans to use hand nets to catch tsetse flies, and to wear clothes covered in sticky substances on their backs in the plantation fields, to act as human "fly traps" (Mckelvey 1973).

Each of these actions increased the risk of encounter with the fly and the likelihood of becoming infected with trypanosomes. Therefore, it is not conjecture to say that many trypanosomiasis outbreaks and epidemics were socially produced by imperialism (Mackenzie 2017; Amaral 2018). Current global policy remains preoccupied with top-down programs that lack significant input from local populations where the policies will be enacted. Complex issues such as African trypanosomiasis and tsetse control require multiscale input and strategies to improve fly control and risk reduction.

The studies of this dissertation are largely conducted at the population and landscape scale. The introduction serves as an important overview to understand the topics discussed in depth. Each individual study examines tsetse and trypanosomiasis control from different yet connected perspectives.

Chapter 2 (Study 1) provides a meta-analysis of the literature over the last 122 years from 1898 – 2020, considering the following questions: what insights can be revealed through a meta-analysis of tsetse and trypanosomiasis literature, have there been shifts in tsetse and

trypanosomiasis control priorities over time, if so, what patterns emerge, and what drivers influence research topic trends.

Chapter 3 (Study 2) characterizes the tsetse and trypanosomiasis risk landscape for Senegal and Tanzania through scalable approaches to risk area identification and simulated tsetse control, exploring the following questions: how will identifying areas at-risk for trypanosomiasis enrich control strategy development, does risk vary across space, and will a two-step trypanosomiasis risk reduction framework improve control systems.

Chapter 4 (Study 3) develops a stakeholder driven policy framework for tsetse and trypanosomiasis control, examining the following questions: what would a global policy for tsetse and trypanosomiasis risk reduction and control require to be successful, how is success measured and, who would be the major stakeholders and what agencies would need to be involved.

Chapter 5 provides a general conclusion and discusses the broader implications of this work, offers future research directions, and final thoughts on the subject. The questions selected for this dissertation offers a comprehensive, spatial-temporal examination of tsetse and trypanosomiasis control and risk reduction. The analysis begins with the broad regional perspective of sub-Saharan African, then zooms in to explore the national risk and control landscapes of Senegal and Tanzania, culminating with multisectoral individual perspectives highlighting local voices.

Figure 1. 2 Image of Tsetse fly (Glossina) show the three anatomically distinct structures: proboscis, wings, and antenna.[2]

[2] Image source: Joseph P. Messina, Professor MSU Geography

A META-ANALYSIS OF TSETSE AND TRYPANOSOMIASIS CONTROL LITERATURE FROM 1898-2020: A QUANTITATIVE APPROACH

2.1 INTRODUCTION

Human African Trypanosomiasis (Sleeping Sickness) and Animal African Trypanosomiasis (Nagana) are vector-borne parasitic diseases transmitted during the blood meal of an infected tsetse fly of the genus Glossina (Ford 1971; Merschjohann and Steverding 2008; Franco, Simarro, Diarra, Ruiz-Postigo, et al. 2014) The tsetse fly is one of Sub-Saharan Africa's oldest impediments to development, and strategies for poverty alleviation on the continent often include a tsetse control strategy (Alsan 2015c; Kohagne et al. 2011). Approaches to control tsetse have taken on many forms over the years, and the literature on tsetse control programs is diverse in academic field, approach, scale, and objective (Vale et al. 2015; Grant 2014; Scoones 2000). Despite decades of research, many questions surrounding tsetse phenology, control programs, and programmatic efficacy still remain, including the drivers behind control strategy differences across countries, regions, and transboundary geopolitical areas (Van Vuuren and Penzhorn 2015; P. Clausen et al. 2010). Such questions serve as opportunities and justification for a meta-analysis of tsetse control and eradication strategies.

The difficulties with control and eradication of tsetse are complex: eliminating the fly and reducing the prevalence and disease burden of sleeping sickness has become a global public health priority (World Health Organization and World Health Organization (WHO) 2013; Sutherland et al. 2015). To spur research and support in this area, the World Health Organization (WHO) set a target priority of the elimination of sleeping sickness as a public health concern and the eradication of tsetse by 2030. However, several issues thwart these

efforts. For instance, little synthesis exists among the research and practitioner communities on which control approaches are the most efficient and economically feasible. Similarly, shifting priorities from low cost mechanical control methods to biogenetic vector management, which are more expensive and take longer to reach fruition, further expand the divide, and compound efficacy issues. Moreover, consensus has yet to be reached on the path to eradication (Menon et al. 2016c; Wamwiri and Changasi 2016b; Mahamat 2015a).

The lack of agreement, trend changes in control, and the absence of a true eradication strategy, will continue to hinder progress towards tsetse elimination (Hotez and Aksoy 2017). One path forward could be to develop a comprehensive understanding of the breadth and depth of the control landscape through a meta-analysis of the literature (Sutherland et al. 2015), including what strategies have been attempted and the degree of success or failure. Understanding the research trends over time may help determine if shifts in priorities are driven by ecological, environmental, or political fluctuations (Mauldin 2006; Wellde et al. 1989). The objective of this chapter is to take a take a comprehensive look at the tsetse literature of the past 122 years using a meta-analysis approach. Building a library of past and present tsetse and trypanosomiasis control programs will help elucidate the drivers of programmatic success or failure (Stephen 1986; Davies 1971; Bottieau and Clerinx 2019). Additionally, a retrospective analysis could inform novel strategies for future control campaigns.

Historically, varying control methods have been attempted; however the resurgence of tsetse in isolated habitats leave newly cleared areas vulnerable to reinvasion, (Vale 1987; Dodge and Messina 2018; Ford 1969) a major reason tsetse eradication has proven difficult (Hendrickx,

Rocque, and Mattioli 2004; Barrett et al. 2003). Past control programs included bush clearing, game culling, and the use of DDT through sequential aerial technique (SAT), all of which were ecologically and environmentally degrading approaches (Ormerod 1986; Yorke 1920; Toit et al. 1954; Clarke 1990). Current control efforts utilize air spraying, insecticides, sequential aerial technique (SAT), sterile insect technique (SIT), traps and targets (Torr et al. 1997; Holmes 1997; Lyczkowski 2006; Vale 1993). However, neither past nor present controls have enjoyed long-term success or sustainability (Kappmeier 2000; Okeyo et al. 2017; Menon 2011).

Systematically analyzing these strategies can increase understanding and improve outcomes of future control programs. Several reviews and meta-analyses on tsetse and trypanosomiasis control have been conducted (Asmare et al. 2017; Kansiime et al. 2018; Odeniran and Ademola 2018; Lenk et al. 2018), albeit limited to specific geographic areas, or focused on understanding the fly, disease prevalence, or the economics of control from a cost-benefits perspective. The meta-analysis conducted for this chapter comprehensively explores the tsetse and trypanosomiasis topics from the 1890's to 2020 and provides a thorough examination of trends over time. The exploration will consider the following questions: (1) what insights can be revealed through a meta-analysis of tsetse and trypanosomiasis literature, (2) have there been shifts in tsetse and trypanosomiasis control priorities over time, if so what patterns emerge, and (3) what drivers influence research topic trends.

2.2 BACKGROUND

The social and economic burden of tsetse and trypanosomiasis has been the backdrop of the human origin story in Africa (Alsan 2015c; Krinsky 2019). Since antiquity, the people of Africa have been living with the burden of tsetse. Control has taken many forms over time including, diverting the Nile river to avoid known tsetse habitats by the ancient Egyptians (Steverding 2008b). To protect herds, gourds were filled with blood and placed along perimeters where livestock were kept (Great Britain Bureau of 1912). Plantations were cleared by patrolling the areas with black cloths and birdlime to attract and capture tsetse (Busvine 1993). Bush was cleared to destroy tsetse habitats (Entomology 1920). Widespread game culling was conducted to remove host reservoirs, the food supply for tsetse (Torr et al. 2011). Traps and targets are used to capture tsetse for observation and to reduce fly populations throughout endemic areas (Johnson 1929b; Bruce 1915; Fèvre et al. 2006). Insecticides in the form of pour-on, dips, and aerial sprays are used to protect livestock and control flies in areas that are hard to reach by foot (Toit et al. 1954; Kuzoe and Schofield 2005). The sterile insect technique is an environmentally friendly control option that includes the release of nuclear irradiated male tsetse to mate with wild females flies as a species eradication step (Hursey 1985; Schofield and Maudlin 2001; Mckelvey 1973).

African trypanosomiasis is an inherently geographic disease which manifests in three forms: West African trypanosomiasis, East African trypanosomiasis, and African animal trypanosomiasis. Incidentally, the distribution of the east and west African strains follows a geographical divide separated by the African Rift Valley. The natural boundary represents the line of demarcation between West African trypanosomiasis, the chronic form of the disease,

and the acute East African strain (Welburn et al. 2001). Further, the rift valley separates the extent of the vector limits for Trypanosoma brucei gambiense (T.b. gambiense) and Trypanosoma brucei rhodesiense (T.b. rhodesiense), respectively. The disease vector, the tsetse fly, is geographically constrained to 36 countries in sub-Saharan Africa, which explains the endemicity of both sleeping sickness and Nagana (McCord et al. 2012). Tsetse is confined between 15 degrees North and 30 degrees South latitude (Ford 1971; FAO 1982; Franco, Simarro, Diarra, Ruiz-Postigo, et al. 2014). The full extent of the tsetse fly belts and the exposure risk of African trypanosomiasis are contained within this region (Scoones 2014). Characteristically, trypanosomiasis is not a single disease (W. Gibson 2007; Lachenal 2017); there are different agents including: different tsetse species (Glossina morsitans, palpalis, austeni), multiple species of trypanosomes (T.b. gambiense, T.b. rhodesiense, T.b. brucei brucei), three distinct disease systems and multiple infection pathways (Lejon, Jacobs, and Simarro 2013; Welburn et al. 2001).

Trypanosomes are an ancient organism, and their development dates back approximately 500 million years (Krüger and Engstler 2018), followed by the ancestral tsetse fly appearing 35 million years ago (Scientist 2009; Krafsur 2010; Steverding 2008b). Humans are the youngest in the evolutionary equation appearing some 2 million years ago, and the battle to exert control over the tsetse has been one (Ilemobade 2009) of humanity's greatest challenges. Like a recipe, African trypanosomiasis requires specific components to develop: the presence of tsetse vector, trypanosomes, and animals and human reservoirs (Cook 2008a). However, as Bruce (1910) attests, presence alone is not enough for disease transmission, regular and sustained exposure is required. Examining past and current literature can aid in the identification of

tsetse distributions habitats, human populations, and cattle pasturelands. Identifying areas at risk for trypanosomiasis is a critical step in the control and suppression process (Ndeffo-Mbah et al. 2019).

The presence of tsetse has been chronicled throughout history from the Holy Bible (Isaiah 7:18-19), Arab literature (Hunter 2003) and at the centerpiece of many accounts during the colonialism of Africa from the 1870's through independence in 1960 (Hoppe 2003). Within the first five years of the 20th century, several major discoveries in tsetse and trypanosomiasis research were made. David Bruce identified tsetse as the vector of both Nagana and sleeping sickness and "haemetazoa" (later named trypanosomes) as the causative agent of the illness in 1895 (Bruce 1910; Cook 2008b). T.b. gambiense was determined to be the infectious parasite for West African trypanosomiasis in 1902 by Joseph Dutton (Steverding 2008b). In that same year, Emile Brumpt linked tsetse to sleeping sickness by noting that the disease trailed the presence of tsetse fly (Lyons 1992) and in 1905, the first anti-trypanosomal drug, atoxyl, was discovered (Ross and Thomson 1910). While advancements have occurred, fewer discoveries have been made over the past 120 years than in the first 10 years of tsetse research (Matthews 2015).

Early attitudes and misconceptions created a number of missed opportunities for advancements in the control and eradication of tsetse and trypanosomiasis. Sleeping sickness was considered not only endemic to Africa but also only transmittable by African natives to the animals (Bruce 1910, 1915). The correct transmission pathways would be discovered later. Additionally, it was presumed that Sleeping Sickness only affected native Africans and animals;

this would be dispelled by Bruce in who in his 1910 address to the British Medical Association proclaimed that “neither African nor European was immune to the disease” (Bruce 1910). Further, and likely inadvertently, Bruce highlighted a key discrepancy and driver behind the high mortality rates among Africans by stating, “in Europeans the chance of recovery and treatment is much better because it is diagnosed in the earlier stage for white people. Symptoms are often overlooked until the disease has progressed in Africans (Bruce 1910).

From 1900 until the late 1960’s tsetse control was the number one priority of health service workers in colonial Africa. However, over time the public health priorities throughout the tsetse belt countries have shifted (W. Ormerod 1976; Stanghellini, Gampo, and Sicard 1994). To galvanize support, and spur research in this area, in 2012, the World Health Organization (WHO) promoted the elimination of sleeping sickness by 2020 and the eradication of the tsetse fly by 2030 (Tiberti and Sanchez 2018). These were very ambitious goals given the array of challenges that complicate control and eradication efforts.

More than a hundred years of research on tsetse and trypanosomiasis has yielded a vast amount of diverse scholarship (Cattand 2001; Taylor 1998). While the information is abundant, organized synthesis of the literature by traditional methods have not capture the breadth and depth of the subject. The meta-analysis of the literature that follows will fill this gap. Some goals of this process are to explore how research efforts on tsetse and trypanosomiasis have developed over time and what if any synergies exist among topics and across reference databases. Using statistical analysis, an examination of the prevalent topics during certain periods can be revealed. Linkages and overlap across disciplines can be determined through the

interplay of the search terms. Additionally, trends among subject matter and publisher can be discovered. The importance of knowing what has been done can better position researchers to improve on past control efforts or conceive of and plan new controls programs.

2.3 METHODS AND ANALYTICAL TOOLS

Using Mendeley reference management software, libraries were created for each term with nested sub-libraries for each associated search database. Following the topic modeling and bibliometric analysis approach adapted from Kane et. al, 2016, a meta-analysis was conducted using Agricola, Ebscohost, Google Scholar, PubMed, Science Direct, Scopus and Web of Science (Agricola 2015; Ebscohost 2019; Scholar 2019; PubMed 2018; ScienceDirect 2015; Scopus 2015; Web of Science 2015) literature databases. Using a list of terms closely related to tsetse and trypanosomiasis topics, published and unpublished works from 1889 to 2019 in the form of articles, lab notes, personal papers, theses, and books were imported to Mendeley for initial processing (see Table 2.1).

2.3.1 Literature and Preprocessing in Mendeley Reference Manager

Mendeley is a free reference management system used to create bibliographies, organize libraries and citations for research papers. Using the built-in web importer extension, searches were conducted through the Michigan State University Library database and the world wide web. To maintain consistency across all the search databases and search terms, an inclusion criteria was adopted using the following constraints: (1) the first five pages of results per search term, per search engine, (2) no more than 150 search results total per search term, per search

engine, or (3) in the event the database search yields fewer than one-hundred fifty results and fewer than five pages, therefore all results in those cases would be retained.

Table 2.1 depicts the scope of the searches conducted across search terms and search engines. The blue shaded areas of the table illustrate the terms that were the most abundant across all search terms, which in this case is *tsetse control methods*, and the search engines with the highest total returns. Despite Google Scholar being an open sourced search engine, with the most lenient inclusion criteria of all the search engines in this study, Google Scholar did not have the highest amount of search terms represented overall.

A total of 16,288 reference items, hereafter referred to as records, were located across the seven search databases and 19 search terms (Table 2.1). The volume of records uncovered across all the searches produced duplicates entries in each individual library across the entire volume, in some cases. The respective Mendeley libraries underwent extensive data processing for record completeness, duplicate merging, and tag entry. The 19 individual libraries were exported into a Microsoft Excel spreadsheet for data cleaning and duplicate removal. A total of 6,389 duplicates were removed across the individual libraries using the Record Number field as assigned by Mendeley. Upon completion of the initial duplicate removals, the Record Number field was removed. The remaining 9,899 records of all 19 libraries were combined into one volume.

Once the libraries were combined into one final volume, the dataset underwent additional processing to ensure uniformity across the volume and to remove artifacts from the Mendeley software. Finally, an ascending order sort was employed and duplicate removal using the

Abstract Note field was performed and an additional 4,435 duplicates discovered and removed. In total, 10,824 duplicate records were removed. A validation review was conducted to remove any false negatives, meaning records that were not considered duplicates by Excel but actually were. Excel requires a 1:1 match within the field to consider a record a duplicate, so subtle differences lead to false negatives.

2.3.2 Preferred Reporting Items for Systematic Reviews or Meta-Analysis (PRISMA) Framework

The remaining dataset of 5,464 records was manually screened according to the steps outlined in the Preferred Reporting Items for Systematic Reviews or Meta-Analysis (PRISMA) workflow diagram (Figure 2.1). The PRISMA workflow diagram is a conceptual framework which provides an iterative process to methodically assess libraries and reduce sampling bias during systematic reviews and meta-analyses (Moher et al. 2009). The following exclusion criteria was applied to the remaining records: corrupt files, language that was unable to be translated (i.e. symbols instead of text), and inability to locate source document via library and web searches. Application of the exclusion criteria resulted in the removal of an additional 191 records in the Prisma screening process and further reductions of 417 records in the Prisma eligibility review.

2.3.3 Bibliometric Analysis in R Studio

The term bibliometric means " the measurement of all aspects related to publication and reading of books and documents" (Otlet 1934). The remaining 4,856 records were saved as a comma separated values (csv) and processed in R Studio (R. Studio Team 2015).

Table 2. 1 Search terms and databases utilized in the meta-analysis.

Search Terms and Search Databases							
Search Terms	**Agricola**	**Ebscohost**	**Google Scholar**	**Pubmed**	**Science Direct**	**Scopus**	**Web of Science**
AATC*	143	71	179	281	208	288	296
AATE*	46	44	148	113	55	131	154
Nagana	198	168	190	251	194	256	273
Sleeping Sickness	143	172	223	215	181	236	207
T.b. gambiense	26	39	131	169	179	163	154
T.b. rhodesiense	18	29	113	162	123	169	173
Tryps cm*	80	57	154	252	199	206	234
Tryps cs*	79	46	151	220	229	199	230
Tryps prev*	58	39	144	146	145	252	190
Tryps pro*	34	28	123	114	174	147	201
Tsetse cm*	152	106	**350**	271	184	286	**308**
Tsetse cp*	74	71	174	156	192	219	214
Tsetse Eradication*	63	64	160	141	155	174	174
Tsetse Control*	91	56	153	194	241	222	191
Tsetse Traps	154	151	171	231	156	218	257
Bush Clearing	12	22	135	23	153	26	54
Odor Bait*	56	94	158	86	152	104	179
Game Culling*	15	12	110	6	55	11	15
SIT*	40	38	130	99	145	129	156
Total	1482	1307	3097	3130	3120	**3436**	**3660**

* denotes terms that were abbreviated to maintain the structure of the table.[3]

[3] The list of terms have been included here for reference: African animal trypanosomiasis control (AATC) , African animal trypanosomiasis eradication (AATE), Trypanosomiasis control methods (tryps cm), Trypanosomiasis control strategies (tryps cs), Trypanosomiasis prevention – Tryps prev ,Trypanosomiasis prophylaxis – Tryps pro, Tsetse bush clearing – Bush Clearing, Tsetse control method – Tsetse cm, Tsetse control programs – Tsetse cp, Tsetse fly eradication – tsetse eradication, Tsetse fly control strategy – tsetse control, Tsetse Odor Bait Control – Odor Bait, Tsetse Game Culling – Game Culling, Tsetse Sterile Insect Technique – SIT. Cells shaded in blue represent the search terms with the highest results and the database with the highest number of results across all databases.

Traditionally, it is used for citation analysis to examine relationships among journal citations (Albort-Morant and Ribeiro-Soriano 2016). In this instance, the bibliometric analysis was used to determine the impact of research within a field, to reveal trends and shifts in published works over time, highlighting periods of publication intensity (Sweileh et al. 2015; Albort-Morant and Ribeiro-Soriano 2016; Kane, Roge, and Snapp 2016).

2.3.4 Topic Modeling using the Latent Dirichlet Allocation Method

Topic modeling was conducted across the combined global library using the document abstracts. Topic modeling is a text mining process that uncovers semantic themes within texts by examining how often words co-occur across a dataset (Blei 2012). The accompanying terms are grouped together revealing clusters of words appearing conjunctionally, thereby forming topics groups. The interdisciplinary nature of the tsetse and trypanosomiasis literature with its contrasting document types (i.e. lab notes, reports, lectures, articles, and books) can make synthesis difficult. The significance of the topic model approach is that it links emerging themes across the literature thereby producing an aggregated list of topics that might not be readily visible (Chang and Blei 2009).

The analysis deployed for this project used the 'topicmodels' package in R which creates the model following the Latent Dirichlet Allocation (LDA) approach (Jelodar et al. 2019). LDA allocates document contents into a specific theme, developing a Dirichlet distribution - a multivariate probability distribution (Ongaro and Migliorati 2013). The culmination of these functions effectively creates two embedded models: (1) an article level model which classifies articles using abstract texts of a topic and (2) corpus level model that classifies words for each

topic and creates the word cluster for the theme within the topic (Phan 2019; Jelodar et al. 2019; Ongaro and Migliorati 2013). In preparation for topic modeling the abstracts underwent format modification by removing capitalization, punctuation marks and other symbols. The outcome of the model determined the top three thematic topics within the literature over time and serves as a representational model of prevailing thoughts and research perspectives on the subjects through history (Phan 2019).

2.4 RESULTS AND DISCUSSION

The results of the bibliometric analysis and the topic modeling illustrate the shift in attitudes and approaches to tsetse and trypanosomiasis control over the past 122 years.

2.4.1 Bibliometric Analysis Results: Interconnectivity and Visualization

A correlations matrix was constructed to examine the linear relationships among the seven search databases based on the number of times they co-occur in the 'Manual Tags' field of the global library. The strength and direction of these interactions are illustrated in Table 2.2. A strong relationship is determined by correlation coefficients closer to +1 or -1, the optimal range is 0.7 to 1.0 and -0.7 to -1.0 (Akoglu 2018). None of the relationships in the sample achieved the strength threshold in either direction, which suggests there is minimal interaction among the search term results across the search databases, this will be further illuminated in later figures. Further, it validates the use of a comprehensive list of search terms and multiple search databases, resulting in a variety of literature providing both breadth and depth of the subject matter.

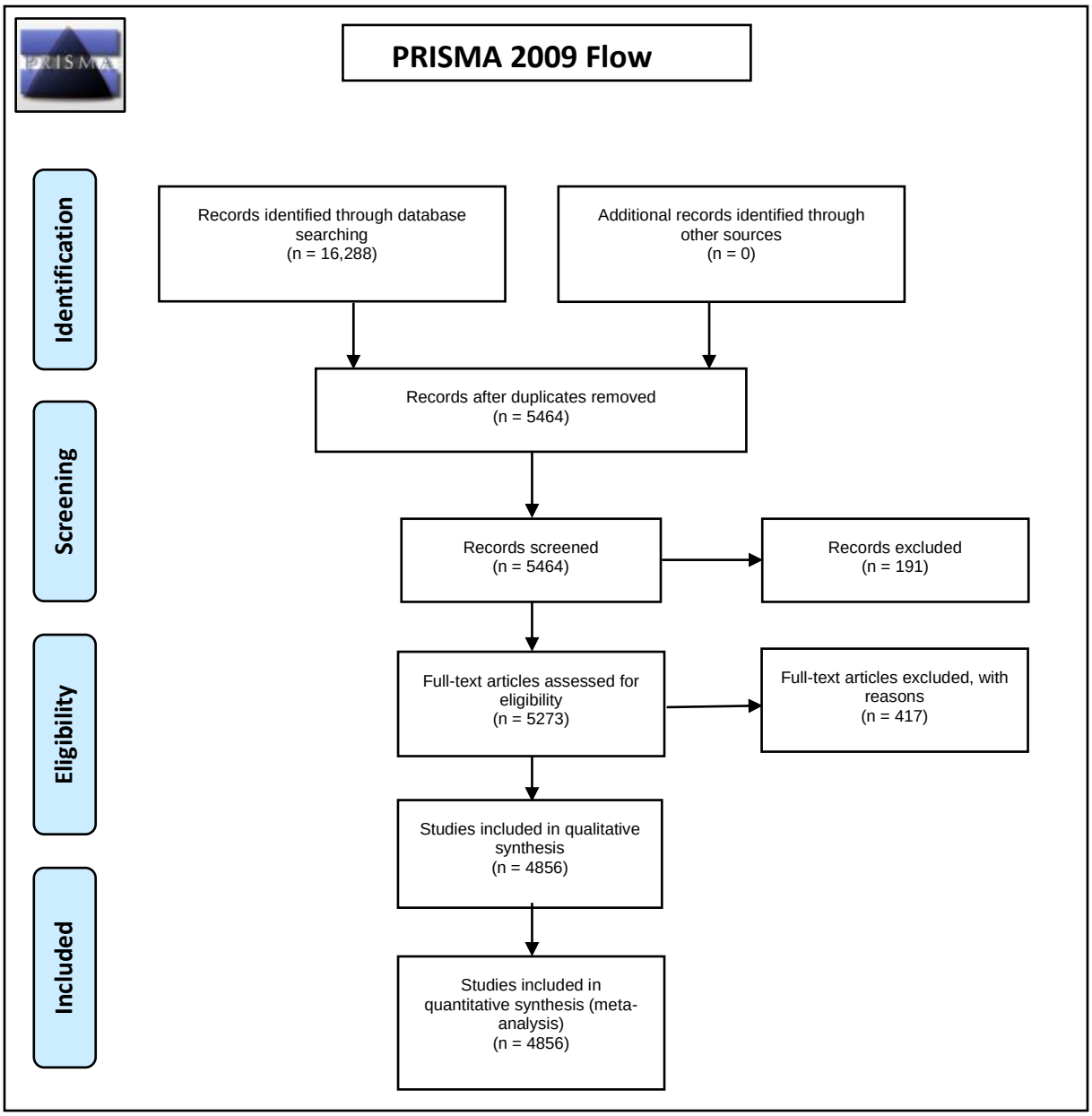
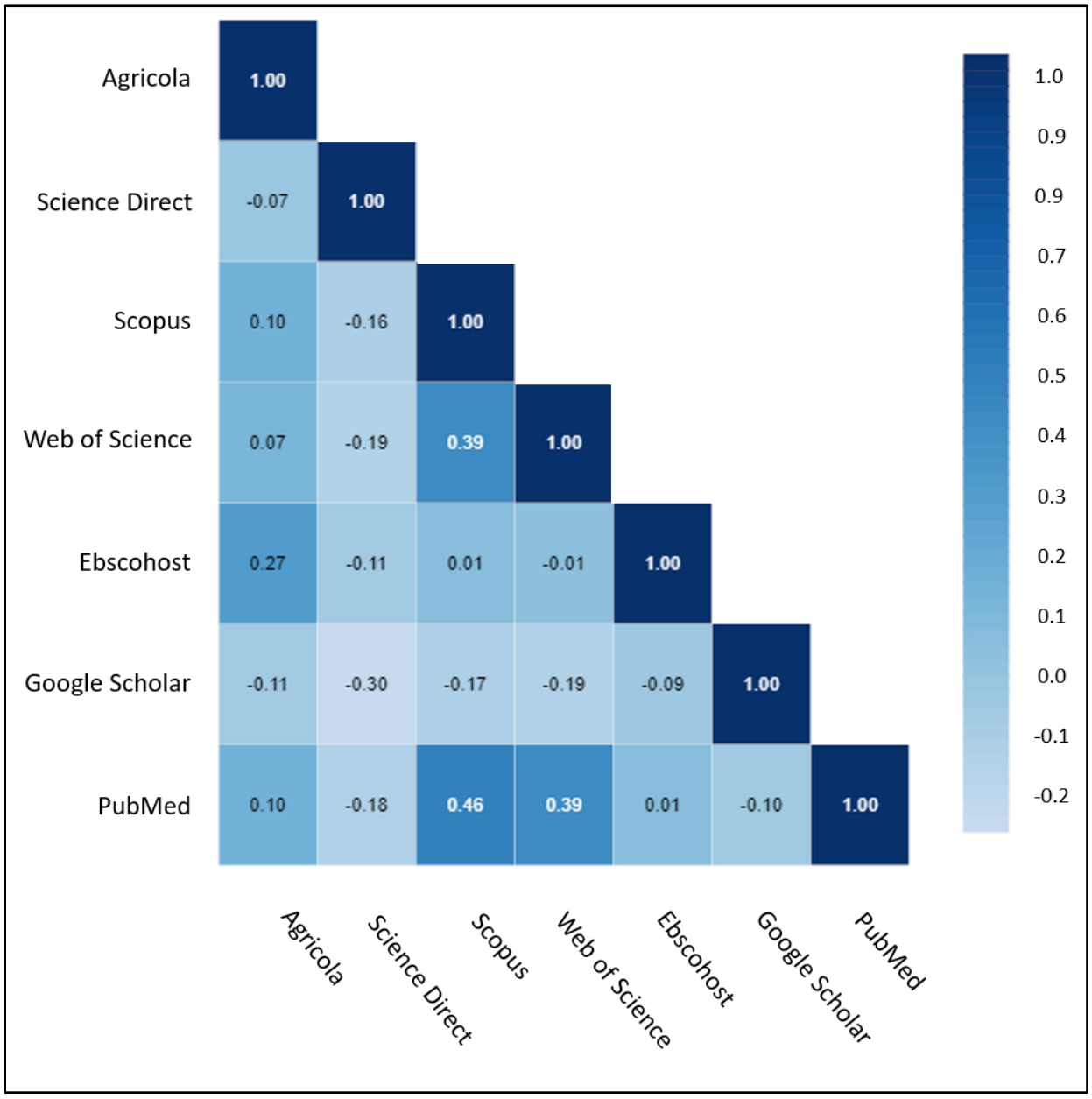


Figure 2. 1 Preferred Reporting Items for Systematic Reviews and Meta-analysis Workflow Diagram template.[4]

[4] Adapted from: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009).

Table 2. 2 Correlation matrix displaying the degree of overlap between the articles in each of the search databases.



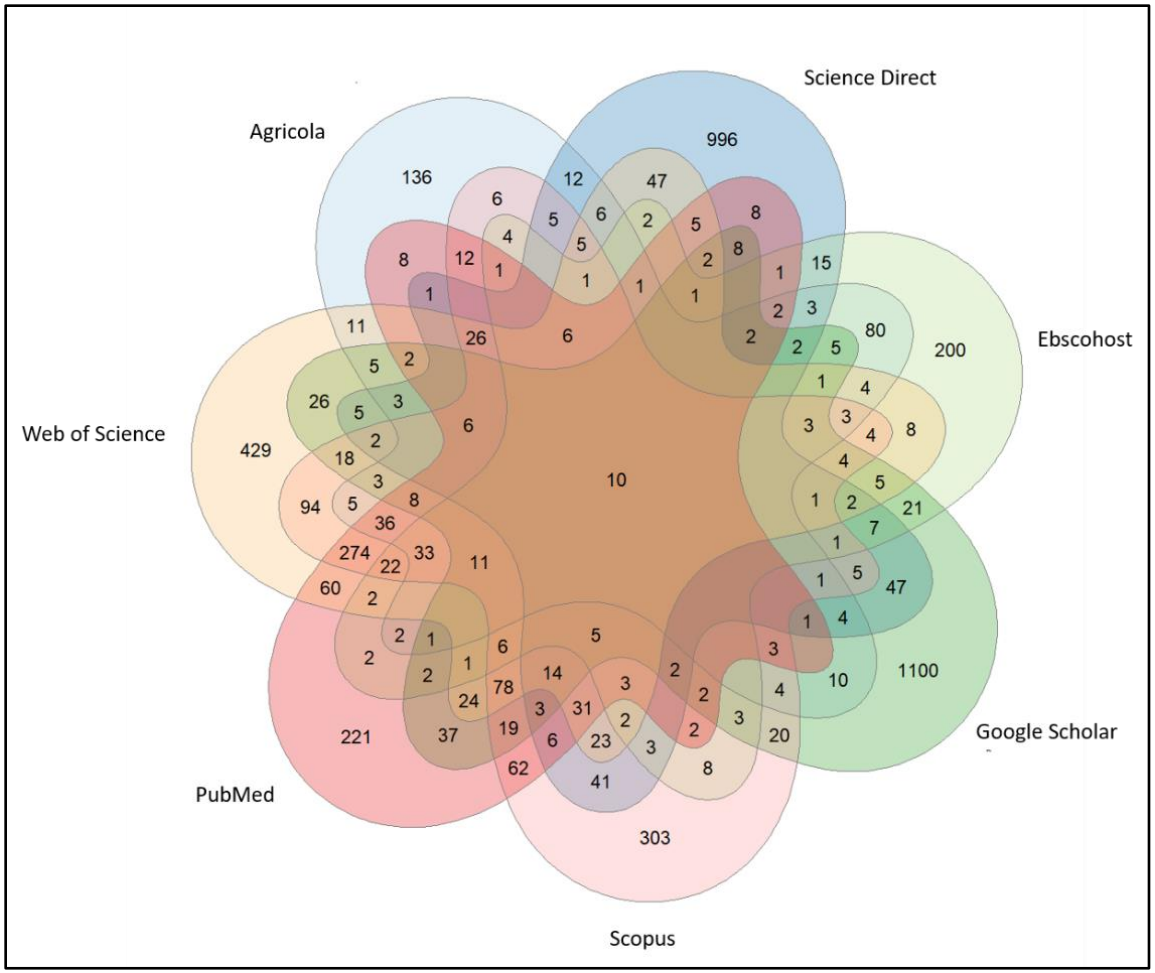


Figure 2. 2 Venn diagram representation of overlap among articles in the search engines of the final global meta-analysis library.[5]

[5]Numbers indicate the number of articles appearing in all search engines indicated by the petals of the polygon.

Scholars have chronicled trypanosomiasis since disease and environmental histories have been recorded. However disparate names over time and sparse details make definitive instances that indicate the presence of Nagana and trypanosomiasis inconclusive (Van Den Berghe 1956; Steverding 2008a; Lewis and Llewellyn-Jones 2018). Therefore, the bibliometric analysis examines the 4,856 records resulting from the 19 specific search terms outlined in Table 2.1 and covering 13 decades starting in the 1890's. During the earliest periods of observation from 1898-1928, the *Bulletin of Entomological Research* had the highest number of publications (Figure 2.3), indicating that scholars were interested in tsetse, its anatomy, and taxonomy.

Since the initial discovery of trypanosome infections of cattle in 1895, the period between 1900 and 1905 would hold the most major findings for trypanosomiasis (Castellani 1903; Mckelvey 1973; Bruce 1910). In 1901 British Surgeon, Michael Forde found human trypanosomiasis infections in the Gambia, Dutton later determined these to be the same trypanosomiasis infections previously discovered in cattle (Cox 2004; Cook 2008c), British pathologist David Bruce proved that tsetse of different families transmitted multiple variants of trypanosomes to humans and animals in 1903 (Bruce 1910), and in 1905, Canadian researcher Harold Thomas determined atoxyl had trypanocidal properties and begin its use as treatment for trypanosomiasis (Nieuwenhove 1999).

Insect science and research continues to drive the direction of tsetse and trypanosomiasis over the period from 1898 through 1928. These led to knowledge surrounding the habitat, ecological niche, behavior, and its role as the vector in Nagana and trypanosomiasis. The middle decades, 1929-1958 and 1959-1988, *Transactions of the Royal Society of Tropical Medicine and Hygiene*

and *Bulletin of Entomological Research* were the top journals, respectively. The latter decade from 1989-2020 saw the most published scholarship over the past 122 years. Notably, there was a significant shift in where the scholarship was published. During this time, no articles were published in either of the two abovementioned leading journals of the previous two 30-year periods. *PLoS Neglected Tropical Disease* has the highest number of publications of the period followed by Acta Tropica which had no prior publications. Figure 2.3 is a graphical representation of the highest publications for all topics across the observation period from 1898-2020. Appendix A contains similar graphs for each individual search term in the database over the same time.

Tsetse and trypanosomiasis literature embodies numerous disciplines including: entomology, veterinary science, microbiology, public health, environmental science, policy, and geography (Courtin et al. 2010; Thaddeus 2016; Isenberg and Nash 2014; Usman et al. 2008; Slegers 2008; Haluza and Jungwirth 2015; T. Barrett and Rossiter 1999). Likewise, the publication outlets are just as varying as the fields where the research is being generated. Figure 2.4 below displays the top five journals with the highest number of publications over the past 122 years. Of the 1,420 journals represented by the literature within the database, 279 of the articles were published in *PLoS Neglected Tropical Disease* representing 20% of the journals in the database as shown in Figure 2.3 below. *PLoS Neglected Tropical Disease* was established in 2007 focusing on endemic infections in tropical regions and has been dominating in the publishing of literature on tsetse and trypanosomiasis ever since (Figure 2.3).

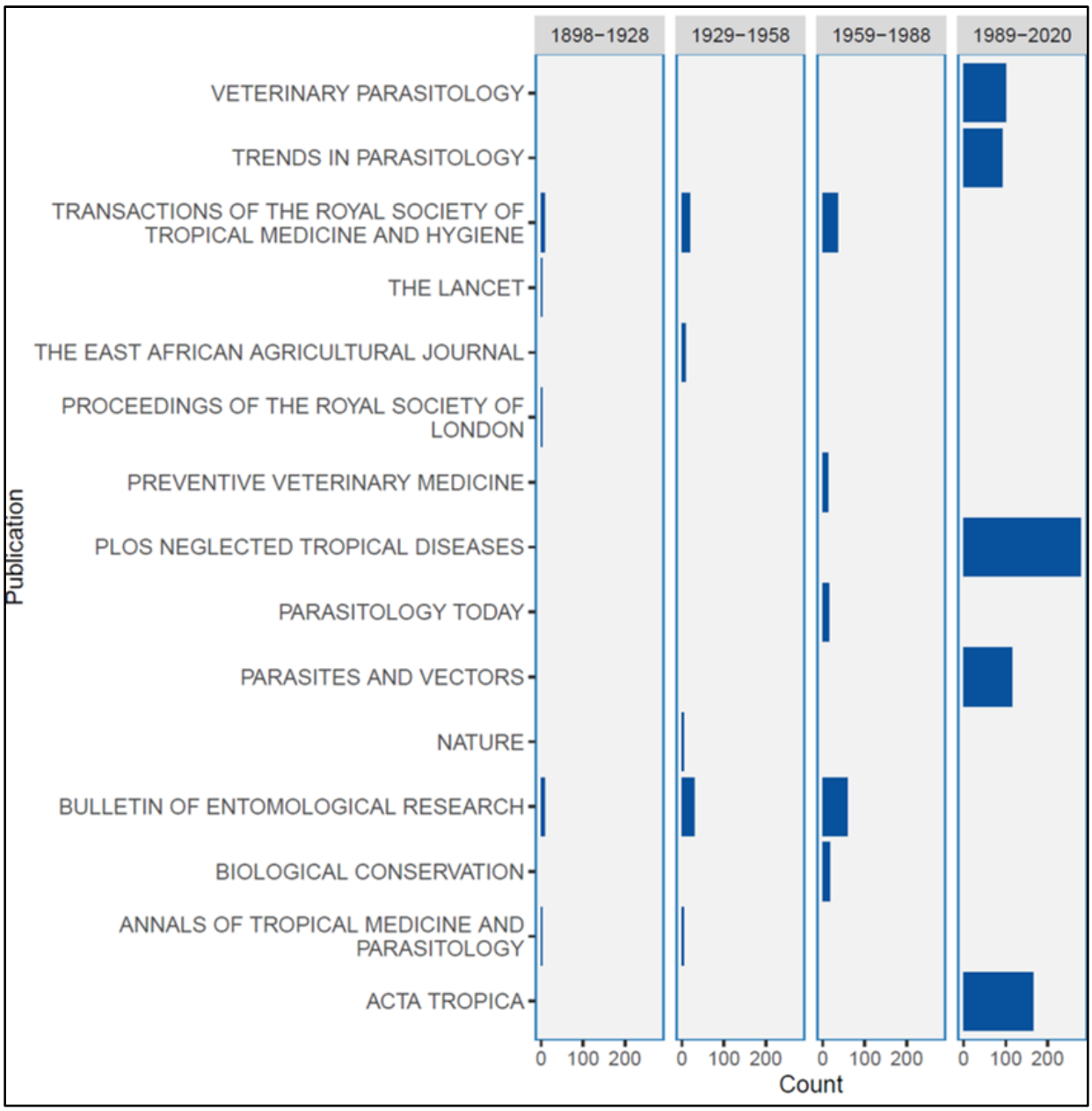


Figure 2. 3 Journals with the highest number of articles on tsetse and trypanosomiasis within each period.

The second most represented journal is *Acta Tropic* with 12% of the publications. *Acta Tropica's* emphasis is biomedical approaches to human and animal health in the tropics. Jointly, the two journals represent 32% of the total publications for the subject matter of the study. Overall, the results indicate submission preference among scholars, certainly suggesting journals' influences on these topics.

2.4.2 Topic Modeling Comparative Analysis Results

Data analytics have improved the way in which large volumes of data and text can be investigated, uncovering details embedded in records that might otherwise go unseen with conventional methods (Wang, Zhang, and Zhai 2011). One such text data mining approach is topic modeling. Using a topic model, prominent themes within the tsetse and trypanosomiasis corpus emerged (Figure 2.5). The resulting word clusters were determined based on the patterns and frequency at which the terms appeared within the semantic structure of the corpus (D. Blei, Carin, and Dunson 2010). The probability distribution, specifically the term posterior probability assignment is a key function of the topic model (Wang, Zhang, and Zhai 2011; Chang and Blei 2009). Posterior probability measures the likelihood that certain words appear within the same abstract. The volume of the universal library improved the posterior probability of the topic assignments, as more abstracts were processed associations between the document and the theme strengthened (Blei 2012).

Figure 2.5 shows the occurrence of subject clusters and the associated terms that form the topic groups within the universal library. The theme of **Topic 1** is the biological classification or taxonomy of tsetse, its population structure and vector control. The tsetse fly is the vector for

both human and animal African trypanosomiasis. Taxonomically, tsetse belongs to the animal kingdom - Order Diptera, Family Glossinidae and Genus Glossina with 23 species (Carpenter 1920; Ford 1971). Tsetse populations have three distinct phylogenetic clades: 1) palpalis (river) group - subgenus Nemorhina, 2) morsitans (savannah) group - subgenus Glossina, and 3) fusca (forest) group belonging to subgenus Austenia (Krinsky 2002; J. Messina, Moore, and Devisser 2012).

Comparably, the word cluster associated with **Topic 2** surrounds the parasitic organism, pathology, and the causative agent of infection. Trypanosomes, in particular Trypanosoma brucei and subspecies T.b. gambiense and T.b. rhodesiense are unicellular parasitic organisms transmitted from host reservoirs to tsetse during a blood meal and transferred through the saliva glands of tsetse to a different host, following a circular transmission cycle (Bouteille and Dumas 2003; Krüger and Engstler 2018). After ingestion, trypanosomes undergo a metacyclic change in the midgut of tsetse and continue to transmit infective parasites to hosts with each subsequent blood meal (Gibson and Bailey 2003).

In Trypanosoma brucei infections, as the metacyclic trypomastigotes migrate through the blood stream and cross the blood brain barrier in the central nervous system of the host, onset of disease symptoms occurs (Pentreath 1995). Acute or chronic disease expression occurs depending upon the variant of trypanosome that caused the infection (Masocha and Kristensson 2019; S.C. Welburn et al. 2009). . Seemingly the terms for this theme depict a propensity towards microbiology and pathogenesis.

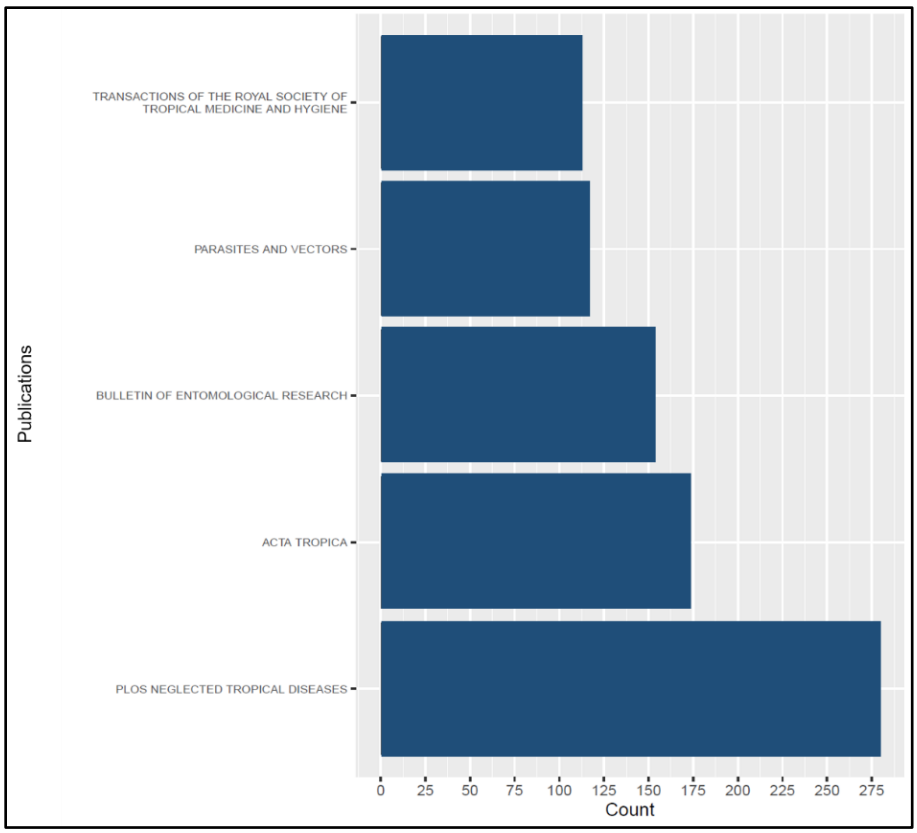


Figure 2. 4 Top five journals for tsetse and trypanosomiasis publications from 1898-2020.

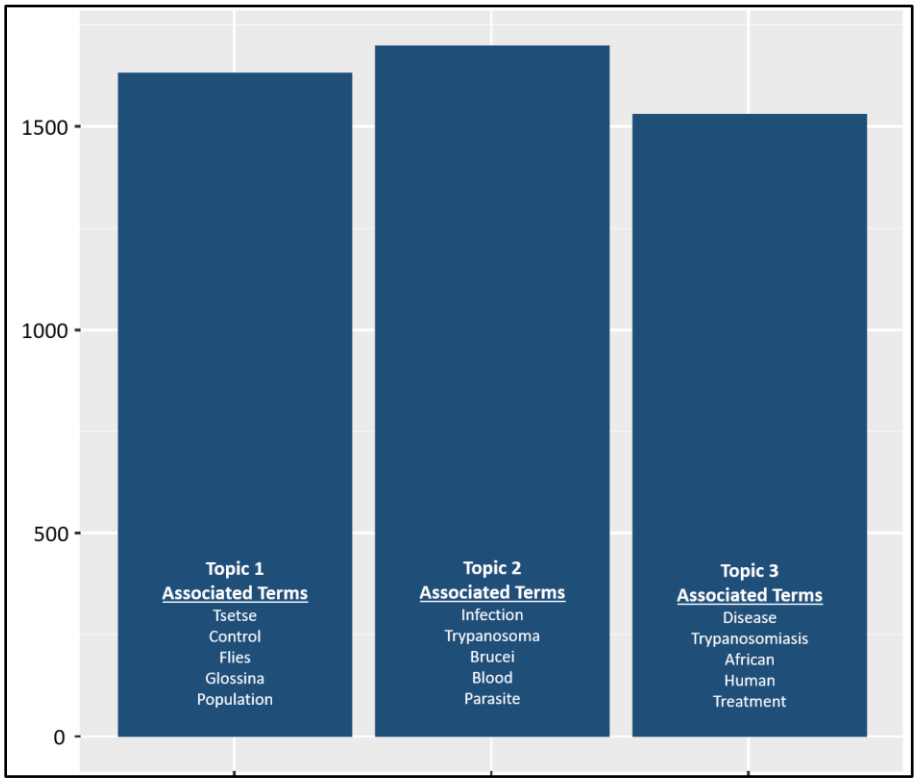


Figure 2. 5 Emerging themes and affilated terms from texts in the global library. The height of the bar indicates the article count for each theme.

When considered temporally, the rate of interest in Topic 2 outpaces all other topics in the corpus in the current decade (Figure 2.6), suggesting that there is still great interest in understanding the transmission and pathology of trypanosomiasis infections, likely to discover ways to disrupt transmission.

The collection of terms in **Topic 3** are connected to African trypanosomiasis disease and treatment. The African trypanosomiases are a group of parasitic diseases caused by unicellular protozoan organisms (Knight 1971; Vidilaseris and Dong 2014). The disease manifests in three forms: (1) chronic, west African trypanosomiasis resulting from a T.b. gambiense infection, (2) acute east African trypanosomiasis caused by T.b. rhodesiense, and (3) Nagana in animals caused by T.b. brucei, Trypanosoma congolense or Trypanosoma vivax infections (Rebeski et al. 1999). The disease is divided into two fundamental stages: (1) the haemolymphatic or early stage characterized by enlarged lymph nodes “Winterbottom’s sign” and, (2) the neurological or advanced stage in which the trypanosomes infect the brain of the hosts and lethargy ensues (Bisser 2016). Early treatment included the arsenic derivative atoxyl, later followed by chemotherapeutics pentamidine, suramin, melarsoprol and eflornithine (Cavalloro and Commission of the European Communities 1987; Malvy et al. 2014; Steverding, Kolosevska, and Sánchez-Moreno 2018). Historically, Topic 3 has trailed the other topics every decade except 2000-2009, even during major epidemics (Figure 2.6).

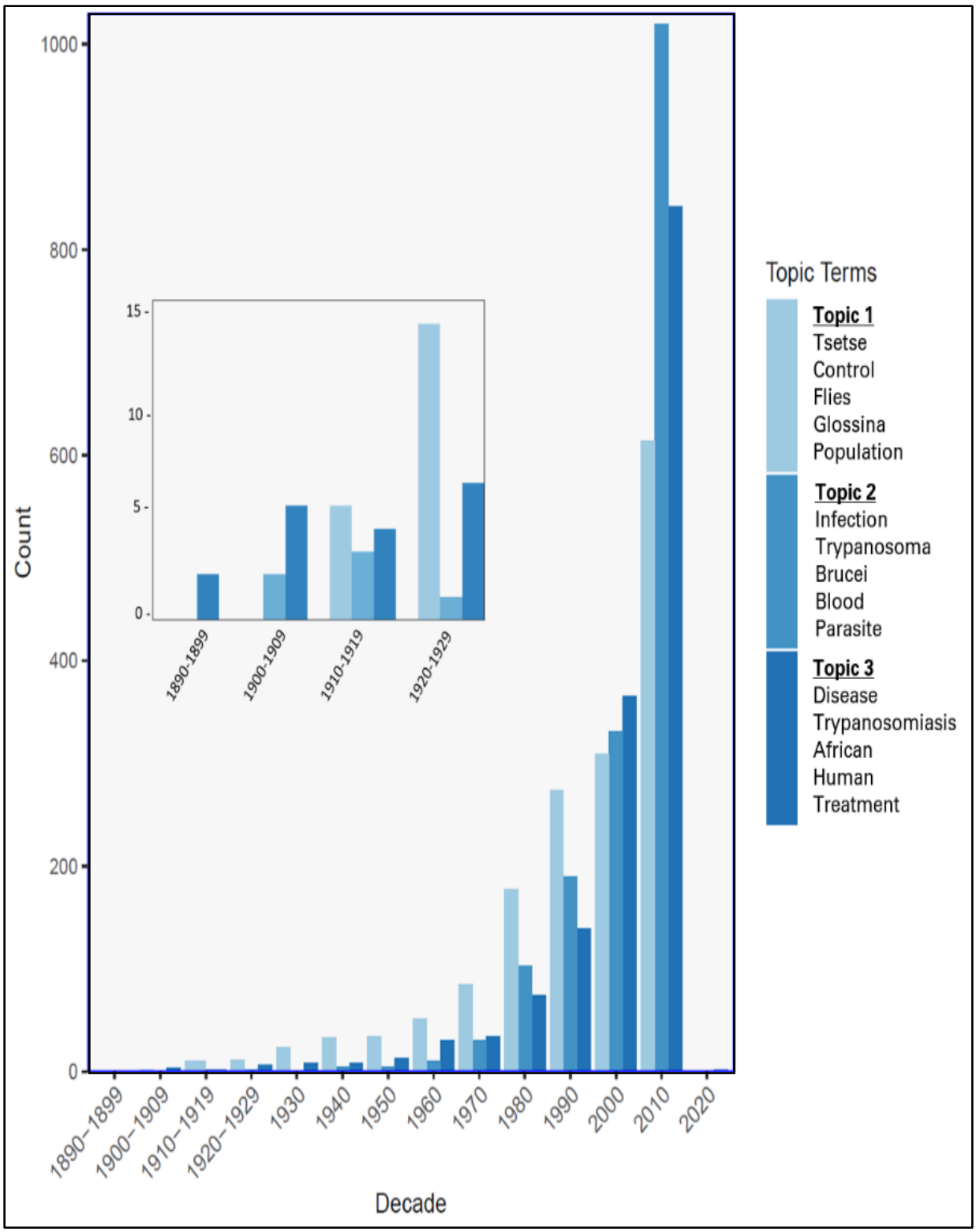


Figure 2. 6 Comparison of publications by topic themes over the decades.[6]

[6] The inset graph represents a magnified version of the first 4 decades of the study

Research relevance is the ability for a research topic to sustain scholastic interest over time, amid shifting scientific priorities, funding allocations and policy changes (Dobrow et al. 2017). It is a dimension of the "value to society" concept, which influences evolving strategies, funding decisions and behaviors towards scientific research and discovery (Dobrow et al. 2017; Floridi 2008). An examination of (Figure 2.6) provides an indication of the research relevance of tsetse and trypanosomiasis over the last 122 years, by topics as defined in (Figure 2.5).

The 40 year period from 1890 to 1929 was the backdrop of two major trypanosomiasis epidemics: 1896 through 1906 and 1920 (Morris 1951; Headrick 2014; Lehane et al. 2016). There were 43 publications identified in the universal library for this era. The graph inset in Figure 2.6 illustrates the themes of those literatures. Early compositions sought to characterize the disease system and potential treatments (Cook 2007; Castellani 1903; Durham 1908). However, around 1910 the shift towards control becomes apparent. In fact, control would remain the dominant topic of the ensuing 90 years through 1999, distantly followed by **Topic 3.** After prominence in the early years, disease etiology became the second most prevalent subject matter through the 1970's. The last major trypanosomiasis epidemic occurred from 1970 through the late 1990's.

Based on the graph in Figure 2.6, in every decade **Topic 1** has been the most published area, likely due to science still seeking to understand the fly, and only recently has there been a shift in exploration of the subject towards **Topic 3**. At the turn of the 21st century, the science of tsetse and trypanosomiasis began moving away from control, a research plateau was almost reached as publication topics harmonized. As research priorities matured, and new genetic

methodologies emerged, parasitology (**Topic 2**) began to emerge as the most published scholarship on tsetse and trypanosomiasis. By the end of the decade from 2000-2009, studies focusing on the infectious agent and pathogenesis surged ahead and remained the leading topic.

Articles were aggregated into the following thematic areas: *Human African Trypanosomiasis*, *Control Methods*, *Animal African Trypanosomiasis*, *Organism of Infection* and *Tsetse Eradication and Control*. Venn diagrams were used to determine the degree of commonality among search term sets across the five collections. Similar to Figure 2.2, the Venn diagrams of Figures 2.7 – 2.11 measure the amount of interaction between search term results of each subcollection. Examining these connection helps to determine if the use of multiple search terms was justified. It will also reveal if some topics were well explained by fewer search terms with greater overlap in the center of the union. For this study, overlap is measured by the number in the central section at the union of all the petals of the Venn diagrams.

The **Human African Trypanosomiasis** thematic group, displayed in Figure 2.7, shows the amount of overlap among the articles in the thematic group collection. Each petal is a subcollection of articles in the thematic group. The section where all the petals join is the union of the diagram. There are three shared articles at the union of the entire collection. Meaning that of the 2095 articles in the HAT thematic group, three articles were found across all the subcollections of the group. All the subcollections are related to the overarching subject of Human African Trypanosomiasis and some degree of overlap among the topics was expected. However, there were a couple of petal topics more closely connected than others for example,

trypanosomiasis control methods and trypanosomiasis control strategies have 120 mutual articles between them. Similarly, trypanosomiasis prophylaxis and trypanosomiasis prevention share 73 common articles.

Based on the outcomes in Figure 2.7, trypanosomiasis control strategies has the greatest amount of overlap with the other subcollections. These linkages suggest that control strategies are an important component of the HAT thematic group and that literature on HAT often includes control strategy references.

The **Control Methods** diagram in Figure 2.8 shows the degree of association among the subcollections of this thematic area. There is slight overlap between the Traps and Targets and Odor Bait Control petals with 88 shared articles, the strongest association of this collection. Interestingly, only one article at the union of the Control Methods collection. The article, *A critical study of the policy of tsetse eradication by Walter E. Ormerod in 1986 has been cited 97 times across the search results of this study* (Ormerod 1986). As the single publication shared across all the subcollections in this thematic group, this publication was in the results of all five search terms of the Control Methods thematic group. Overall, there is minimal overlap between the topics indicating that the subcollection of each individual petal provides unique literature to the Control Methods collection and as such to the breadth and depth of this project as a whole. However, when considering both figures jointly, the lack of mutual journal articles at the union of the venn diagrams indicates the topics were well explained by the search term results.

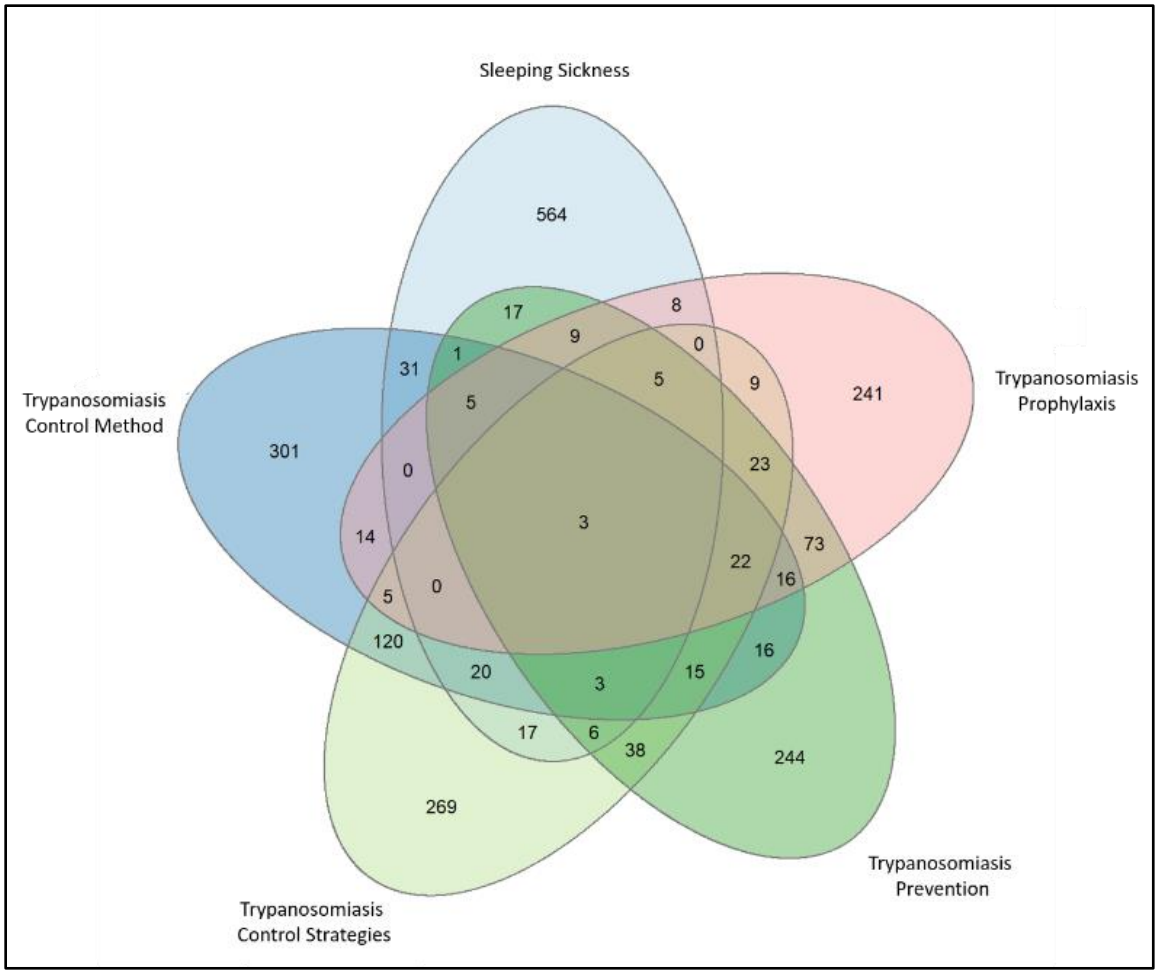


Figure 2. 7 Venn diagram of the Human African Trypanosomiasis thematic group. Numbers on each section represent the number of articles for the subgroup and the degree of overlap between subgroup themes

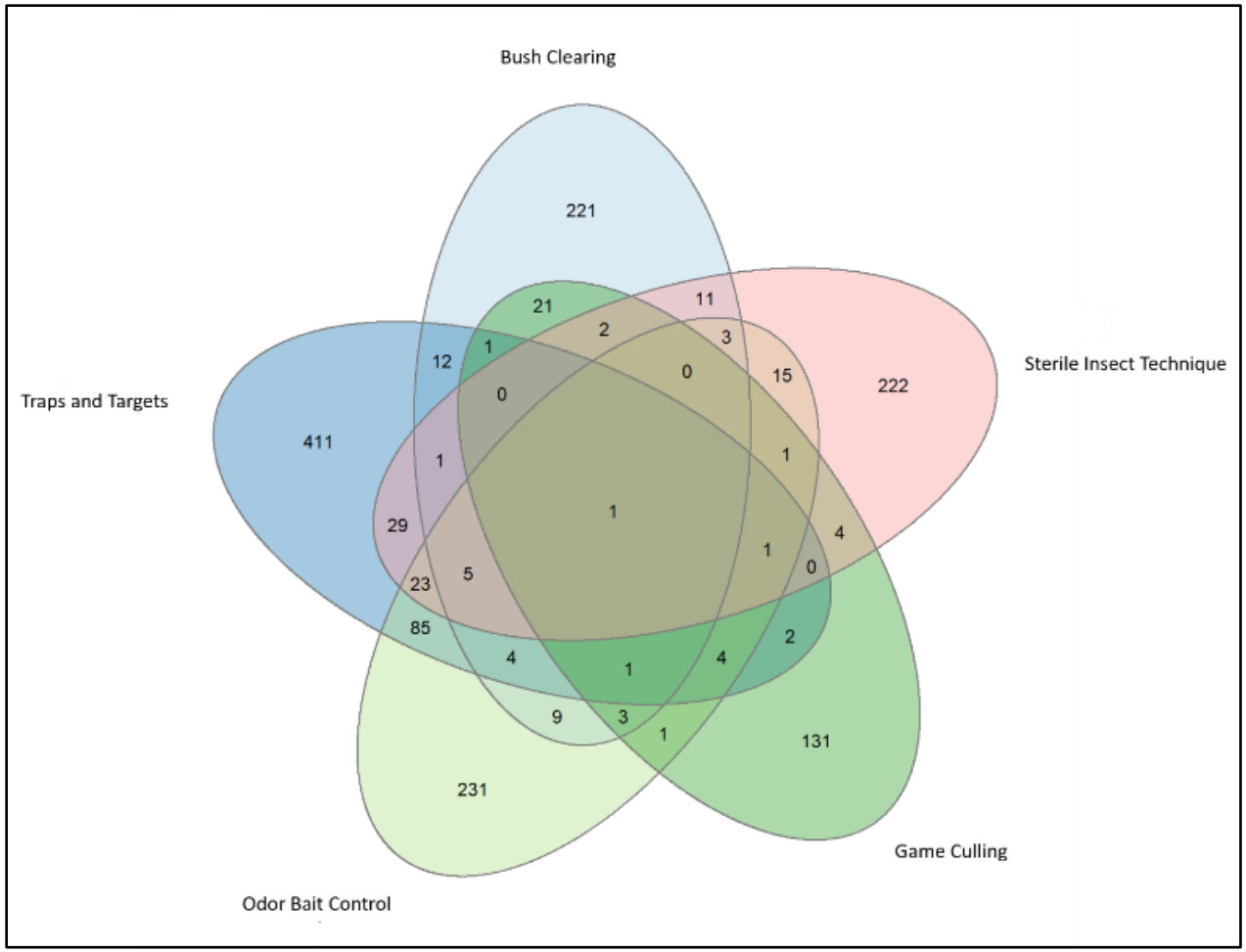


Figure 2. 8 Venn diagram of the Tsetse Control Methods thematic group. Numbers on each section represent the number of articles for the subgroup and the degree of overlap between subgroup themes.

Figure 2.9 shows a number of associations within the **African Animal Trypanosomiasis** article collection. The three subcollections in the interlocking spheres show a strong connection between Nagana and African Animal Trypanosomiasis Control and African Animal Trypanosomiasis Control and African Animal Trypanosomiasis Eradication with 133 and 78 articles, respectively. While there is a connection between the literature in the African Animal Eradication and Nagana literature collections, it is relatively minimal. There are 16 mutual articles at the union of the Venn diagram for this thematic group (Figure 2.9). The Nagana subcollection is the most abundant within this group. Nagana is the colloquial name for African Animal Trypanosomiasis. It is not surprising that there overlap between Nagana and African American Trypanosomiasis topics, it is interesting that there is not more connection since the terms are synonymous.

Trypanosoma brucei subspecies, T.b. gambiense and tb rhodesiense are infectious organisms in human and animal trypanosomiasis infections. While other trypanosomes cause infections in animals, the Trypanosoma brucei group organisms infect both and therefore are the focus of the **Organism of Infection** thematic group. Moreover, Figure 2.10 shows substantial association between T.b. gambiense and T.b. rhodesiense subcollections which have 188 mutual articles in common. The high degree of overlap reflects the co-occurrences of each topic in texts on the subject matter.

The **Tsetse Eradication and Control** thematic group has the strongest relationships among all the Venn diagrams in Figures 2.7-2.11. Unlike some of the previous thematic groups in which the associations get weaker the more subcollections overlap, the associations among the

subcollections in Figure 2.11 increases with more overlap. The strengthening in the association of the petals indicate that the subcollections are correlated, signifying that fewer terms could have explained the subject matter of the collection sufficiently.

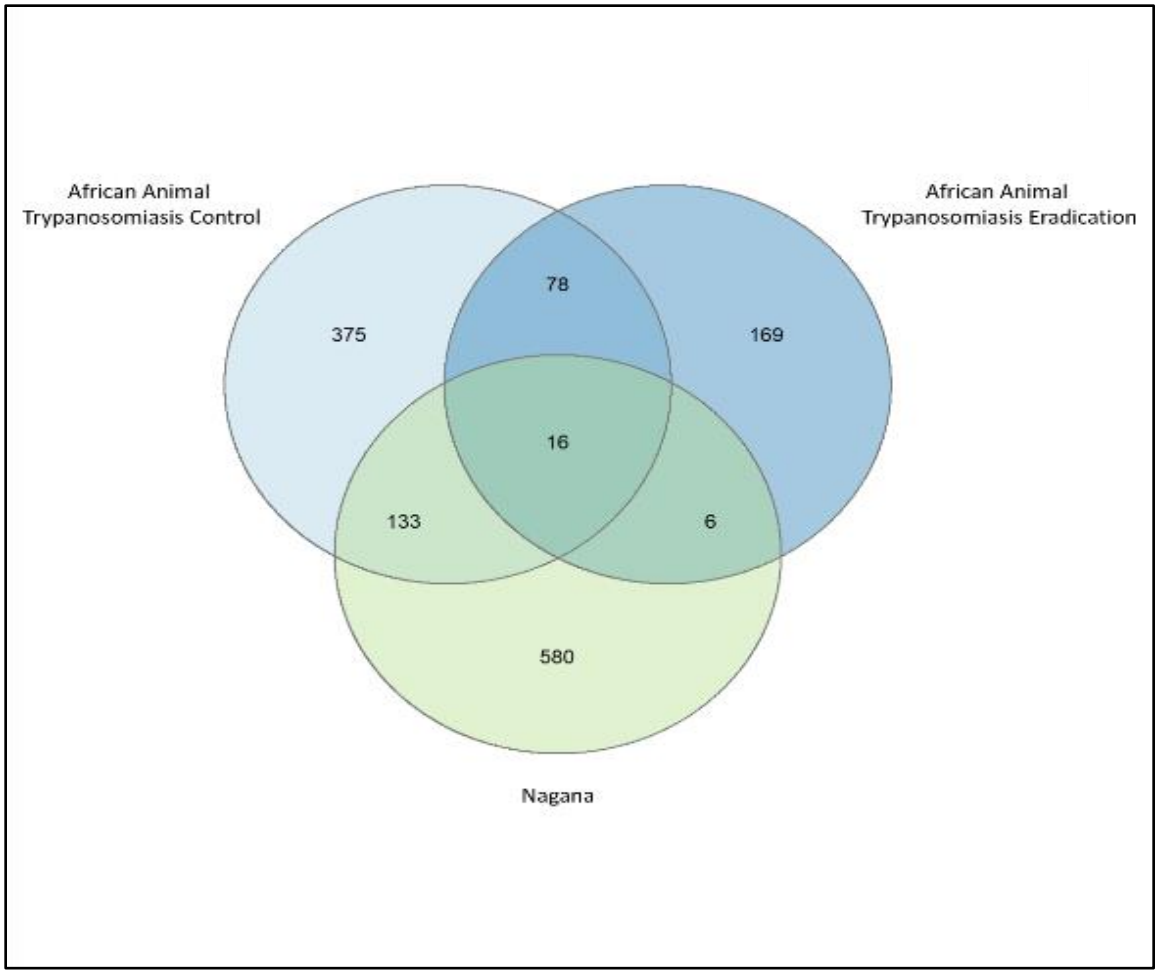


Figure 2. 9 Venn diagram of the African Animal Trypanosomiasis thematic group. Numbers on each section represent the number of articles for the subgroup and the degree of overlap between subgroup themes.

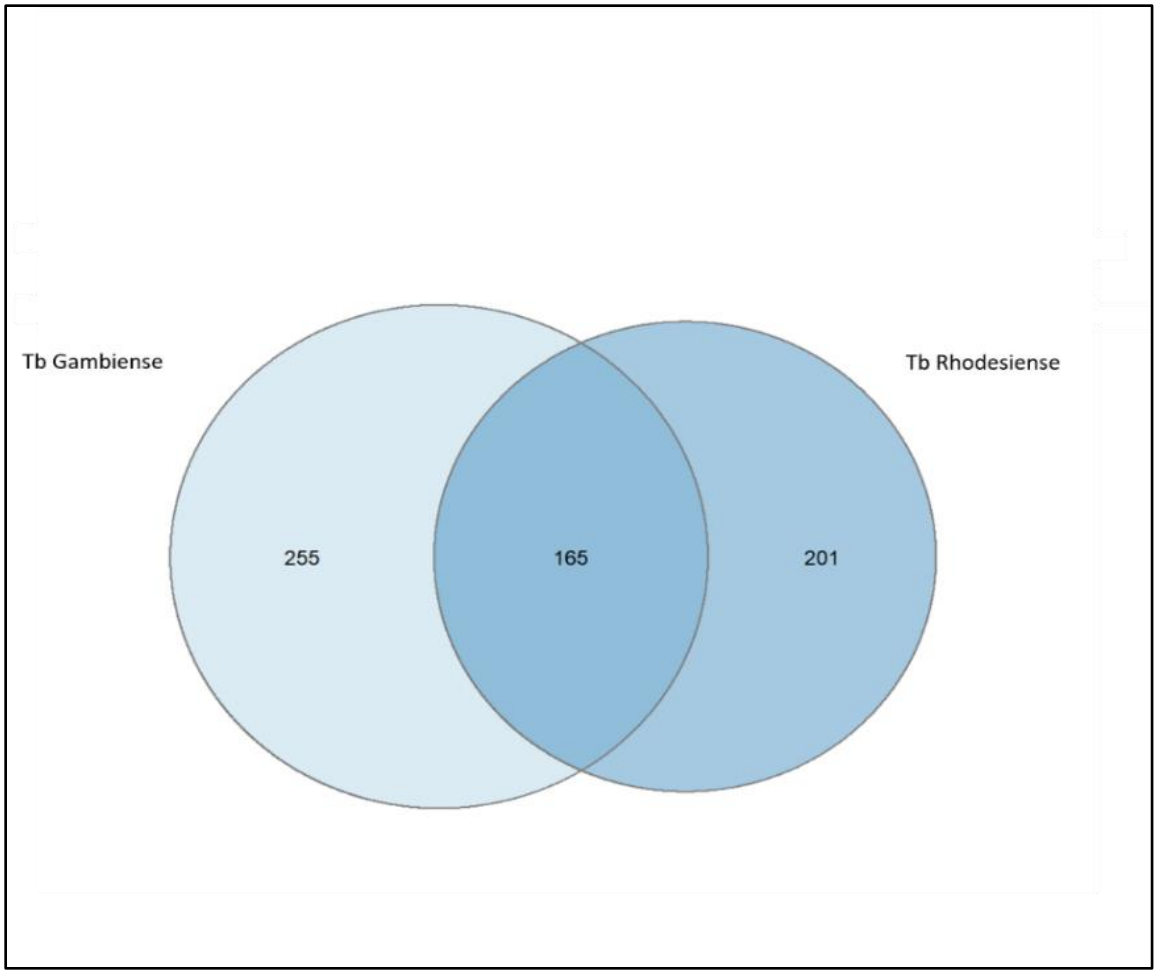


Figure 2. 10 Venn diagram of the Organisms of Infections in the human and animal African Trypanosomiasis thematic group. Numbers on each section represent the number of articles for the subgroup and the degree of overlap between subgroup themes.

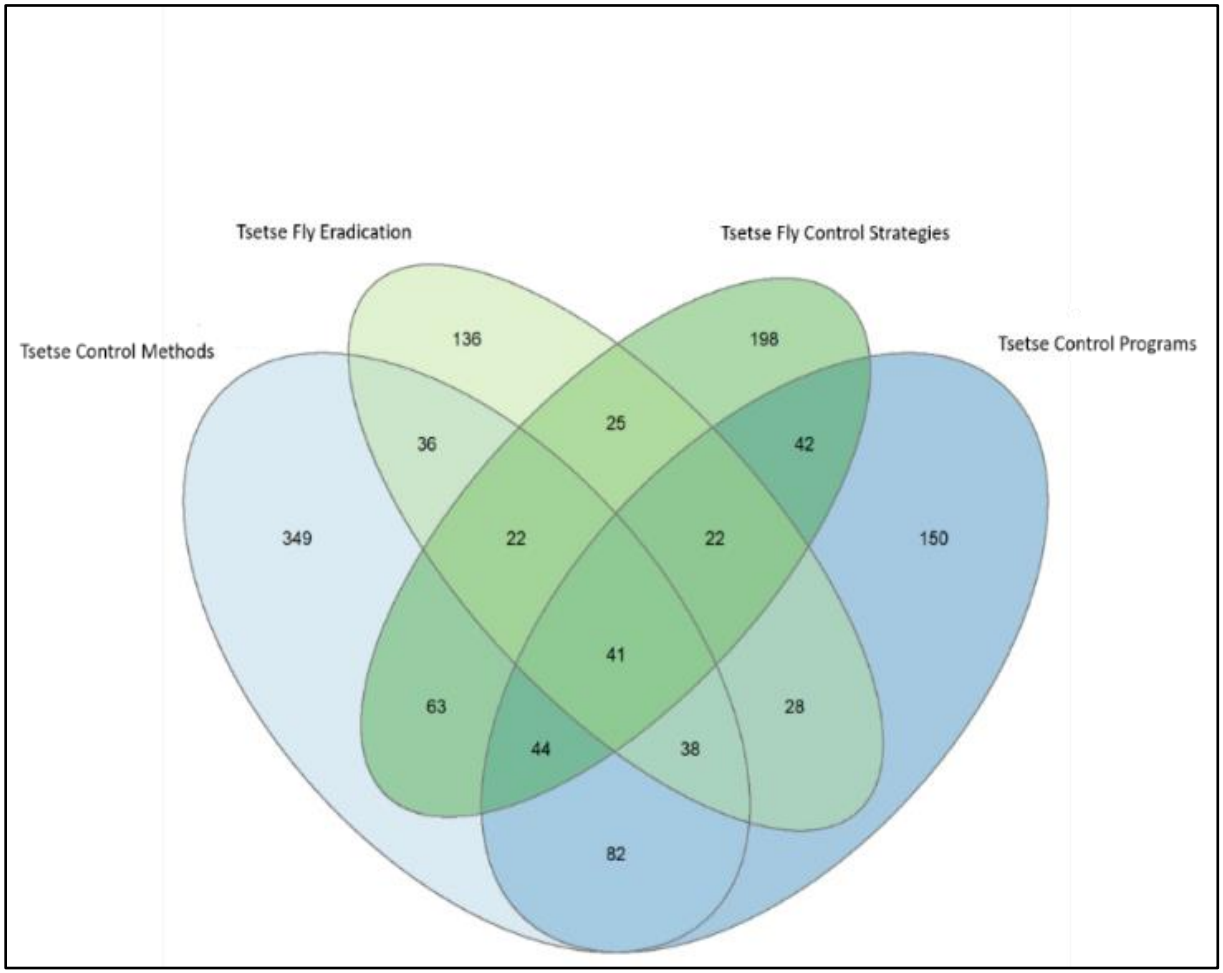


Figure 2. 11 Venn diagram of the Tsetse Eradication and Control thematic group. Numbers on each section represent the number of articles for the subgroup and the degree of overlap between subgroup themes.

2.5 LIMITATIONS

The study provided a meta-analysis of tsetse and trypanosomiasis literature from 1890 to 2020. The results presented an evolutionary view of trends throughout the time period, shifting scientific priorities and duration of efforts towards tsetse and trypanosomiasis prevention, control, eradication, and treatment. The most significant limitation was reference quality and missing data in the form of incomplete records during the search process. Abstracts and full text for some records could not be located, resulting in the exclusion of those documents from the analysis. In some instances, although the name of the text was available, exhaustive web and library searches for the actual document or abstract proved unfruitful. The potential impact those contributions could have on the study outcomes cannot be realized.

Similarly, some records were corrupt and riddled with indecipherable non-phonetic characters which made the document illegible, further reducing the available documents that could be analyzed. Since the study methodology included bibliometric analysis and topic modeling which rely heavily upon the completeness of the record and the presence of an abstract, records without those key items were removed. The inclusion of those records could have altered the outcome of the three major topic areas, the topic trends over time and associations among the search term results. However, given the volume included, those few removed were very unlikely to have affected the outcome. Despite the limitations, the study afforded the opportunity to review large volumes of literature on the subject matter using a variety of models that (re)organized the data in meaningful ways to enhance our understanding of the

subject matter and reveal nuance that might not emerge with traditional literature review methods.

The bibliometric analysis revealed the top five journals for tsetse and trypanosomiasis control topics over the past 122 years are: Transactions of the Royal Society of Tropical Medicine and Hygiene, Parasites and Vectors, Bulletin of Entomological Research, Acta Tropica, and PLoS Neglected Tropical Diseases. The results illustrate shifts in journal preference from Transactions of the Royal Society of Tropical Medicine and Hygiene and Bulletin of Entomological Research in the first 60 years of observation, to PLoS Neglected Tropical Diseases which has published the highest number of articles on tsetse and trypanosomiasis control since 1989.

The topic modeling time analysis illustrates shifting research priorities evidenced by publication trends. For example, control was the dominant research topic for 100 years however, over the past two decades it has lost prominence. Despite control being of critical importance to the tsetse and trypanosomiasis subject matter, the sustained reduction in publications could influence funding decisions, impact control program development, and contribute to disparate control outcomes throughout the endemic region. The interconnectivity analysis of the topic model affirms the use of 19 search terms and 7 search databases to comprehensively examine the tsetse and trypanosomiasis control subject matter. The minimal overlap at the union of Figure 2.2 and in sections 2.4.2 demonstrate that each term captured mostly unique texts with few common documents across the specific sets of search terms.

Lastly, journals and publications influence patterns and practice, including the abundance of literature thus creating trends in dominant thoughts and perspectives. When seeking to answer questions surrounding control research priorities over time, a driving factor could be shifts in publication emphasis and importance. Over the past 12 decades, tsetse and trypanosomiasis research has been impacted by political will, funding constraints and other socio-economic and technical barriers, resulting in suboptimal control outcomes regionally. Projects like this can offer new insights with the potential to improve understanding and generate interest in this area.

MODELING AND MAPPING THE TSETSE AND TRYPANOSOMIASIS RISK AND CONTROL LANDSCAPES: A SCALABLE APPROACH

3.1 INTRODUCTION

African trypanosomiasis is a parasitic infection caused by pathogenic protozoa of the genus Trypanosoma. The parasite is transmitted through the salivary glands during a tsetse fly bite (Baig 2017). Colloquially known as 'sleeping sickness' or 'Nagana', African trypanosomiasis is a neglected tropical disease endemic to 36 countries in sub-Saharan Africa (Ormerod and Rickman 1988). Despite decades of research to control tsetse, trypanosomiasis continues to threaten the health and well-being of people and animals across the African continent (Kioy and Mattock 2005). Compounded by resource constraints, African trypanosomiasis is poorly understood (MacLean et al. 2004), underreported (Scoones 2014), often misdiagnosed (Veerle Lejon, Jacobs, and Simarro 2013) and ultimately fatal (Rodgers 2009). The disease has a case fatality rate of nearly 100% and available treatments are expensive and mildly toxic (P. P. Simarro et al. 2012; Sutherland and Tediosi 2019). Thousands of people and animals die from the disease annually and an estimated 60 million Africans are at risk illuminating the necessity for risk reduction strategies (Mogk et al. 2012).

Risk is characterized as the estimation and probability of exposure to hazards, resulting in the occurrence of potentially adverse health effects (Sarrif 1996). For the people of sub-Saharan Africa, trypanosomiasis risk is a consequence of daily existence (Jamison et al. 2006). Trypanosomiasis has caused challenges and threatened the livelihood of African residents for years. There are geographic variations in risks and this chapter examines African

trypanosomiasis risk through a scalable approach to risk identification and risk reduction. Through this inquiry the following questions will be explored: (1) how will identifying areas at-risk for trypanosomiasis enrich control strategy development, (2) does risk vary across space, and (3) will a two-step trypanosomiasis risk reduction framework improve control systems.

Tsetse have always been present throughout history. While all tsetse species are now confined to continental Africa, fossilized remains of tsetse have been found in North America, assumed to be relics left from Pangea (Lambrecht 1980). Tsetse belongs to the Family Glossinidae, genus Glossina and is the vector of both human and animal African trypanosomiasis (Carpenter 1920; Ford 1971). Tsetse is an ecologically dependent vector, geographically constrained to the sub-Saharan region of African due to environmental and climatic factors that make the area more suitable (Ford 1971; FAO 1982; Franco et al. 2014). The internal limits of tsetse habitats are south of the Sahel (15°N) and north of the Kalahari (20° S) with coastal limits along the eastern perimeter of the continent (FAO 1982; Jose R. Franco, Simarro, Diarra, and Jannin 2014; Mahamat 2015a).

There are three biological groups of tsetse: 1) palpalis of subgenus Nemorhina vector for the anthroponotic chronic infections 2) morsitans of subgenus Glossina vector for the zoonotic acute infections and African animal trypanosomiasis (Nagana) and 3) fusca of subgenus Austenia (Krinsky 2019; Emerson et al. 2007; Takeet et al. 2016). The typical habitat for morsitans tsetse is woodland and open savannahs that are neither humid nor dry with temperatures that range from 19-28° Celsius (FAO 1982). The habitat for Glossina morsitans includes scattered thickets and forest edges (FAO 1982; Mahamat 2015a). In hot conditions,

morsitans behaves more like a riverine fly and seeks cool moist habitats (FAO 1982, 2006, 2016). The palpalis tsetse prefers gallery forest, swamps and river edges with a high relative humidity and shade (FAO 1982, 2006, 2016).

Tsetse and trypanosomiasis risks impact all areas of productive life for the rural people of sub-Saharan Africa. Household chores and subsistence activities such as water and firewood procurement, and pastoralism provide the greatest source of exposure risk of being bitten by an infected tsetse fly and increases the risk of infection (Sunseri 2013; Muimba-Kankolongo et al. 2015). Although all tsetse are vectors of trypanosomiasis, not all tsetse carry trypanosomes (Aksoy et al. 2014). However, regular and sustained exposure to tsetse increases the likelihood of being bitten by the fly and thereby increases the probability of infection (Cunningham et al. 2016).

3.2 BACKGROUND

Researchers lamented that tsetse and trypanosomiasis continuously posed a threat to African development and advancement since before written records (Alsan 2015c; Buxton 1947). The vastness of the sub-Saharan Africa region has made control of tsetse and trypanosomiasis challenging. Many underlying factors contribute to the complexity of tsetse and trypanosomiasis control. A review of the literature from Chapter 2 reveals that ecological awareness of the tsetse habitat preference, epidemiological knowledge about the distribution of trypanosomiasis, and genetic comprehension of tsetse's microbiology have improved with time. Some potential causes for the differences across space are that tsetse control initiatives are often designed site-specifically, are not generalizable which can make scaling up or down

between the local, regional, or national level difficult. Further complicating matters are political tensions and the effects of tribalism, which prevent countries and their border partners from comprehensive collaborative control efforts in order to address transboundary reinvasion threats. Moreover, some isolated tsetse populations remain unreachable by low-tech control methods and require expensive approaches such as sequential aerial spraying (SAT) or sterile insect technique (SIT), which are not economically feasible options for many countries.

Researchers have defined risk areas as rural sub-Saharan Africa and at-risk populations as those for whom daily activities regularly require engagement with tsetse habitats, at times when tsetse are active (Franco et al. 2016). However, risk is not uniform, ubiquitous, nor continuous across the landscape. This project contributes to literature and addresses this gap by classifying risk from multiple drivers, characterizing risk magnitude, developing a comprehensive determinants of risks framework, and producing control and risk reduction strategies. Additionally, this project is a departure from traditional site specific approaches and attempts to address risk from a geospatial perspective. The central hypothesis is that a coordinated, simultaneous, scalable, and generalizable control strategy will improve outcome efficacy across space and time.

Systemic differences in control and eradication methods have led to mixed results (Rayaisse et al. 2010). Current tsetse control efforts follow two models: 1) reservoir reduction through epidemiological surveillance and clinical treatment and 2) vector control through traps, targets, aerial pesticides, and sterilized insects (Brun 2010; Headrick 2014). These efforts are conducted singularly or in tandem with other approaches (Meyer et al. 2016). While epidemiology and

vector control studies have contributed immensely to the research on tsetse and trypanosomiasis, many of them have been 1) spatially dependent, in other words, created specifically for one location, 2) lack broad applicability, that is to say, they are often not generalizable beyond the location the approach was created for, and 3) have not been sustainable long-term. This chapter will explore risk through a case study analysis of Senegal and Tanzania, examining the risk landscape and the determinants of trypanosomiasis risk, develop a series of risk models, and conduct a comparative analysis of simulated control approaches.

3.3 CASE STUDY

The case study for this project explores the determinants of risk, identifying risk areas, and risk reduction approaches for Senegal and Tanzania. Senegal is a coastal, Francophone, west African nation. The country occupies a 197,000km^2 area at the far western extent of the tsetse belt, in the Sahel. Senegal is flanked by the Atlanta Ocean to the west, Mauritania to the north and Mali to the east (Pison et al. 1995). Senegal has a population of approximately 16 million people with densely populated urban and rural areas ("WHO | Senegal" 2020). Senegal is a flat, semi-arid country dominated by savannahs, woodlands, gallery forest and some wetlands. The temperature ranges, relative humidity, and vegetation combine to create suitable habitats for tsetse populations (Table 3.1). Senegal is home to several species of the fly including: *Glossina Gambiense palpalis, Glossina morsitans submorsitans, and Glossina Longipalpis* (Table 3.1).

The United Republic of Tanzania is the largest country in East Africa and includes the Zanzibar Archipelago. Situated in the Africa Great Lakes region, the landscape of Tanzania provides

extremely suitable habitat for tsetse. Tanzania has an area of 947,000km^2 with varied terrain including vast grasslands, savannas, and mountain ranges. Tanzania is home to both the Serengeti National Park and Mount Kilimanjaro, the highest mountain in Africa. The country is bordered by the Indian Ocean to the east, Burundi, Rwanda and the Democratic Republic of the Congo to the west, Mozambique and Malawi to the south, and Kenya and Uganda to the North. Tanzania is a large country with a population of 56 million residents in Dar es Salaam excepted, mostly people live in small, albeit densely populated rural settlements ("WHO | United Republic of Tanzania" 2020).

The temperature, vegetation types, and humidity levels create the right conditions for habitat suitability for tsetse. Tsetse is abundant in Tanzania and numerous species of the fly exist throughout the country (Rogers and Williams 1993; Adams et al. 2006). Table 3.1 lists tsetse species in the United Republic of Tanzania. The island of Zanzibar was home to forest tsetse, Glossina austeni, and in the 1990's became the first place in the world to eradicate the fly, however Glossina austeni still exists on the mainland.

Humans and animals are the host reservoirs for trypanosomes. The classic transmission pathways for African trypanosomiasis follow four primary routes exhibited in Figure 3.1. The origin of each path starts with the mammal host.

Table 3. 1 Characteristics of the Senegal and Tanzania case study areas.

		Study Areas				
Country	**Area**	**Population**	**Tsetse Species**	**Habitat Type**	**Trypanosomiasis**	**Control Programs**
Senegal	197,000 km^2	15.85 million	G. Gambiense palpalis G. morsitans submorsitans G. Longipalpis	Riverine Savannah Savannah	West African ***(human/chronic)*** Nagana ***(animals)***	Insecticide Traps Sterile Insect Technique ***(SIT)***
Tanzania	947,303 km^2	56.13 million	G. morsitans-morsitans G. Centralis mochado G. swynnertoni G. austeni G. pallidipes G. longipennis G. brevipalpis G. fuscipleuris G. Fuscipes G. fuscipes martini	Savannah Savannah Savannah Forest Savannah Forest Forest Forest Riverine Riverine	East African ***(human/acute)*** Nagana ***(animals)***	Insecticide Traps Targets Sterile Insect Technique ***(SIT)***

Trypanosomes are ingested by the tsetse fly during the blood meal of both male and female flies (Franco, Simarro, Franco, et al. 2014). The trypanosomes undergo a binary division in the midgut of the fly and convert to the epimastigotes (Hendry and Vickerman 1988). The epimastigotes migrate to the salivary glands where they multiply and transform into metacyclic trypomastigotes, the infectious form that is injected into mammal hosts as tsetse takes a blood meal (Sharma et al. 2009). The trypanosomes multiply at the injection site and travel through the body via the lymphatic system (D'Archivio et al. 2013). The host becomes symptomatic after the trypanosomes cross the blood-brain barrier in the central nervous system of the host (CDC 2019b). Figure 3.2 demonstrates the trypanosome life cycle and the human and animal trypanosomiasis transmission cycle.

The case study countries present all three models of the infection. Both human and animal African trypanosomiasis follow the aforementioned infection transmission process, however the disease outcomes differ significantly based on the causative agent. The trypanosome species that causes the infection in each region will differ as well (see Table 3.2). Trypanosoma brucei gambiense (T.b. gambiense), named for the region where it was discovered, is the agent of infection for West African trypanosomiasis. Senegal is one of the countries where T.b. gambiense can be found (see Table 3.2).

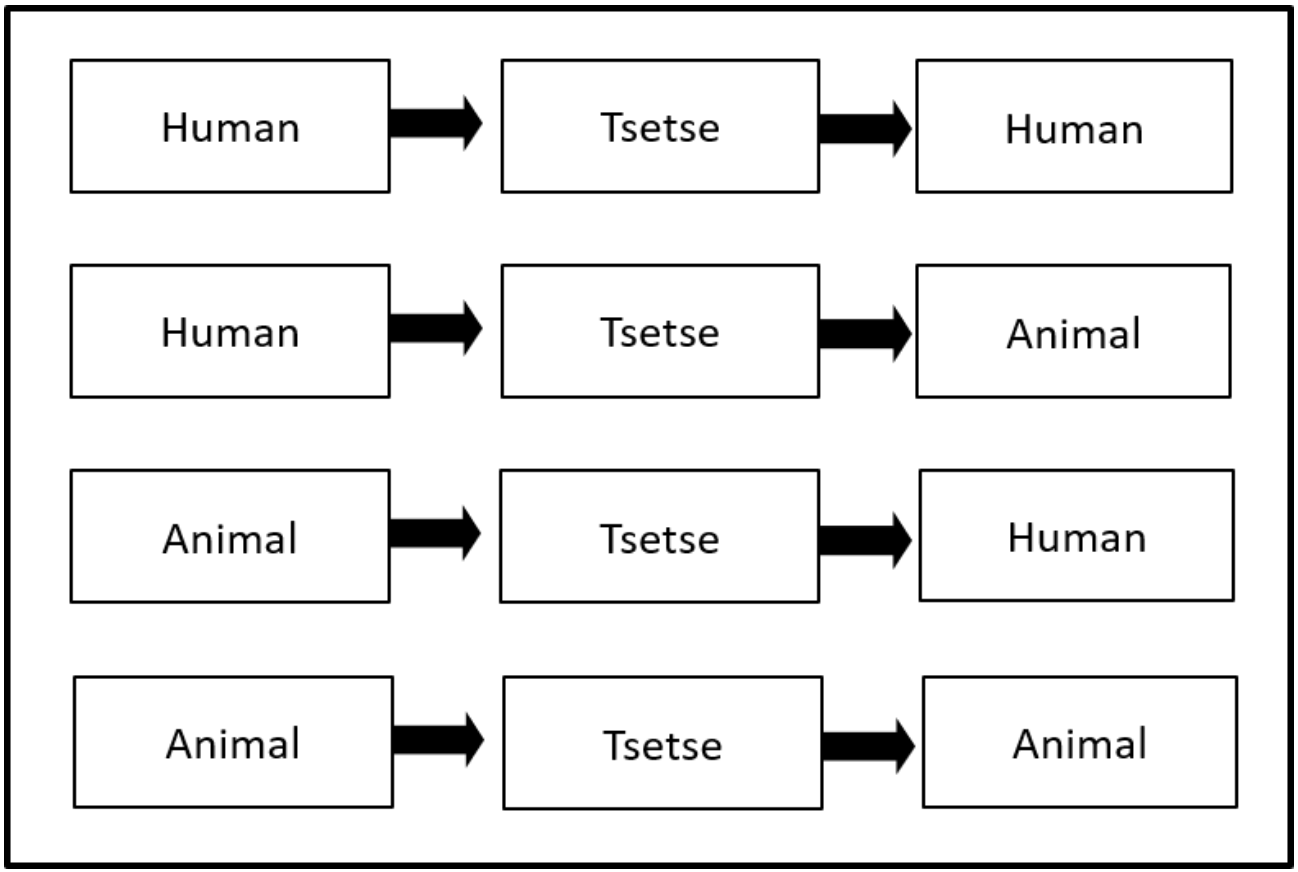


Figure 3. 1 African trypanosomiasis disease transmission pathways. There are four ways in which the trypanosome enters tsetse flies and become infective in the fly before being passed to human or animal hosts: human fly human, human fly animal, animal fly animal and animal fly human. The human fly human transmission results in the chronic disease and the animal fly human results in the acute infections with a 6-month life expectancy if untreated.

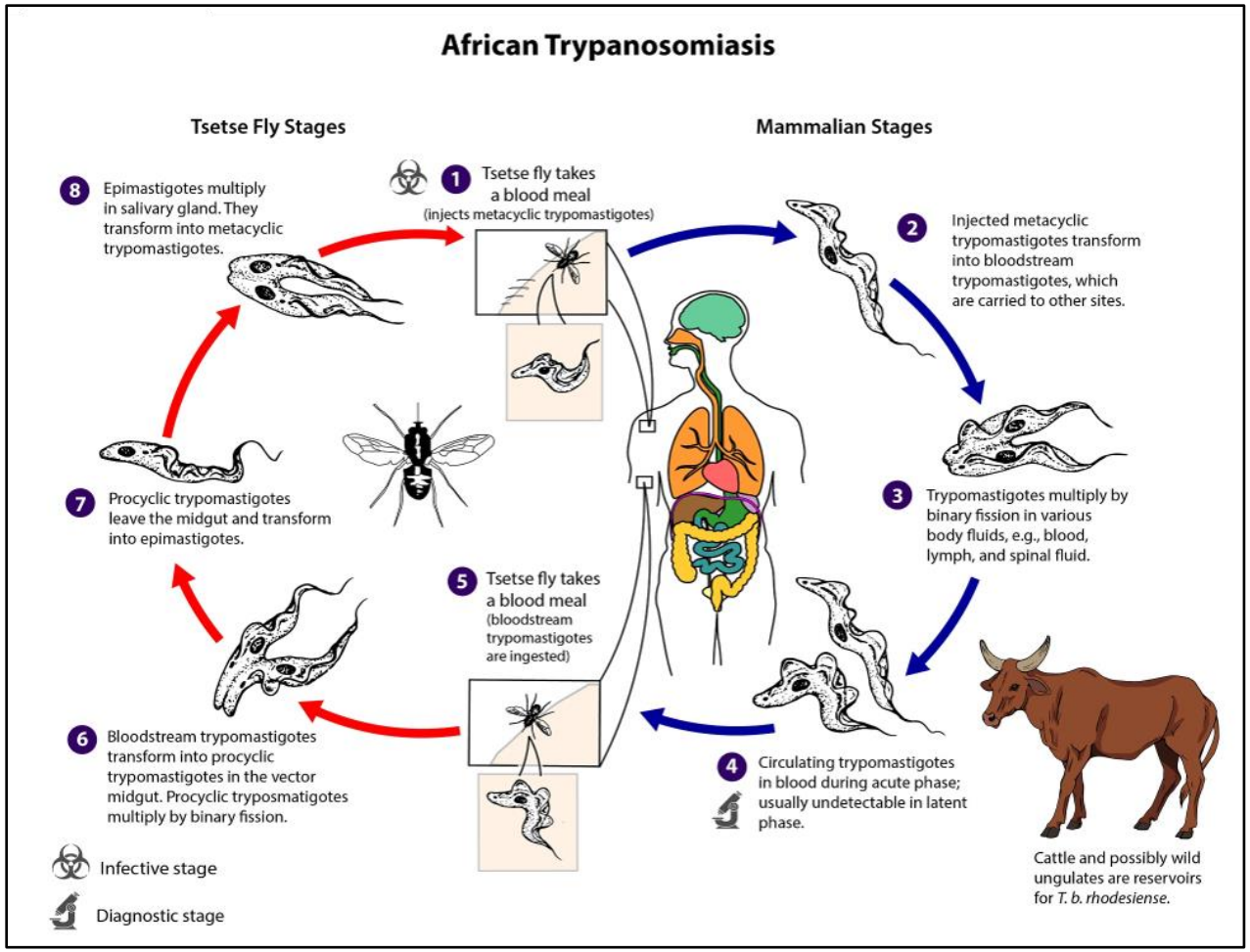


Figure 3. 2 Trypanosome life cycle in the infective and diagnostic stages of Human and Animal African trypanosomiasis.[7]

[7] Image source: Centers for Disease Control and Prevention, Division of Parasitic Disease.

The chronic variant of sleeping sickness with a 2-3 year life expectancy for the host post infection. Additionally, T.b. gambiense is responsible for 98% of reported sleeping sickness infections (Mulenga et al. 2019). Table 3.2 displays the countries of West and Central Africa where T.b. gambiense is present. East African sleeping sickness is caused by Trypanosoma brucei rhodesiense (T.b. rhodesiense). The zoonotically derived infection is more virulent in humans and host death occurs within 6 months of trypanosome transmission (Kennedy 2008). Although the illness is rare, risk of infection is a concern for rural people of Tanzania and other East African countries (Wengert et al. 2014; Van Den Berghe 1956). Table 3.2 shows the countries of the East and South Africa where T.b. rhodesiense infections occur.

Uganda is the only country with both forms of sleeping sickness, however, there is currently no convergence between the disease foci (Menon et al. 2016b). Animal African trypanosomiasis or Nagana caused by Trypanosoma brucei (T.b.), Trypanosoma brucei vivax (T.b. vivax), and Trypanosoma brucei congolense (T.b. congolense) is distributed throughout sub-Saharan African crossing both east and west regions. Nagana has a devastating effect on cattle herds and severely impacts dairy production in endemic countries with active outbreaks (Alingu et al. 2014)The disease affects livestock and wild animals all over sub-Saharan Africa. The pathogen transmission cycle in animals is the same process for human Trypanosoma brucei infections (CDC 2019a)

Figure 3.3 shows the geographic distribution of the two distinct African trypanosomiasis disease models, T.b. gambiense infections in east Africa and T.b. rhodesiense infections in west Africa. Examining African trypanosomiasis risk from the perspectives of two geographically different

countries with distinct strains of the diseases will allow for a comprehensive exploration of the subject matter. The comparative aspects will vary mildly but can lead to advancement in the understanding of risk.

3.4 CHARACTERIZING THE RISK LANDSCAPE

There are many determinants of risk for African trypanosomiasis. For the purpose of this paper, risk is characterized as the combination of exposures that can potentially lead to negative health outcomes, adapted from the Oxford Dictionary. This conceptual diagram in Figure 3.4, depicts the determinants of risk for African trypanosomiasis, the exposure risk pathways, and the subsequent health outcomes. The exposure risk pathways are reliant upon and intensified by the interplay between the physical, ecological, and social determinants. The endemicity of African trypanosomiasis is driven by ecological determinants.

Environmental and climatic conditions specifically temperature, vegetation type, and soil moisture drive habitat suitability, tsetse presence and the propagation of tsetse populations. Temperature is the fundamental predictor of tsetse presence (Moore et al. 2012; Rogers, Hay, and Packer 1996). Tsetse thrive best in mild to moderate temperatures ranging between 16-32°C (Are and Hargrove 2020; Torr and Hargrove 1999). Lower temperatures induce a coma like state for the fly and can cause death (Jack 1939). Higher temperatures affect fecundity, prevent larval production, lessen pupal development period, reduce pupae emergence and increase overall mortality (Pagabeleguem et al. 2016).

Humidity has an impact on tsetse activity causing an orthokinetic reaction among some species (Bursell 1956a). Bursell and colleagues found that flies are less active in wet air where humidity saturation was reached than in dry air (Bursell 1956b; Mellanby 1936; Buxton and Mellanby 1934). Tsetse were also found to be more active nearer the time for blood meals at 7am and 5pm providing humidity remained lower (Bursell 1956b). Optimal climatic conditions encourage tsetse population density increases, as a result (Dicko et al. 2015; Dodge and Messina 2017; Munang'andu et al. 2012), exposure risk is increased due to the increased presence of the fly.

Macro level factors such as those listed in the physical determinants section (Figure 3.4), outline the large scale drivers of African trypanosomiasis risk. Land use can have both an exacerbating and mitigating effects on African trypanosomiasis risk (FAO 2006). For instance, development and the urbanization of natural environments destroy tsetse habitats, and, as a result, risk is low in densely populated settled areas (Tshimungu et al. 2008). On the other hand, increased pasture, animal density, and large expanses of bush created by increased rainfall and climate change, can lead to increased host availability (Konnai et al. 2009; Mweempwa et al. 2015). Additionally, poor soil and water quality and other environmental stressors on the land, could increase pressure to shift settlements and grazing activities to areas at or adjacent to existing tsetse habitats (Rocque, Augusseau, and Guillobez 2001).

Table 3. 2 Tsetse and trypanosomiasis regions, endemic countries, and Trypanosome of infection.

	Tsetse and Trypanosomiasis Endemic Countries	
Region	**Countries**	**Trypanosome (Infection)**
West and Central Africa	Angola, Cameroon, Central African Republic, Chad, Congo, Cote d'Ivoire, Democratic Republic of Congo, Equatorial Guinea, Gabon, Guinea, Nigeria, Sierra Leone, South Sudan, Uganda, Benin, Burkina Faso, Gambia, Ghana, Guinea-Bissau, Liberia, Mali, Niger, Senegal, Togo	T.b. gambiense ***(Chronic Sleeping Sickness)*** T.b. congolense ***(Nagana)*** T.b. vivax ***(Nagana)***
East and South Africa	Burundi, Kenya, Malawi, Mozambique, United Republic of Tanzania, Uganda, Zambia, Zimbabwe, Botswana, Ethiopia, Namibia, Rwanda, Swaziland	T.b. rhodesiense ***(Acute Sleeping Sickness)*** T.b. congolense ***(Nagana)*** T.b. vivax ***(Nagana)***

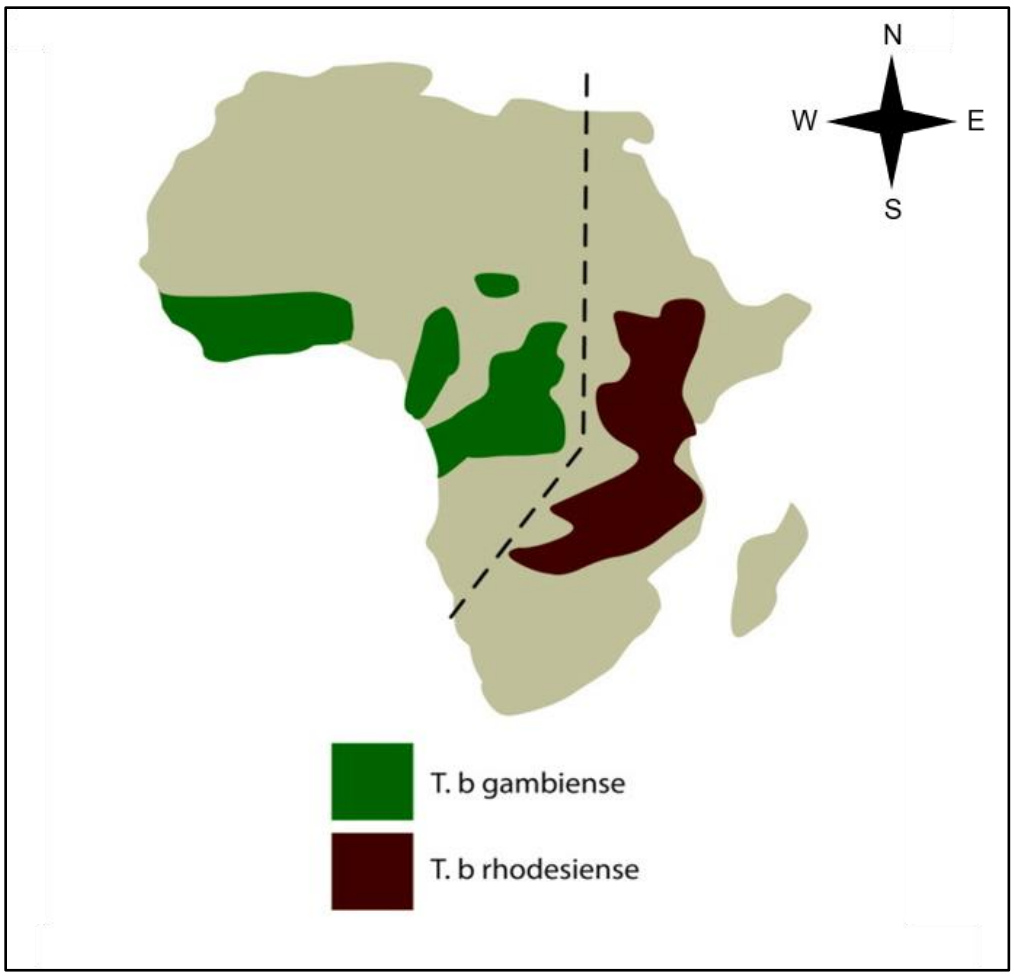


Figure 3. 3 The geographic distribution of the two distinct African trypanosomiasis disease models. T.b gambiense, the chronic form of the infection occupies the East African region. T.b. rhodesiense, the acute form of the infections occupies the West African region.[8]

[8]Adopted from PGE Kennedy 2008. Annals of Neurology, Volume: 64, Issue: 2, Pages: 116-126, First published: 28 August 2008, DOI: (10.1002/ana.21429). Copyright permission to use granted by John Wiley & Sons.

The social determinants delineate the micro level components that influence individual and community risk. Political stability and governance play a central role from a policy enforcement perspective (Beard et al. 2016). Global and regional health policies surrounding tsetse and trypanosomiasis such as those developed by the World Health Organization require national and local government support. Turbulence, tension, and tribalism interfere with the effectiveness of community sensitization efforts (Rijpma 2015).

Community support and participation are crucial to the success of tsetse and trypanosomiasis control efforts (Mahamat 2015a). Population displacement and the influx of refugees from conflict areas exacerbate risk (Ford and Thomas-Slayter 2001). Sometimes unsettled lands are not the most desirable, as the most suitable areas for settlements have been claimed by the permanent residents. Similarly, refugees are often unfamiliar with the places they settle and can inadvertently create villages near tsetse habitats or create suitable habitat where previously none existed (Armstrong 1991).

The combinations of these circumstances endanger the health and safety of refugee populations and elevate exposure risk. Poverty and food insecurity are pervasive throughout Africa (Shereni et al. 2016). When economic inequality is coupled with famine, and poor community infrastructure, health and well-being are threatened, and risk is worsened (Giblin 1990; Lester 1939). Lack of access to adequate healthcare limits diagnosis and treatment options for common ailments amplifying the deleterious effect of potential trypanosomiasis infection (Namatame 2016; Frieden et al. 2011).

Millions of people and animals are at risk for African trypanosomiasis infections, annually. All of these influencing factors can affect individual and community risk. The combined cumulative impact of the physical, ecological, and social determinants creates considerable susceptibility among inhabitants. Understanding the complexity of the risk-scape of African trypanosomiasis reinforces the necessity of risk area identification and risk reduction strategies to lessen exposure.

3.5 METHODS

A two-step trypanosomiasis risk reduction framework was developed including three scalable models that integrate hazard and risk for the identification of areas to prioritize control. A two country case study was conducted to explore the implications of tsetse control using an enhanced strategy for area wide vector control.

The conceptual diagram in Figure 3.5 illustrates the components of the Simulated Models for Areas at Risk for Trypanosomiasis (SMART). Coupling the Google Earth Engine Tsetse Ecological Distribution (GETED) (Figure 3.6) model which simulates tsetse habitat suitability, with Moderate Resolution Imaging Spectroradiometer (MODIS) landcover product as a proxy for grazing areas, and LandScan population data, the SMART were created. Each of the inputs for SMART are discussed below.

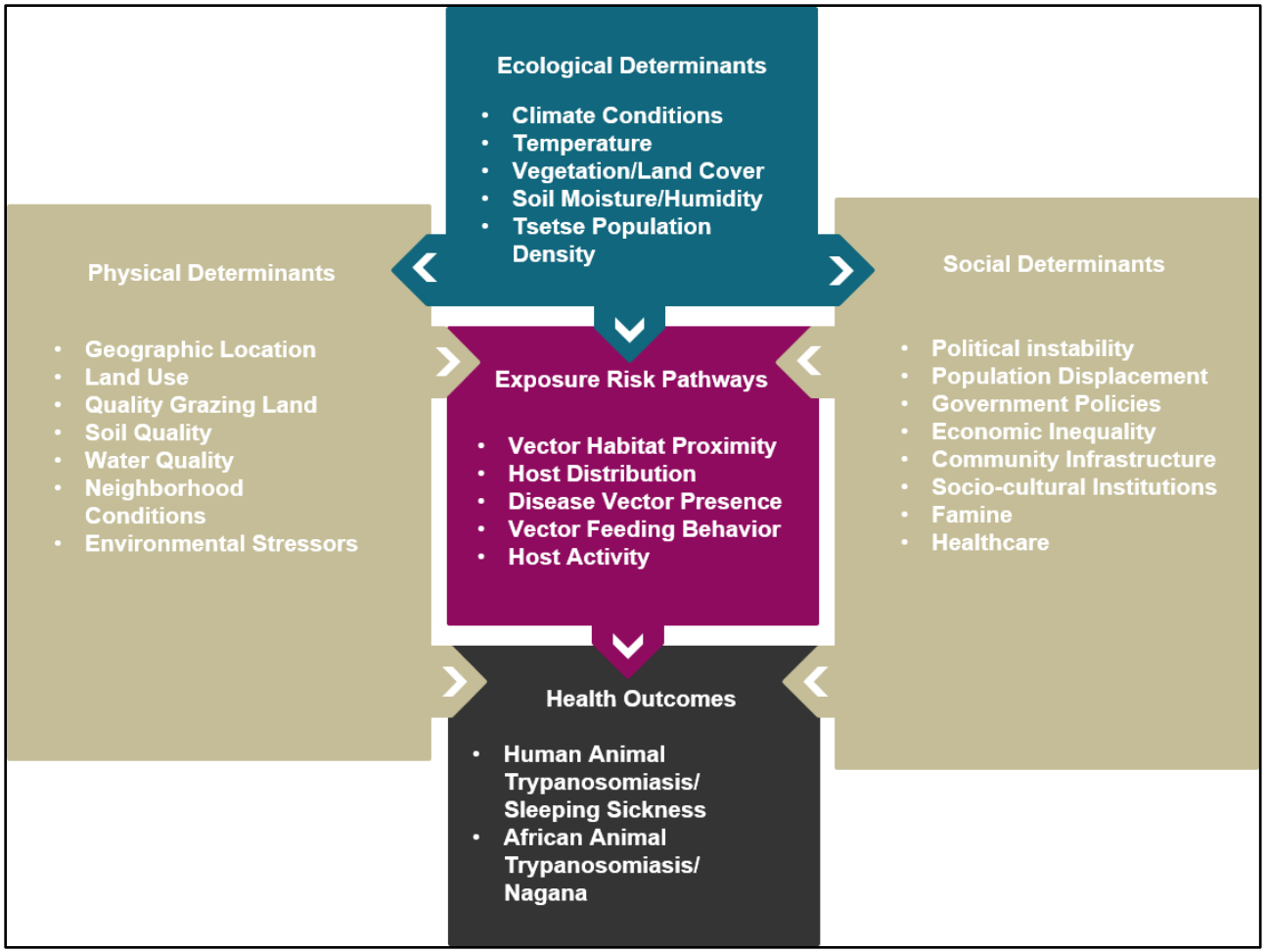


Figure 3. 4 Conceptual diagram depicting the determinants of risk for African trypanosomiasis.[9]

[9] Adopted from Beard et al. 2016.

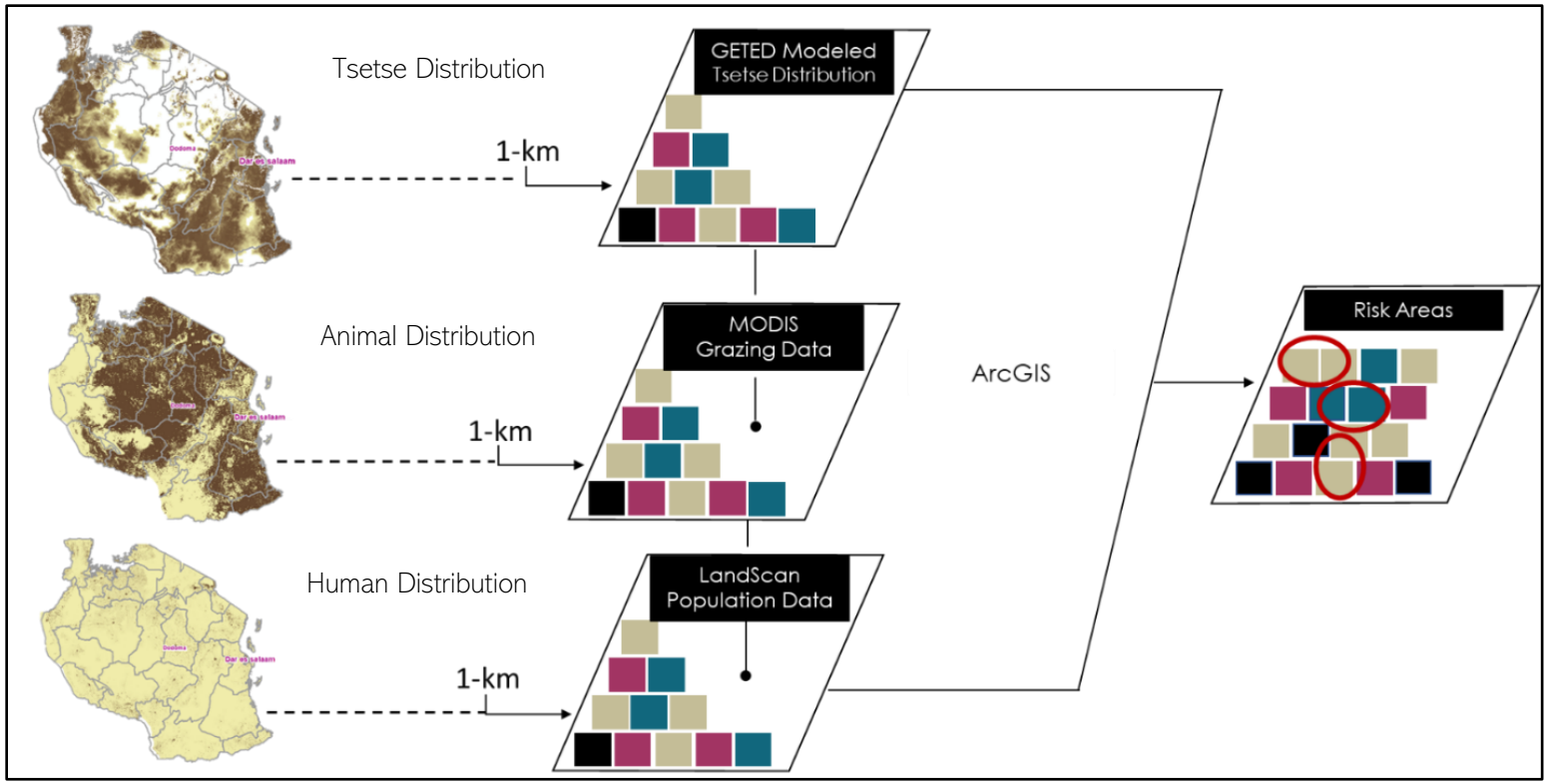


Figure 3. 5 Conceptual diagram illustrating the input layers for the Simulated Model of Areas at Risk for Trypanosomiasis (SMART). The SMART models require three specific inputs: (1) the output of the Google Earth Engine Tsetse Ecological Distribution (GETED) model which acts as the proxy for tsetse distribution, (2) Moderate Resolution Imaging Spectroradiometer (MODIS) landcover product vegetation classes for grasslands and savannas which acts as the proxy for animal distribution, and (3) Landscan global population distribution which acts as the proxy for human distribution.

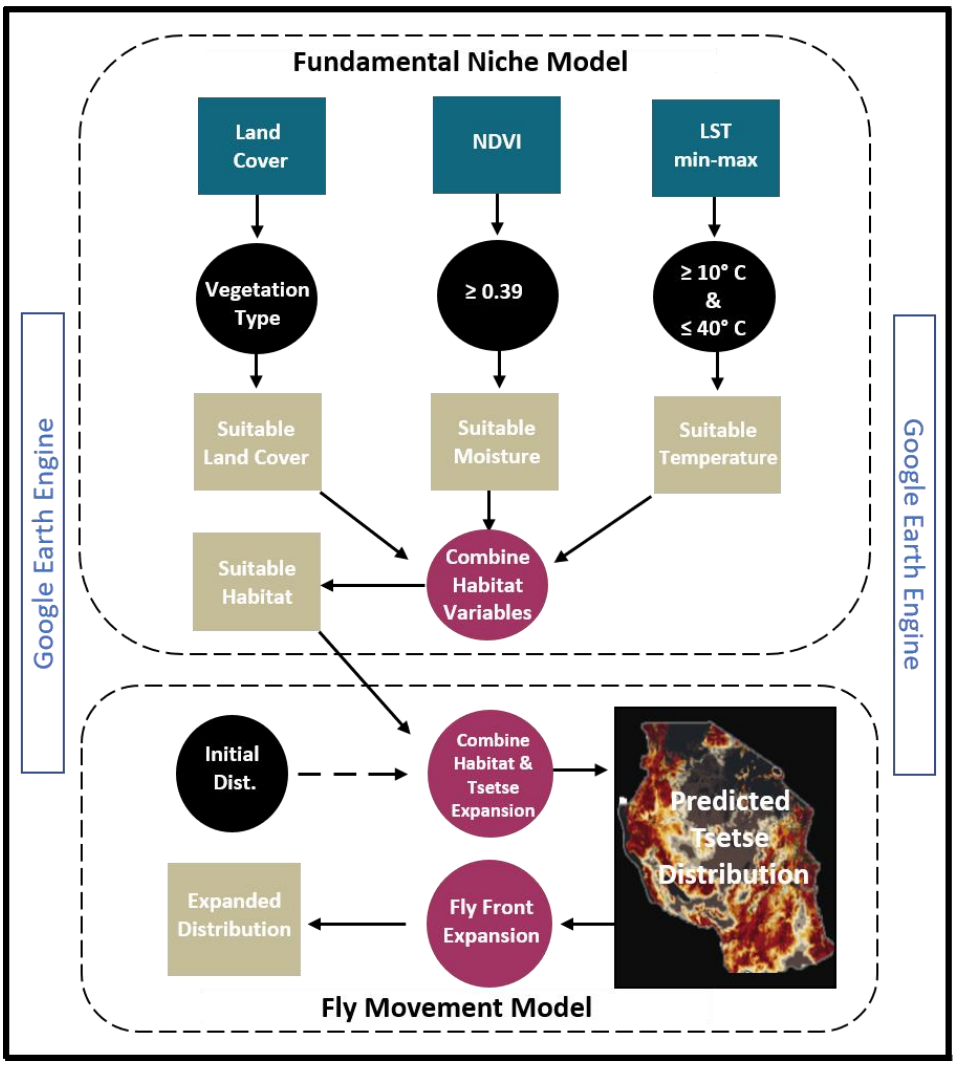


Figure 3. 6 Google Earth Engine Tsetse Ecological Distribution Model for Tanzania.[10] The GETED model shown on the left is a combined model that includes the fundamental ecological niche model that is driven by environmental factors including: landcover or vegetation, Normalized Difference Vegetation Index, which is a proxy for soil moisture, and Land Surface Temperature which tells if an area is suitable for tsetse. GETED is a modified version of the Tsetse Ecological Distribution (TED) model.

[10] Adapted from Devisser et al., 2010.

3.5.1 SMART Model Inputs

1. *Google Earth Engine Tsetse Ecological Distribution (GETED) Model*

GETED adapted from the tsetse ecological distribution (TED) model developed by (Devisser et al. 2010), is an integrated model comprising the fundamental niche and fly movement models (Figure 3.6). GETED uses three remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) data sets to predict the distribution of tsetse species across space and time. As depicted in Figure 3.6, the fundamental niche model predicts suitable habitats for tsetse species based on day and night Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), a proxy for soil moisture (B Williams et al. 1992), and Land Use and Land Cover (LULC) vegetation. The fly movement model considers the active movement of tsetse during specific intervals by increasing the predicted habitat from the fundamental niche model to produce the realized niche (Pollock 1992). Similar to the TED model, GETED generates 250 meter spatial resolution output raster of tsetse presence probability maps every 16 days, based on habitat suitability and the rate of movement of tsetse. Selected data years 2008-2019 for 10 years of modeled data with 2 years of model initialization.

Adjustments were made to the GETED model parameters to accommodate the climatic and ecological differences between the case study sites of Senegal and Tanzania. The ecological niche of Gambiense palpalis in the Niayes region of Senegal is distinct from the East African conditions and flies which the original TED model was developed to characterize. The differences include a higher minimum and maximum temperature level (Dicko et al. 2014), and a lower NDVI threshold based on empirical observations of Gambiense palpalis in Senegal (Bouyer et al. 2010). Table 3.3 displays the inputs and MODIS product parameters for each country.

Table 3. 3 Data and parameters in the Google Earth Engine Tsetse Ecological Distribution (GETED) Model.

Country	Inputs	Data Products	Parameterization
Senegal	Moisture	MODIS NDVI Terra Vegetation Indices 16-Day Global 250m (MOD13Q1.006)	NDVI ≥ 0.19
	LST (min-max)	MODIS Terra LST Emissivity 8-Day Global 1km (MOD11A2.006)	13.3°C – 40.2°C
	Vegetation	MODIS Land Cover Type Yearly Global 500m (MCD12Q1.051)	10 of 17 classes identified in Devisser et al., 2010 Table 2
Tanzania	Moisture	MODIS NDVI Terra Vegetation Indices 16-Day Global 250m (MOD13Q1.006)	NDVI ≥ 0.39
	LST (min-max)	MODIS Terra LST Emissivity 8-Day Global 1km (MOD11A2.006)	10°C - 40°C
	Vegetation	MODIS Land Cover Type Yearly Global 500m (MCD12Q1.051)	10 of 17 classes identified in Devisser et al., 2010 Table 2

2. *Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Product*

MODIS Land Cover is a United States Geological Service remotely sensed global land cover product, with annual classifications from 2001 through 2019 (Sulla-Menashe and Friedl 2018). Combining the grasslands and savanna classes from the MCD12Q1.051 version produced grazable lands as a proxy for livestock presence. Grazing land is defined as grass and grass-like vegetation used for animal production (Milne et al. 2015). While savannas are the optimal grazing option, the presence of the fly limits the ability to access these lands, so other grasslands are utilized (Hausner 1992).

3. *LandScan Global Population Distribution*

LandScan is a multilayered spatial model of global population distributions developed by Oak Ridge National Laboratory (ORNL). Using sub-national level census data, high resolution remotely sensed imagery, and demographic data, the population distribution model calculates the likelihood of human presence over 24 hours (Bhaduri et al. 2002). The ambient population counts are distributed in raster format with 1km spatial resolution (ORNL 2019).

3.5.2 Risk-scape Models

The abovementioned inputs were used to generate three risk models. Additionally, the risk models include three parameterized variable inputs: *Tsetse Presence, Human Presence and Animal Presence*. The **Tsetse Presence** input parameters, adopted from Yang et al. 2017, range from 0 to ≥ 52 and describe the number of tsetse per pixel in the dataset. The data were aggregated using the Natural Breaks classification, which follows the natural arrangement of the data values (Lobben 2003). The **Human Presence** definitions were derived from the

European Commission's Degrees of Urbanization (European Commission 2020). The categories range from 0 to ≥ 1500, representing the human population in each pixel and the density classification of each level (Dijkstra et al. 2020). **Animal Presence** is a binary variable representing the potential presence or absence of cattle, livestock, or other host animal in each pixel. The definitions in Table 3.4 characterize each variable input and method used to obtain the thresholds entered in the risk models. Moreover, equations 3.1 and 3.2 illustrate how the definition governed the ranking of each entry variable.

The input data were projected to UTM and appropriate datum of the respective case study country. The data were resampled to a 1 km spatial resolution for alignment and reclassed according to the threshold definitions in Table 3.3. The population presence and animal presence variables were combined to produce the host presence variable. Equation 3.1 and Equation 3.2 shows the reclassification of the tsetse presence and host presence variables, respectively.

$$TPR = \begin{cases} 0 \ if \ TP < 0.43 \\ 1 \ if \ 0.43 \leq TP < 25 \\ 2 \ if \ 25 \leq TP < 52 \\ 3 \ if \ TP \geq 52 \end{cases}$$

(Equation 3. 1)

where, TP is tsetse presence in percent probability. TPR is a variable with 4 classes.

$$HPR = \begin{cases} 0 \ if \ (HP = 0 \ and \ AP = 0) \\ 1 \ if \ (HP = 2 \ and \ AP = 0) \ or \ (PP \leq 1 \ and \ AP = 1) or \ (PP = 1 \ and \ AP = 0) \\ 2 \ if \ (HP = 2 \ and \ AP = 1) \ or \ (PP = 3 \ and \ AP = 0) \\ 3 \ if \ (HP = 3 \ and \ AP = 1) \end{cases}$$

(Equation 3. 2)

where, HP is the human population density per square kilometer, AP is animal presence or absence. HPR is a variable with 4 classes.

Based on equations 3.1 and 3.2, three risk models representing the interaction among vector and host presence were created: *Vector Model*, *Host Model*, and a *Combined Vector and Host Model*. The three models selected provide a comprehensive analysis of trypanosomiasis risk from multiple view-points. The models assign a risk magnitude level based on host presence. The model inputs (Figures 3.7-3.8) and the three conceptual diagrams (Figures 3.9-3.11) demonstrate each approach and provides an overview of their differences in each phenomenon across space.

3.5.2.1 Host Model

The host model combines human density and animal presence into a single variable, which serves as the proxy for the distribution of hosts throughout the area. The host model approach weighs the presence of hosts and zeros out pixels where vector presence is zero. Following the labels on the right side of the diagram, the host presence outcomes range from HH to LL with risk magnitude ranging from Level 3 – high risk, Level 2 – moderate risk, Level 1 – low risk and Level 0 – no risk. Risk magnitude is a function of host presence as host availability is the driver behind trypanosome transmissions and subsequent trypanosomiasis infections. The risk magnitude is indicated by the number in each square on the grid. Figure 3.9 outlines the potential combinations.

3.5.2.2 Vector Model

The vector model is influenced by the distribution of tsetse throughout the region. This approach weighs the presence of tsetse and zeros out pixels where host presence is zero. Following the top label of the diagram, the vector presence outcomes range from HH to LL. The risk magnitude ranges from Level 3 – high risk, Level 2 – moderate risk, Level 1 – low risk and Level 0 – no risk and are driven by host density on the vector presence. Figure 3.10 outlines the potential combinations.

3.5.2.3 Combined Multicriteria Model

The combined multicriteria model considers the interactions between both vectors and hosts across the landscape (Figure 3.11). This model weights abundance of tsetse and hosts across the geography. This approach considers both variables equally and detects areas of overlap, meaning pixels where both vector and host presence occur simultaneously. The consequence of weighting both creates a diagonal stepwise configuration with low magnitude areas in the lower left and high magnitude in the upper right. The outcomes range from HH to LL with a risk magnitude range from Level 3 – high risk, Level 2 – moderate risk, Level 1 – low risk and Level 0 – no risk. Figure 3.11 outlines the potential combinations and weighting structure.

Table 3. 4 Description of parameters used in the risk-scape models.

Variable	Thresholds	Definition	Method	Source
Tsetse Presence	0 ≥ 0.43 & < 25 ≥ 25 & < 52 ≥ 52 *per km^2	No Tsetse Presence Low Tsetse Presence Moderate Tsetse Presence High Tsetse Presence	Natural Breaks Classification	Yang et al., 2017
Human Presence	0 > 0 & < 300 ≥ 300 & < 1500 ≥ 1500 *per km^2	No Population Low Density Population Moderate Density Population High Density Population	Degrees of Urbanization	European Commission - Eurostat and DG for Regional and Urban Policy, 2020
Animal Presence	0 1	No Livestock Presence Livestock Presence	Binary	Van de Steeg et al., 2013

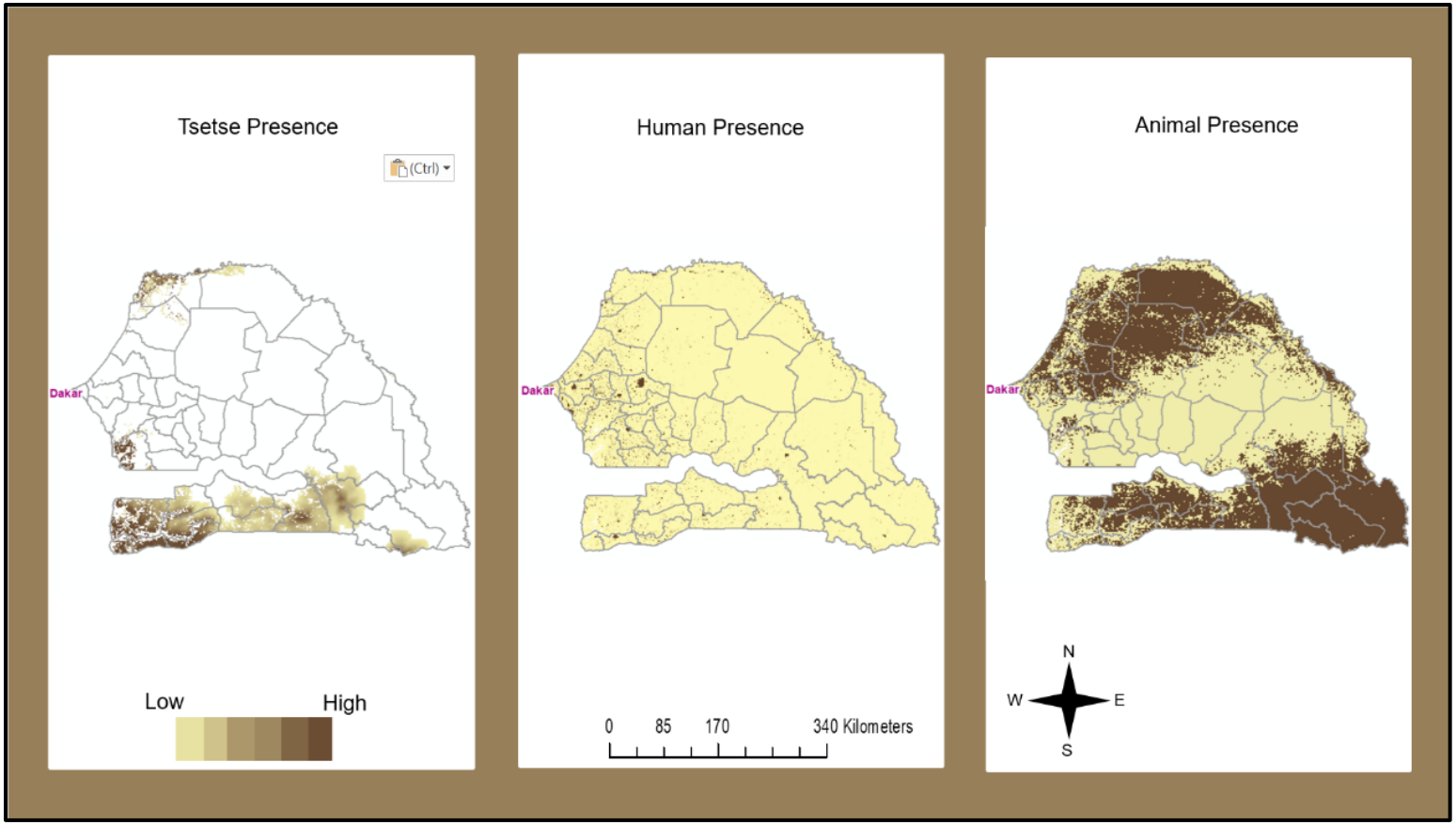


Figure 3. 7 Individual risk-scape model inputs for Senegal. Darker shaded areas indicate higher densities.

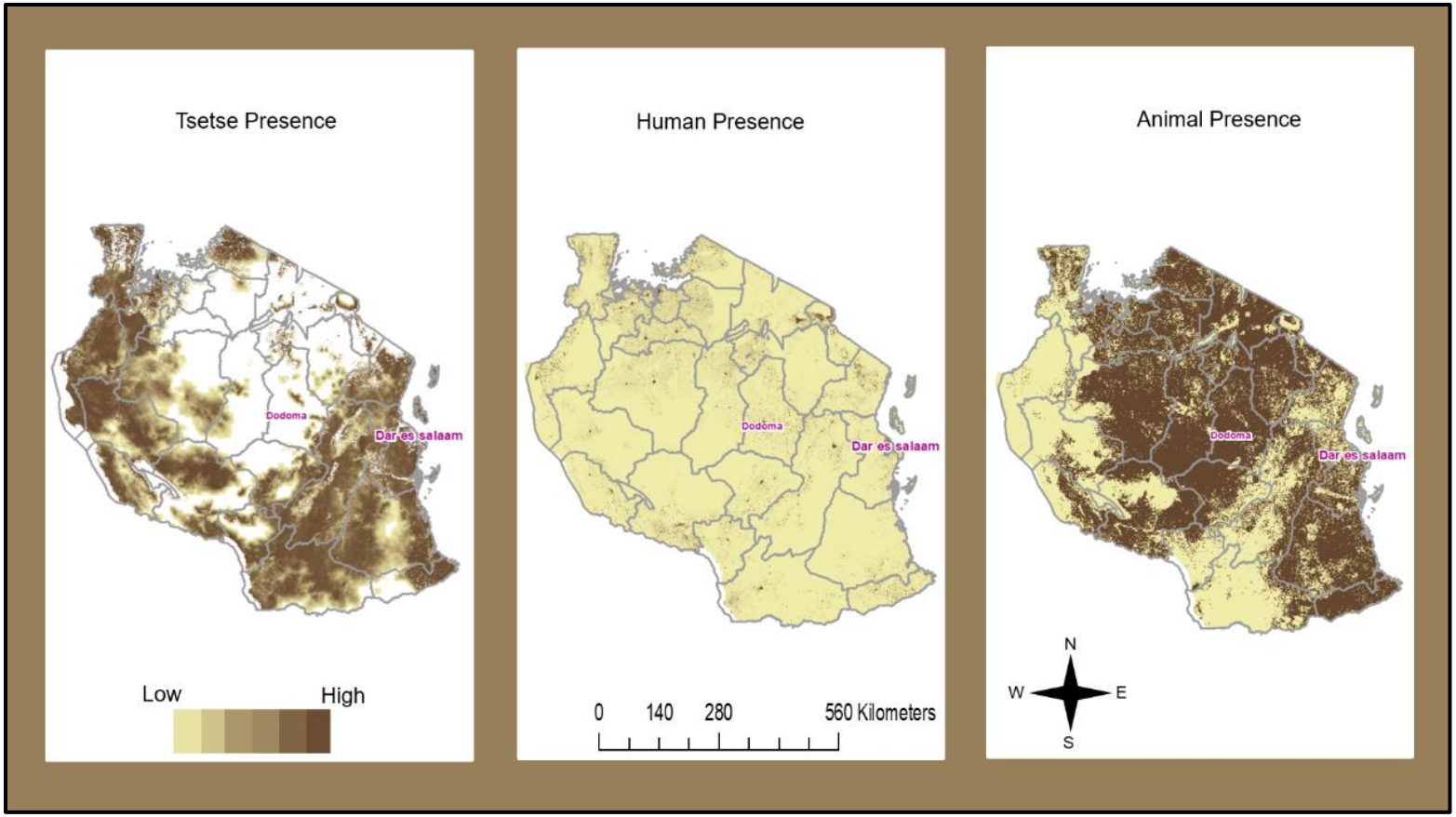


Figure 3. 8 Individual risk-scape model inputs for Tanzania. Darker shaded areas indicate higher densities.

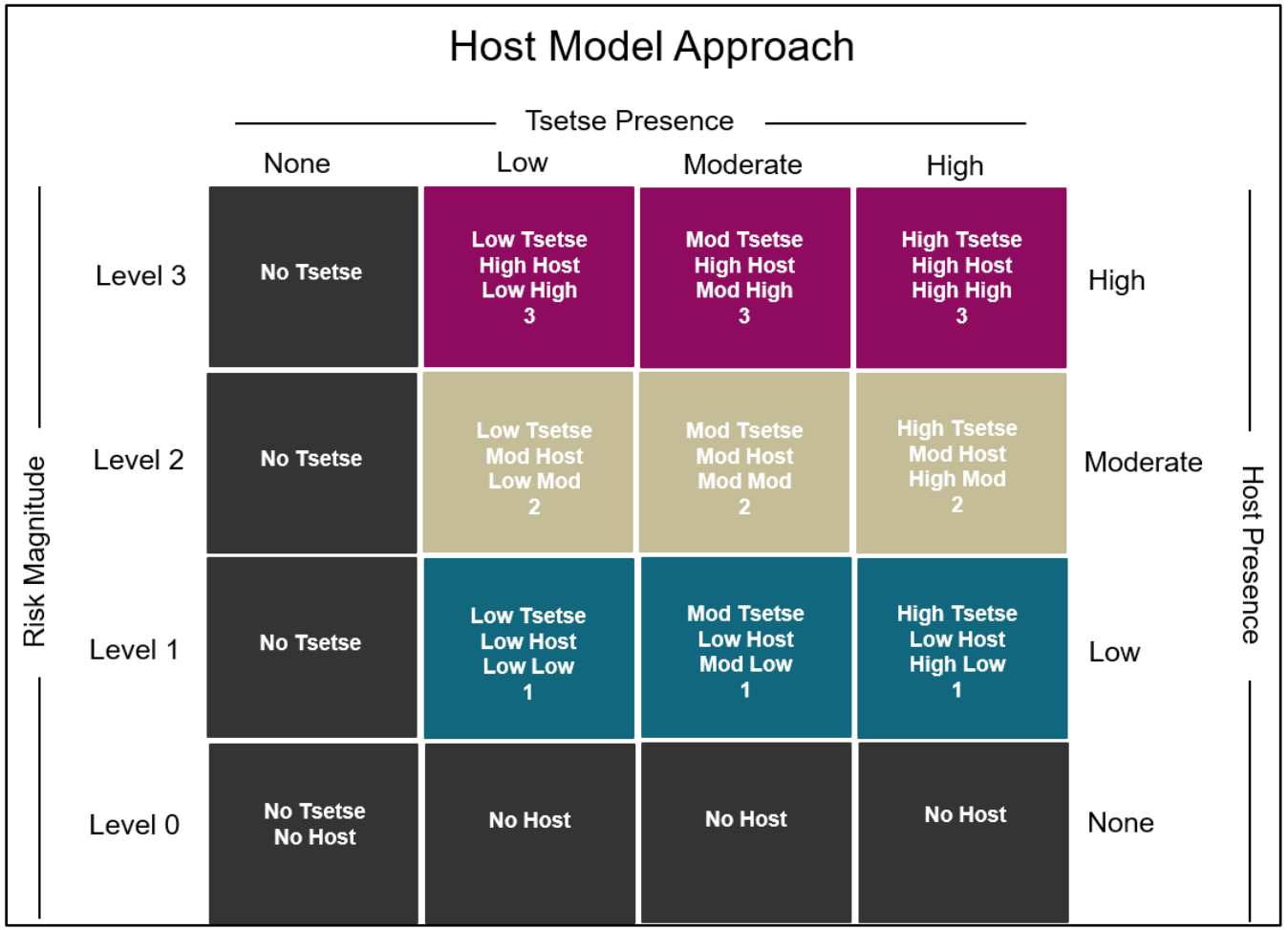


Figure 3. 9 Diagram of the host model depicting the influence of tsetse presence on the model.

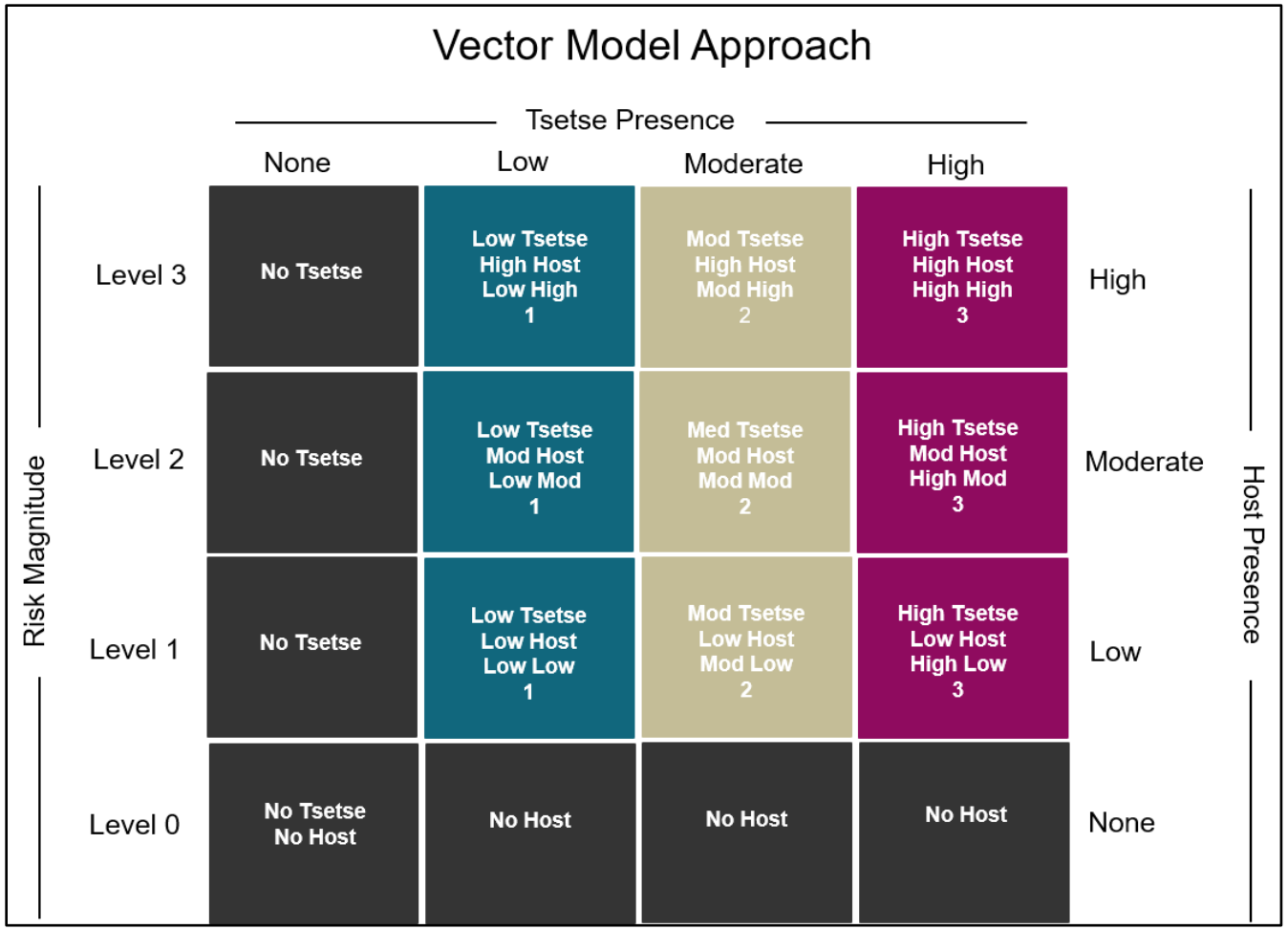


Figure 3. 10 Diagram of the vector model depicting the influence of human and animal presence on the model.

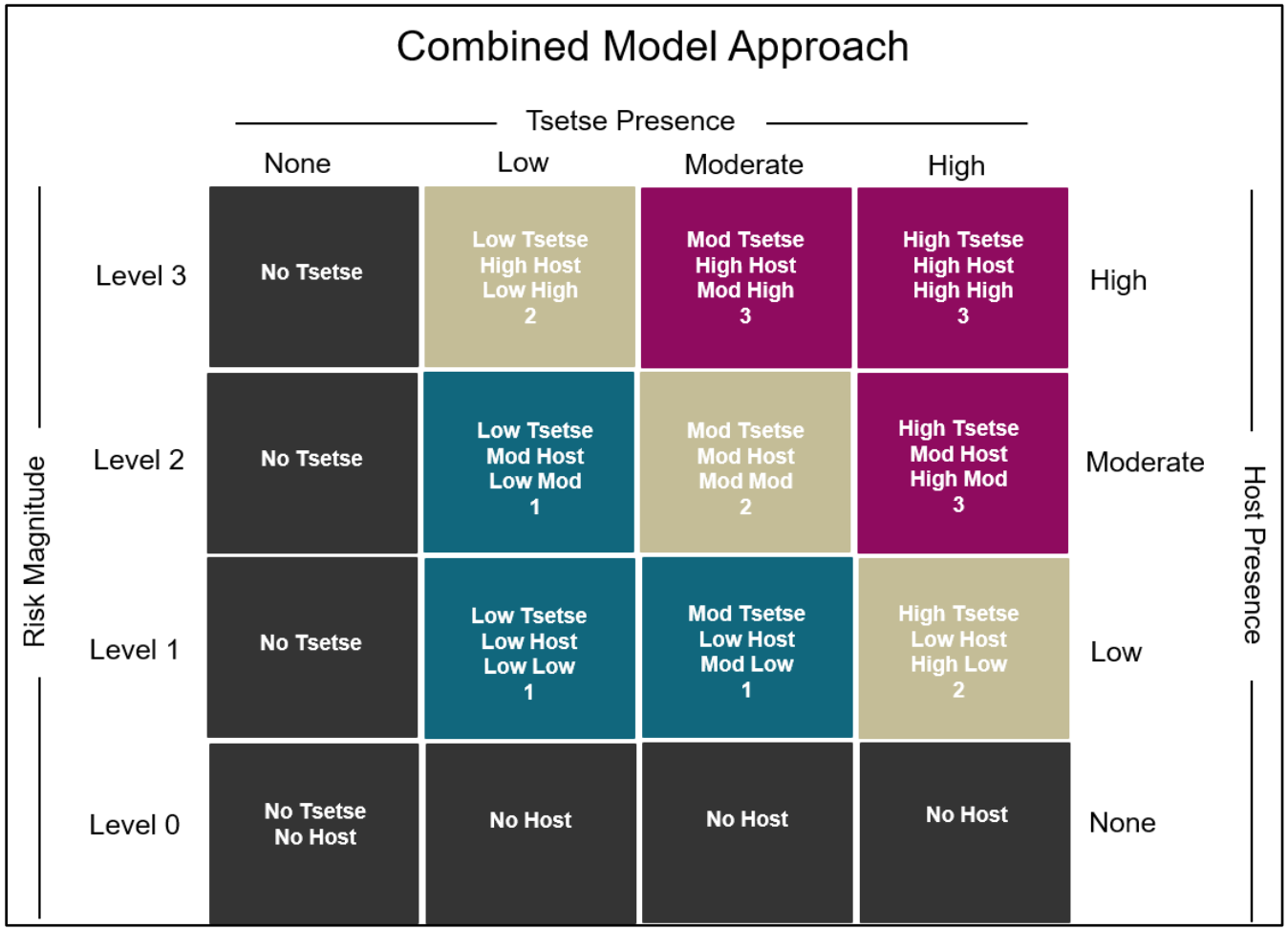


Figure 3. 11 Diagram of the combined model equally weighting vector and host presence on the model.

3.5.3 Controlled Application to Neutralize Vectors Across Space (CANVAS) Method

The **C**ontrolled **A**pplications to **N**eutralize **V**ectors **A**cross **S**pace (CANVAS) method is an enhanced vector management strategy that focuses on broad application and generalizability through standardizing intervention parameters (Teal et al. 2007; Vreysen 2006; Vreysen et al. 2014). CANVAS is a modified area wide approach that standards specific control strategy parameters: (1) length of campaign, (2) coverage area – including borders, and (3) control application selection. The CANVAS method attempts to control and suppress tsetse populations and reduce trypanosomiasis risk to host. The CANVAS application method was simulated using scenarios in the Tsetse Plan 2 application (Vale and Torr 2005). Tsetse Plan 2 is a Microsoft Visual Basic based simulation that allows users to develop and test a control strategy for different tsetse species. The model assesses control strategy feasibility based on the estimated distribution and abundance of tsetse, vegetation type, temperature extremes, host presence, duration, and monitoring (Vale et al. 2015).

3.5.4 CANVAS Method demonstrated in the Tsetse Plan 2 simulation environment

Two CANVAS responses were modeled using the Tsetse Plan 2 (TP2) scenario-based simulation application, a homogenous woodland environment response which served as the experimental control, and an environment adapted from SMART risk-scape environment which served as the exploratory case (Ramirez et al. 2015; Torr and Vale 2011). Table 3.5 demonstrates the inputs used to create the pre-control campaign environment. Glossina palpalis fuscipes was selected as the tsetse species to model because the fuscipes group exists in both case study countries (Table 3.1), and is the most important spreaders of human African trypanosomiasis infections (Tirados et al. 2011). The simulation environment was characterized as a settled area with flat

terrain. In TP2, a flat terrain is representative of the woodland savannahs similar to those in Senegal or Tanzania. The vegetation drives the simulation as the critical indicator of tsetse presence is habitat suitability. The vegetation type column in Table 3.5 provides the land cover class, a numerical code number to identify the class in the model and if the corresponding vegetation type is suitable for tsetse. The woodland areas are the most appropriate landcover types, and the cultivated areas are the most unsuitable.

Similar to the SMART models, three hosts were included in the simulation scenario: humans, cattle and other hosts, most likely wild animals (Okuonghae and Osemwenkhae 2006). The density of hosts per square kilometer was based on the scenario suggestion (Matthews, McCulloch, and Morrison 2015; Gondwe et al. 2009). There are 40 humans per km^2, in the cultivated area, more than any other hosts. Wild animals in the "other" host group dominate the woodland area at 8 per km^2 where tsetse is most likely present. The "other" host presence demonstrates one of the critical barriers to trypanosomiasis elimination, reservoir diversity (Mehlitz, Zillmann, and Scott 1982; Mehlitz and Molyneux 2019). Cattle and human hosts are similarly represented in the sparse vegetation. A town was included in the vegetation scheme to simulate an area that would not have the possibility of being an appropriate habitat for tsetse. In the subsequent control simulation, this area will not receive any control application since there is no threat of tsetse.

Table 3. 5 Environmental and ecological parameter inputs for Tsetse Plan 2 simulation environment.

Vegetation Type			Hosts per Square Kilometer		
Code No.	Landcover Type	Suitability for Tsetse	Humans	Cattle	Others
1	Woodland	Most Suitable	5	4	8
2	Open Woodland	Suitable	10	8	4
3	Sparse Cover	Least Suitable	20	16	2
4	Cultivated	Unsuitable	40	8	1
5	Town/City	No Go Area	N/A	N/A	N/A

Using the tsetse and host interaction risk model definitions from Figures 3.9-3.11, a vegetation scheme was created in TP2 (Table 3.6). The vector and host level pairs correspond to the vegetation pattern in the TP2 operational area to model the risk landscape in the simulation. The vector-host interactions have been classified into three groups: high, medium, low, driven by vector presence. Each group has been assigned to one quadrant in the operational area and will receive one of the two control applications: (1) insecticide treated cattle (ITC) or, (2) artificial bait (AB) see Table 3.6. The parameterized control patterns were based on field work observations and represent common control operations.

The simulation environment was setup to run 4 control scenarios, two performed on an all woodland landscape and two on the SMART model landscape in a four quadrant, 50x50 operational area outlined in red (Figure 3.12). Both scenario sets include one traditional more site specific control campaign with an open control pattern that does not account for the threat of reinvasion, meaning control on both sides of the inner borders of the operational area. The CANVAS method scenario includes a contiguous control pattern for maximum coverage, including control on both sides of the internal border of the operational area to address re-invasion threat, two of the scenarios will include the CANVAS method.

Similar contiguous control patterns and simultaneous control applications were used on the island of Unguja (Zanzibar) during their successful tsetse eradication campaign of the 1990's (Saleh et al. 1997; Msangi et al. 1998). Zanzibar is the only place declared tsetse free by the World Health Organization, however there's evidence that other countries like Botswana and Namibia who followed similar adjacent control patterns and dual control applications have to reduced tsetse to unrecoverable rates and effectively eradicating the species in those countries (Senior 2009; Allsopp and Phillemon-Motsu 2002).

Two point source control strategies applied simultaneously were used in the simulations: (1) insecticide treated cattle (ITC) displayed in red in Figure 3.12 and (2) artificial baits (AB) shown in yellow. The economic feasibility of these options combined with the slow rate of reproductivity of tsetse make these viable options for fly population suppression and control (McCord et al. 2012; Yang et al. 2017; Bouyer et al. 2014a). Both control campaigns were scheduled to run 216 days in accordance to guidance outlined by (McCord et al. 2012 Table 3). The full extent of the 50x50 control area was monitored for both control campaigns. The maximum total cells monitored was 2500. The woodland area has an average adult tsetse of 1898.2 per km^2 and a maximum adult tsetse of 2531.3 per km^2.

Table 3. 6 Simulated Model of Areas at Risk for Trypanosomiasis (SMART) landscape equivalents for Tsetse Plan 2 simulation environment.

SMART Model Landscape in Tsetse Plan 2						
Vector Level	Host Level	Vegetation Equivalent Pairs	Color	Equivalent	Quadrant	Control
High Tsetse	High Host	1,4	1	4	Q2	AB
High Tsetse	Moderate Host	1,3	1	3	Q2	AB
High Tsetse	Low Host	1,2	1	2	Q2	AB
Moderate Tsetse	High Host	2,4	2	4	Q4	ITC
Moderate Tsetse	Moderate Host	2,3	2	3	Q4	ITC
Moderate Tsetse	Low Host	2,2	2	2	Q4	ITC
Low Tsetse	High Host	3,4	3	4	Q3	AB
Low Tsetse	Moderate Host	3,3	3	3	Q3	AB
Low Tsetse	Low Host	3,2	3	2	Q3	AB

*ITC = Insecticide Treated Cattle, AB = Artificial Bait

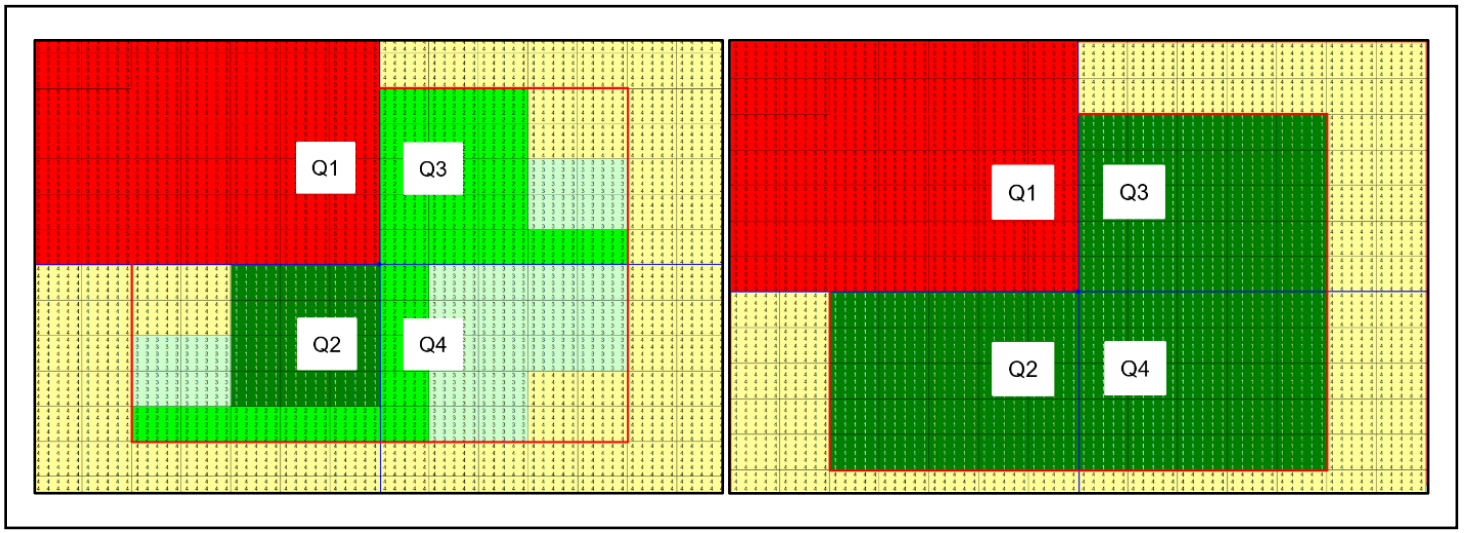


Figure 3. 12 TP2 landscape input maps: a. SMART Model landscape (left); b. Woodland landscape (right).

The SMART landscape has an average adult tsetse of 769.7 km^2 with a maximum adult tsetse of 3,436 km^2. Fly behavior is an important consideration for a control program (Rogers and Randolph 1985). Some species such as Glossina palpalis fuscipes are a more stable tsetse, meaning the flies are less active and stay relatively stationary within their habitat (Ford 1971; Carpenter 1920). A control program that is small in scale is acceptable with this species due to their stationary nature. However, the control model can be scaled up for more active tsetse species such as the morsitans group.

Reinvasion is one of the most critical barriers to control campaign success (Milligan and Baker 1988). According to the WHO, "efficient trap deployment is a compromise between high density to maximize the likelihood of fly capture, and low trap density to minimize costs" (Kuzoe and Schofield 2005). Most traditional control has a trap/target density of 3-4 per km2 depending on the fly species being targeted for control (Dransfield 1984; Williams, Dransfield, and Brightwell 1992). Control operations sometimes lack a barrier either natural or built into the control application, at the fly front, which leaves the area being controlled susceptible to reinvasion (Kuzoe and Schofield 2005). The patterns of control applications can play an important role in preventing the occurrence of reinvasion.

Figure 3.13 demonstrates the difference between a traditional control pattern and the CANVAS method pattern. The interstitial spaces between the control placement intervals for traditional placement of traps/targets provides an area of opportunity for tsetse to infiltrate the control area during and especially following the campaign (reinvasion). Other breaks in control

consistency such as controlled and non-controlled parcels within active tsetse areas create an additional level of reinvasion susceptibility.

The image on the right shows the CANVAS method which applies a control to the entirety of the control campaign area in a tighter pattern with fewer breaks in application. Decreasing the application placement interval and reinforcing the control area with a barrier the length of the control operation in the same interval distance strengthens the overall control effect in the primary control site as well as the surrounding areas. **Appendix B** includes images from the simulations showing the enhanced control effect. The CANVAS method utilizes a maximum coverage through closer application intervals to increase the effect of control and reduce the reinvasion threat.

3.5.5 Insecticide Treated Cattle

Insecticide treatment of cattle and other livestock consists of using pyrethroids, a group of synthetic pesticides, in the form of cattle dip or pour-on applications (Hargrove et al. 2000; Bardosh, Waiswa, and Welburn 2013; Bouyer et al. 2007). The ITC control strategy simulation used the default kill rate for male and female flies in the model is 70% with a drop in minimum efficacy to 65% after 10 days. Kill rates measure the number of flies that die within 24 hours of feeding on an ITC treated animal (Hargrove 2003). The insecticide was applied to the cattle every 14 days at medium density of 50% (Saini, Orindi, and Andoke 2017).

3.5.6 Artificial Bait

Artificial baits are odor attractants applied to traps and targets used to lure tsetse to the insecticide treated device (Green 1994; Laveissiere, Vale, and Gouteux 2018). The bait density is 3-4 per km^2 with a kill rate of .30% and .33% respectively for male and female flies age 0-1 days from emergence (Vale, Bursell, and Hargrove 1985). The rise to maximum efficacy is reached in 10 days and the kill rate among mature flies is 1.50% males and 1.65% females. Efficacy among older male flies age > 40 days 1.35 and older females age > 60 days at 1.49 with no degradation in efficacy (Bekele et al. 2010; Mangwiro et al. 1999).

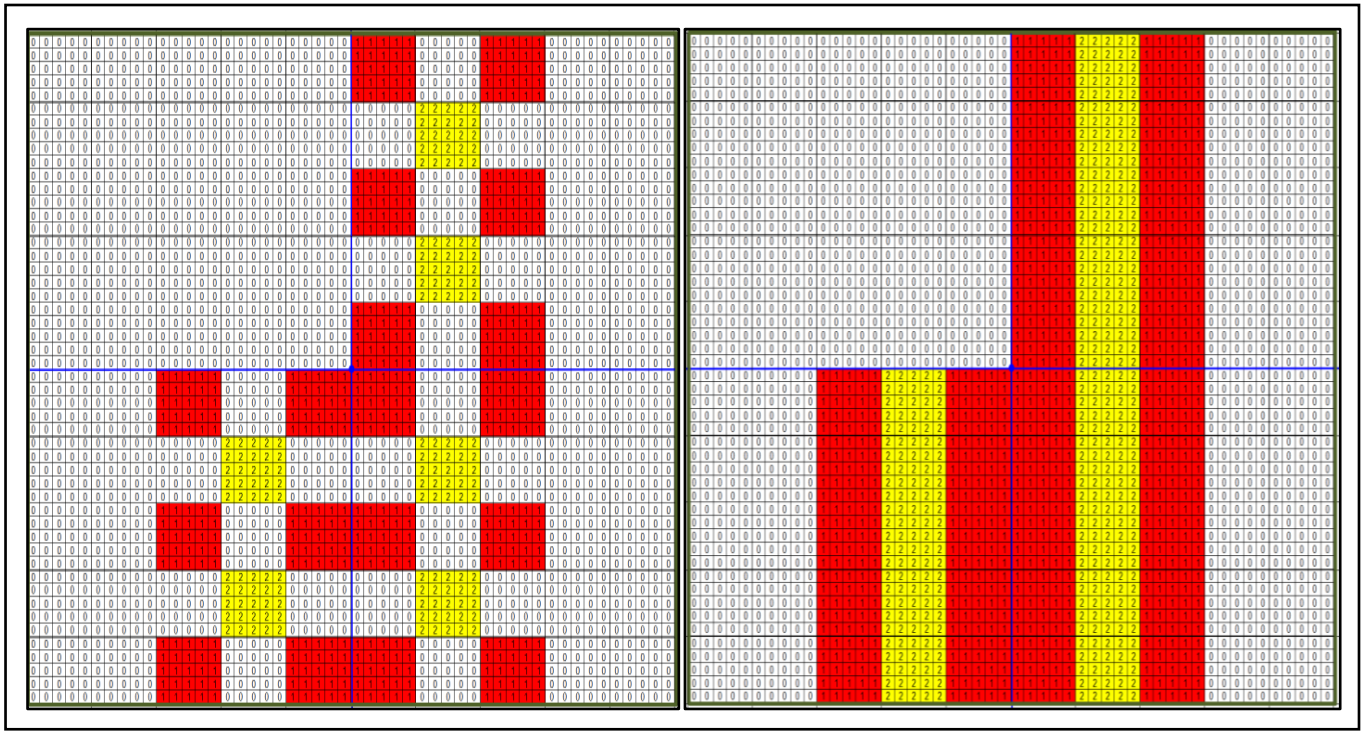


Figure 3. 13 Simulated control schemes: a. traditional control pattern (left); b. the CANVAS method (right). The traditional control scheme has open intervals or spaces between the control application. The CANVAS control pattern covers the area as much as possible reducing the interval between the placement of traps, targets, or insecticide treatments to cattle.

Table 3. 7 SMART model results for Senegal and Tanzania. Areas at-risk and their relative percentages are reported for all three models approaches across four levels of observation.

Modeled Risk Area Results								
Country	**Land Area**	**Area with Tsetse**	**HMA Risk Area**	**% Risk**	**VMA Risk Area**	**% Risk**	**CMA Risk Areas**	**% Risk**
Senegal	197,000 km^2	52,308 km^2						
Level 0			44,550	85.08	44,494	85.05	44,494	85.05
Level 1			7,729	14.76	4,056	7.75	5,866	11.21
Level 2			82	0.16	1,827	3.49	1,918	3.67
Level 3			2	0.003	1,930	3.69	29	0.05
Tanzania	947,303 km^2	910,676 km^2						
Level 0			434,520	47.71	434,505	47.71	434,505	47.71
Level 1			466,452	51.21	96,365	10.58	187,411	20.57
Level 2			8,805	0.97	93,314	10.24	282,553	31.02
Level 3			914	0.1	286,492	31.46	6,207	0.68

HMA = Host Model Approach, VMA = Vector Model Approach, CMA = Combined Model Approach

3.6. Results and Discussion

3.6.1 Smart Model Output

Simulated Models for Areas at Risk for Trypanosomiasis (SMART) are multicriteria spatially explicit output developed to: (1) identify areas at risk, (2) rank the hazard and exposure (3) prioritize control site selection and planning. The SMART models are scalable and can be used in small or large geographies to aid in pre-control campaign planning. The models are constrained by the tsetse distributions of Senegal and Tanzania (see Figures 3.7-3.8).
The countries occupy a land area of approximately 197,000 km^2 and 947,000 km^2, respectively. The areas with tsetse differ from the land areas of the two countries (see Table 3.7). Therefore, the model results and percentages were spatially restricted to areas with tsetse.

3.6.2 Host Model Approach

Figures 3.14-3.15 illustrate the Host Model Approach across the countries of Senegal and Tanzania. According to the host model definition above (Figure 3.9), the host model weighs areas of human and animal presence. The SMART model results outlined in Table 3.5, reveal that roughly 85% or 44,550 km^2 of the modeled area in Senegal fall with a Level 0 risk class magnitude, indicating that about 15% of the area observed have a risk of trypanosomiasis. Tanzania is quite different. Tanzania has a substantially larger modeled area, 910,676 km^2, of which 434,520 km^2 or 47% are in the Level 0 priority area. The Level 0 risk magnitude indicates one of two conditions: (1) areas where there are no vector or host presence, and (2) areas where there is a vector presence but no host to be at risk. The Level 0 risk magnitude is indicated by the charcoal grey color on the subsequent maps and the definition will remain

constant for all models. In both countries the areas in the immediate vicinity of the capital city is in a Level 0 risk magnitude area. Alsan and others have argued that development and urban environments are not suitable to tsetse (Alsan 2015c; Tshimungu et al. 2008).

The lack of tsetse presence in and near Dakar is consistent with literature which describes urban areas as unsuitable habitats for tsetse (Devisser and Messina 2009; Chikowore et al. 2017; Cecchi et al. 2008). However, it should be noted that confirmed tsetse presence, research and active control is occurring on an isolated discrete population of Glossina palpalis gambiensis at Parc Forestier et Zoologique de Hann in Dakar (Solano et al. 2010; Bassène et al. 2017). Parc Hann as it is colloquially called, has the appropriate ecological and environmental conditions as well having as a sufficient host presence to support the fly populations for the more “opportunistic feeders” such as Glossina palpalis gambiensis (Courtin et al. 2005; Ciss et al. 2019).

The shifting landscapes and competition for space to expand cash crop operations and create new encampments, have altered and fragmented the original West African tsetse habitats leading to the adaptive behavior of palpalis gambiensis to survive and propagate peri-urban areas, increasing vector-host contact (Courtin et al. 2010, 2005). These peculiarities add another layer of complexity to attempts to control the fly and reduce risk of disease transmission to human or animal hosts. Furthermore, such instances of isolated populations in atypical locations, challenge the efficaciousness of control strategies. Additionally, there are instances of confirmed tsetse presence in the urban areas of other east and west Africa countries.(Fournet et al. 2000; Robays, Kadima, and Lutumba 2004; Bouyer et al. 2010).

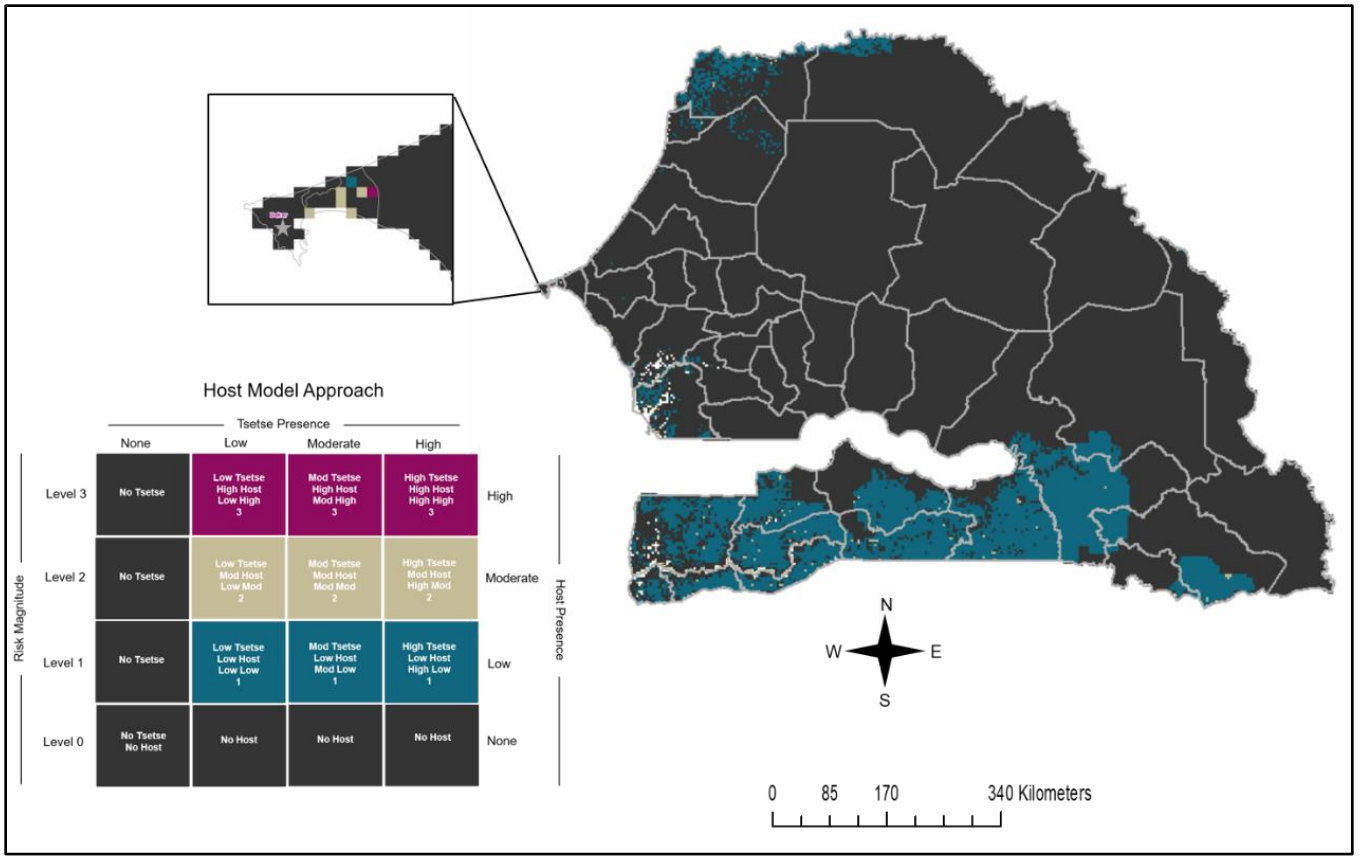


Figure 3. 14 Diagram of the Senegal Host Model Approach and a map of the model output. The inset map shows details of the Dakar, Senegal area. The Host Model Approach weights the presence of host per pixel across the modeled area.

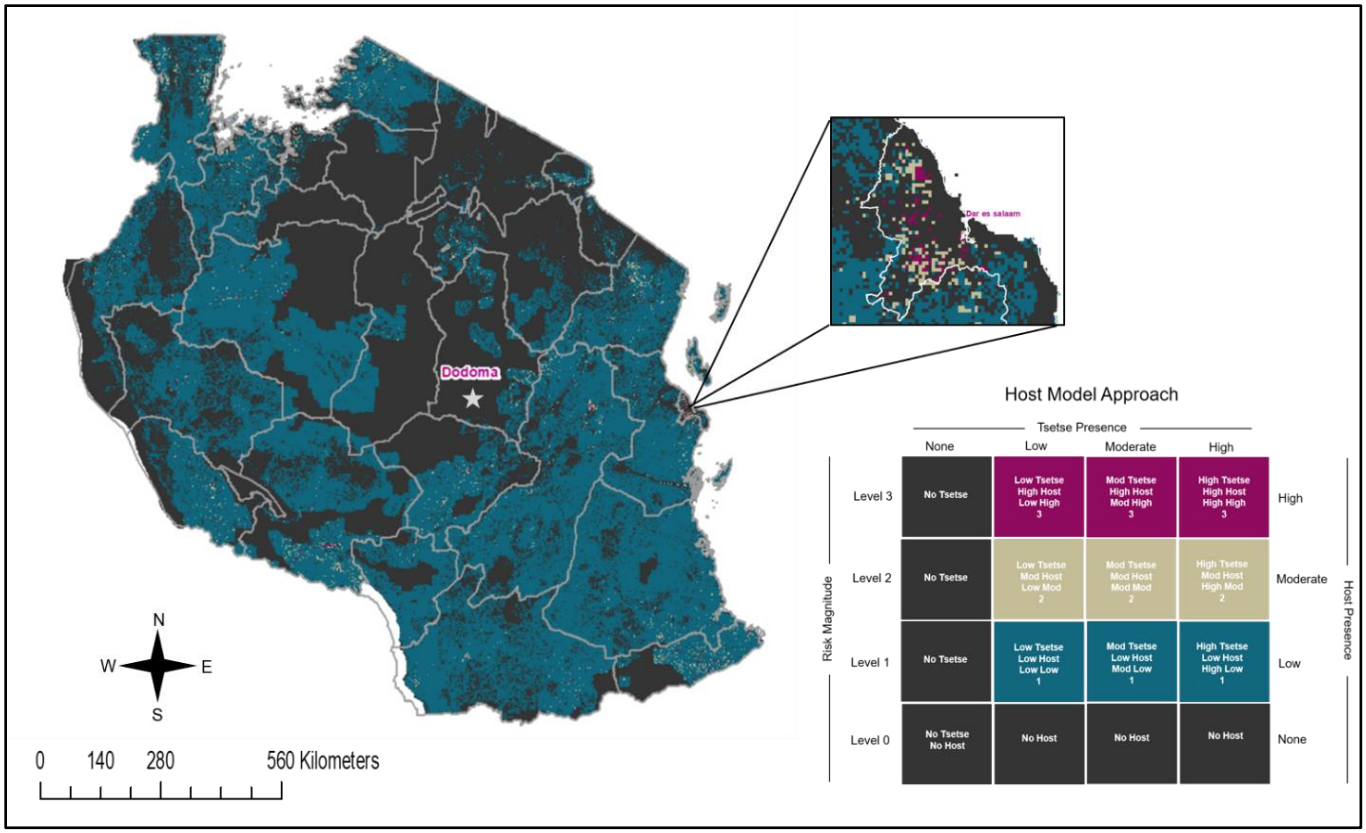


Figure 3. 15 Diagram of the Tanzania Host Model Approach and a map of the model output. The inset map shows details of the Dar es Salaam, Tanzania area. The Host Model Approach weights the presence of host per pixel across the modeled area.

For the host model, approximately 15% or 7,700 km^2 of Senegal and 466,452 km2 or 51% of the modeled area in Tanzania are in the Level 1 risk magnitude class. Represented by the teal color on the map, the low host areas have the following definitions: (1) no vectors and low host presence, and (2) low, moderate, or high vector presence and low host presence. The majority of the host model approach results for both countries fall within the low host areas and present a low risk priority level. In Senegal, the results have a fragmented distribution in the northern part of the country, sparsely distributed in the middle with a cluster near the Sene-Gambia region and a dense distribution throughout the southern region.

In Tanzania, the Level 1 areas are pretty evenly distributed throughout the landscape. For the Host Model Approach, the land area at risk is greatly reduced as the risk priority level increases. The Level 2 risk magnitude area encompasses 82 km^2, roughly 0.16% in the Senegal model, and includes those areas classified as moderate host presence represented by the sand color on the map in Figure 3.14. Alternatively, Level 2 risk magnitude area in Tanzania covers 0.97% or 8,805 km^2 scattered throughout the country as evidenced on the map in Figure 3.15.

Similar to the low host category, the moderate host presence class has the following definitions: (1) no vectors and moderate host presence, (2) low, moderate, or high vector presence with moderate host presence. Moderate host presence elevates the level of risk due to the availability of a blood meal for feeding flies (Späth 2000; Ngonyoka et al. 2017). Adequate access to a constant food supply reduces starvation rates among recently emerged or teneral flies, as well as mature fly populations (Hargrove and Williams 1995; Du Plessis 1934;

Hamilton 1911). The high host presence, Level 3 risk magnitude class accounts for exceedingly small areas 0.003% and 0.10% in Senegal and Tanzania, correspondingly.

The level 3 areas at risk are symbolized by the magenta color on Figures 3.14-3.15. The definitions for this group are: (1) no vectors and high host presence and (2) low, moderate, and high vector presence and high host presence. Persistent and regular contact with tsetse increase the likelihood of the fly alighting on hosts, biting, and passing trypanosomes, increasing the risk of trypanosomiasis (Torr and Vale 2015; Torr et al. 2012; Vale et al. 2013). Areas in the high host presence classification have a level 3 risk magnitude. However, very few pixels in the host model approach fall within this category Figure 3.14-3.15.

3.6.3 Vector Model Approach

The Vector Model Approach emphasizes vector presence as shown in Figures 3.16-3.17. All classes are represented in this model's results, indicated by the colors representing each individual category in Figures 3.16-3.17 below. Level 0 as previously addressed is represented by the charcoal gray color in the map, meaning those modeled areas have no risk of trypanosomiasis. Like the host model, the definition for a Level 0 risk magnitude are: (1) pixels with no vector presence and no human or animal host availability, or (2) areas of low, moderate or high tsetse presence with no host available for tsetse to feed upon.

The lack of host availability increases starvation among tsetse populations, reduces copulatory responses among the vectors and is directly correlated to tsetse survival rates (Wall 1988;

Briceño and Eberhard 2017; Lord et al. 2017). The Level 1 risk magnitude covers 4,056 km^2 or 7.75% of the area modeled in Senegal and 96,365 km^2 or 10.58% in Tanzania.

The conditions for a Level 1 risk magnitude for the vector model approach occurs are: (1) low vector presence and no host presence or (2) low vector presence and low, moderate or high host presence. The lower risk is due to patchy tsetse populations which inhibit frequent vector-host contact (Auty et al. 2016). The pattern for the Level 1 risk priority is symbolized by the teal color in the grid and maps in Figure 3.16-3.17.

The limited number of vectors reduce the hazard likelihood, specifically the interaction with tsetse which lowers risk of trypanosomiasis (Ponte-Sucre 2016; Ford 1963). However, Vale 2014 asserts, the threat of tsetse are worst where they are scarcest. That is to say, there are instances where natural host and vegetation tend to be scarce and tsetse density is low and the flies in those areas feed in high proportions on any available host, increasing the risk of disease transmission (Vale et al. 2014).

The Senegal vector model has a Level 2 risk magnitude area of 1,827 km^2 and Tanzania has 93,314 km^2 meaning 3.49% of Senegal and 10.2% of the Tanzania area modeled has increased risk of trypanosomiasis due to moderate vector presence. The criteria for this category are: (1) moderate vector presence and no host or, (2) moderate vector presence and low, moderate, or high host presence, represented by the sand color on the map in Figure 3.16-3.17. The moderate vector presence class in Senegal is mostly clustered in the southern region and lightly

peppered in the northern region. This category is more concentrated in the central, coastal, and southern regions of Tanzania, and scantily located in the Lake Victoria region.

The final class of the Vector Model Approach is the Level 3 risk magnitude which constitutes 1,930 km^2 or 3.69% in Senegal and 286,492 km^2 or 31.46% in Tanzania. The Level 3 risk magnitude area characterized by the magenta color on the map below, is larger than the area at risk in the Level 2 class for both countries. Level 3 is the highest category of risk within the modeled area. The class is defined as: (1) high vector presence and no host or, (2) high vector presence and low, moderate or high host availability.

Due to high vector prevalence, the opportunity for regular encounters between tsetse, human and animal hosts are highly probable (Aksoy, Gibson, and Lehane 2003). Pixels in level 3 are widespread throughout the model's distribution area, illuminating these areas as the potential locations for critical tsetse control campaigns. The SMART models are useful intervention site selection approaches which can support the pre-planning control efforts.

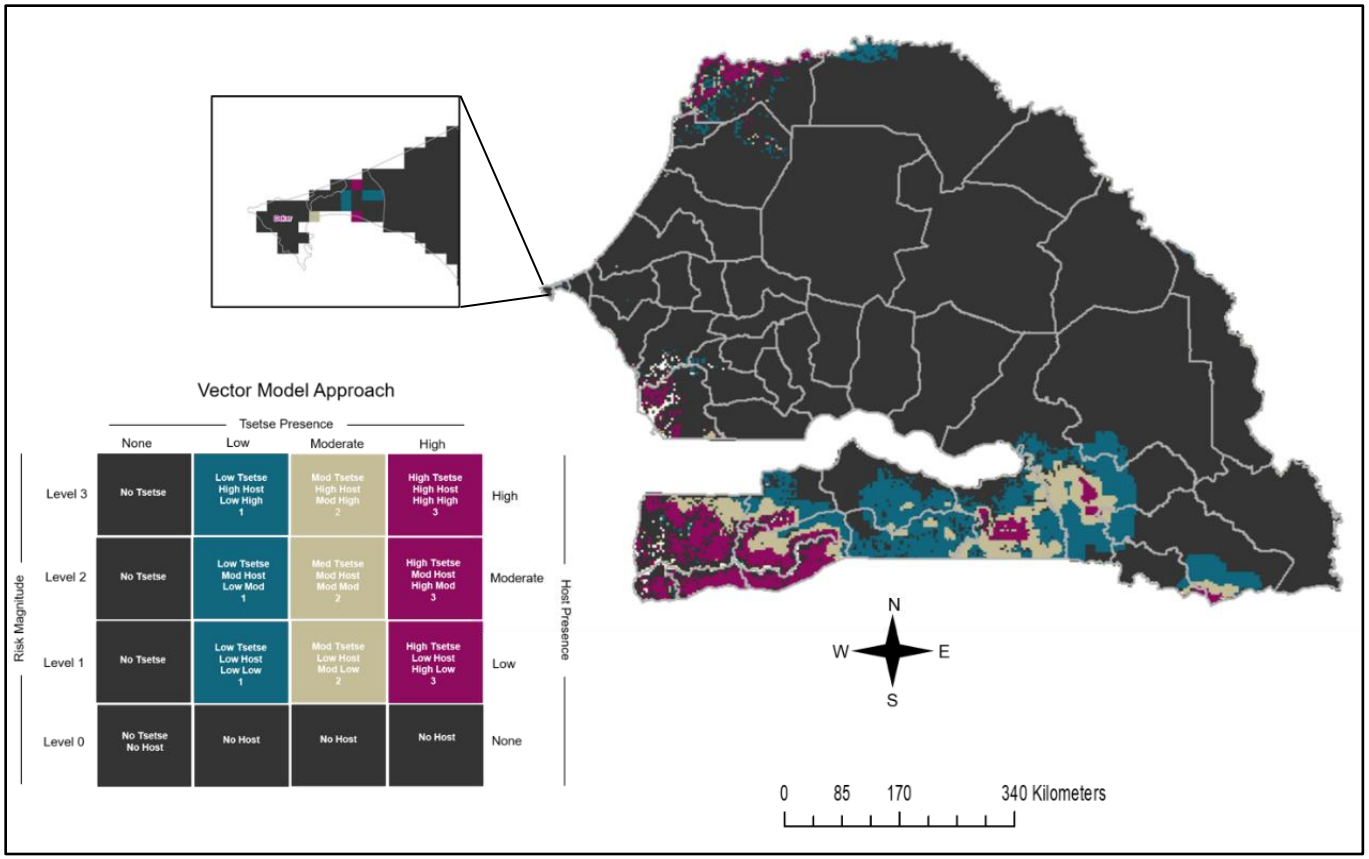


Figure 3. 16 Diagram of the Senegal Vector Model Approach and a map of the model output. The inset map shows details of the Dakar, Senegal area. The Vector Model Approach weighs the presence of vectors per pixel across the modeled area.

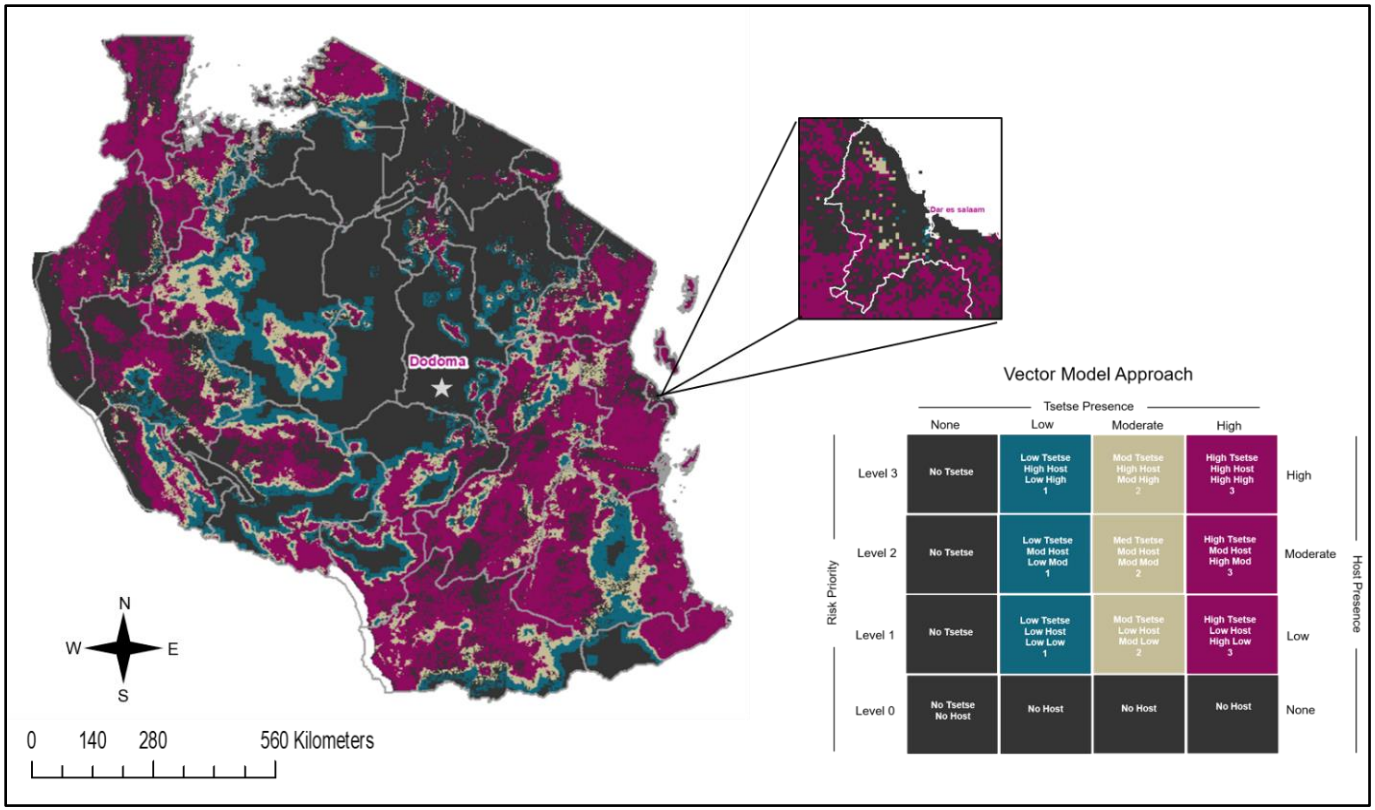


Figure 3. 17 Diagram of the Tanzania Vector Model Approach and a map of the model output. The inset map shows details of the Dar es Salaam, Tanzania area. The Vector Model Approach weighs the presence of vectors per pixel across the modeled area.

3.6.4 Combined Multicriteria Model Approach

The Combined Model Approach measures the instances when both the host model and vector model conditions are collocated in pixels across the landscape. Level 0 conditions persist as it has in the previous models. Risk magnitude Level 1 displayed in teal, consists of: (1) low vector presence and low or moderate host presence, or (2) moderate vector presence and low host presence. Level 1 areas make up around 11% and 21% of the remaining modeled area in Senegal and Tanzania, respectively.

The 5,866 km^2 area includes districts in the northern and southern regions Senegal and the 187,411 km^2 area in Tanzania are most abundant in the central and southern regions. Level 2 risk magnitude areas are indicated by the sand color and follow a diagonal pattern in Figure 3.18-3.19. The definition for this class are those pixels where there are: (1) low vector and high host presence, or (2) moderate vector and host presence and (3) high vector and low host presence. This class strikes a balance between tsetse, human and animal host occurrence across the modeled area (see Figure 3.18-3.19). Additionally, this class coupled with the Level 1 category, demonstrates the spatial variability of the risk over the environment.

Risk is not continuous, it is fragmented over the modeled area, however as evidenced by the maps in Figure 3.18-3.19 below, risk magnitude levels shift abruptly and sometimes categories of risk abut one another creating a clustering effect. In the Combined Model Approach, the highest risk magnitude, Level 3 covers only 29 km2 or 0.05% of the at risk areas in Senegal while accounting for 6,207 km^2 or .68% in Tanzania. Level 3 risk occurs when: (1) moderate or high vector presence and high host presence and (2) high vector presence and moderate host

presence. For both countries this class is peppered throughout the modeled area. The combined model offers a view of the interaction between vectors and hosts in the model outcomes and evens out the presence and absence of each variable across space. Providing a more comprehensive and unbiased lens into the push-pull relationship between these factors. The combined model shows the greatest amount of diversity among the outcomes emphasizing the bidirectional impact of both host and vector.

3.6.5 CANVAS Simulation Results

Figures 3.20-3.21 show the effects of both control applications on a 15x15 km^2 woodland control area in quadrant 2, 3, and 4. The Woodland vegetation is the most suitable habitat for tsetse (see Table 3.6), which means higher tsetse densities will be pervasive throughout the landscape. Figure 3.17 shows the operation area after the traditional control application. The legend to the right of the figure shows the tsetse population density and can be used to examine the post control results for figures 3.20-3.21. As the colors transition from lighter whites and yellows to the darker more saturated shades of orange, red, brown, and black it denotes higher tsetse density in each pixel, which represents 1 square kilometer (sqkm). The areas in red at the outer perimeter of each quadrant represents an active tsetse habitat and reinvasion threat. The areas where either control application where placed received mild control benefits.

The lighter the color in the area the more effective the control application and greater the reduction of tsetse. Alternatively, the darker the color the lower the control impact. The

traditional pattern providing the most control benefit to the areas it was applied as evidenced by the light yellow areas in the control field. While providing some limited control to the adjacent areas in red on the outer perimeter, the areas left open in the pattern demonstrate the reinvasion opportunity. For this control scheme the maximum control results occur around the center of the operational area where all the quadrants meet. The combined strength increased the intensity of the control and subsequently provided some benefit to those cells that received no control intervention.

Figure 3.21 illustrates the CANVAS method on a woodland area. As seen in Figure 3.12, the CANVAS method applies control in a contiguous pattern within the control field, when possible. The benefit of a consecutive, abutting pattern is increased control strength and reduction in reinvasion susceptibility. The increased dose strength also benefits the areas that were not included in the control operation or for whom no control was applied. The orange line behind the red area on the outer perimeter in Figure 3.21 evidence the above mentioned phenomena of shared control in the areas that had no control applied. The areas in light yellow and white throughout much of the control area shows the tsetse density is nearly inexistent in these areas.

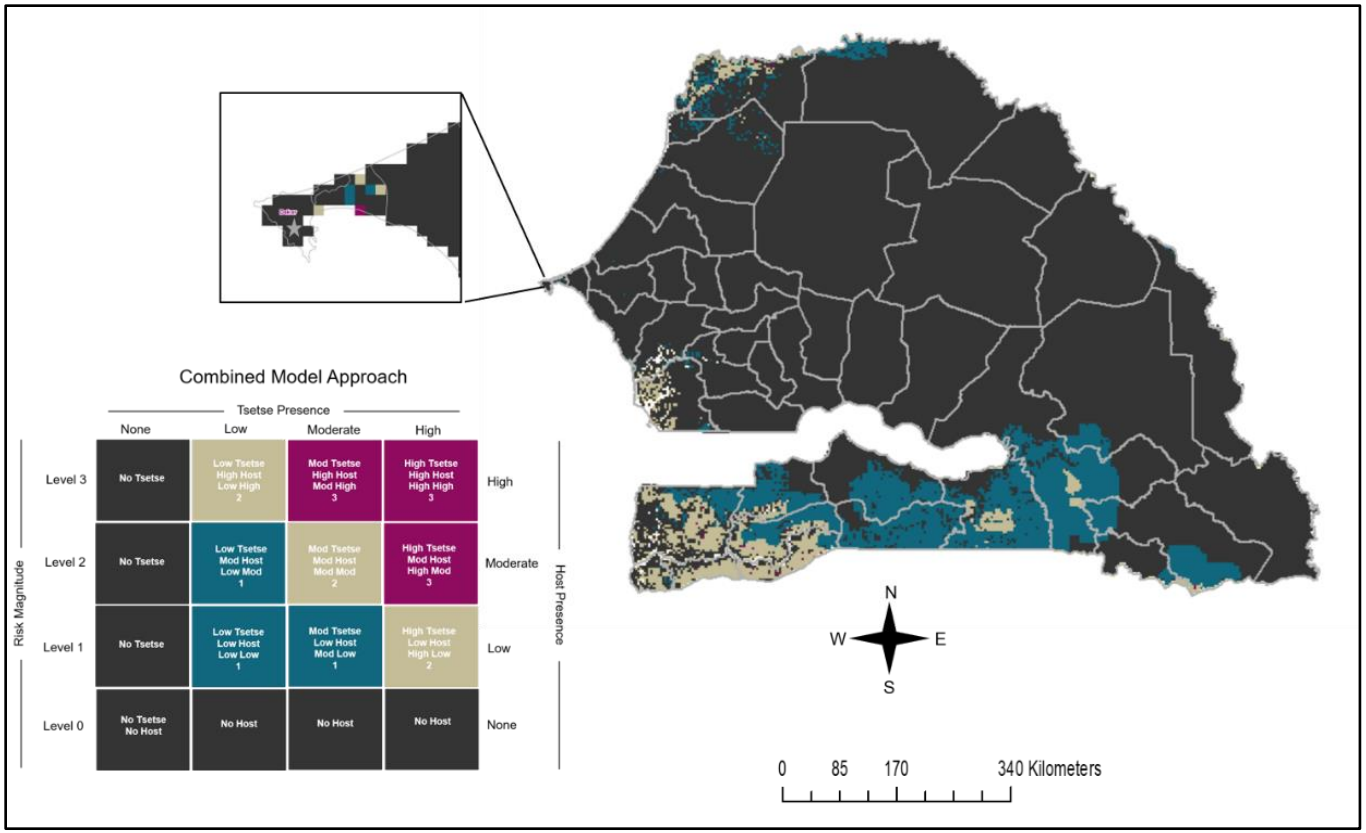


Figure 3. 18 Diagram of the Senegal Combined Model Approach and a map of the model output. The inset map shows details of the Dakar, Senegal area. The Combined Model Approach equally weights vector and host presence per pixel across the modeled area.

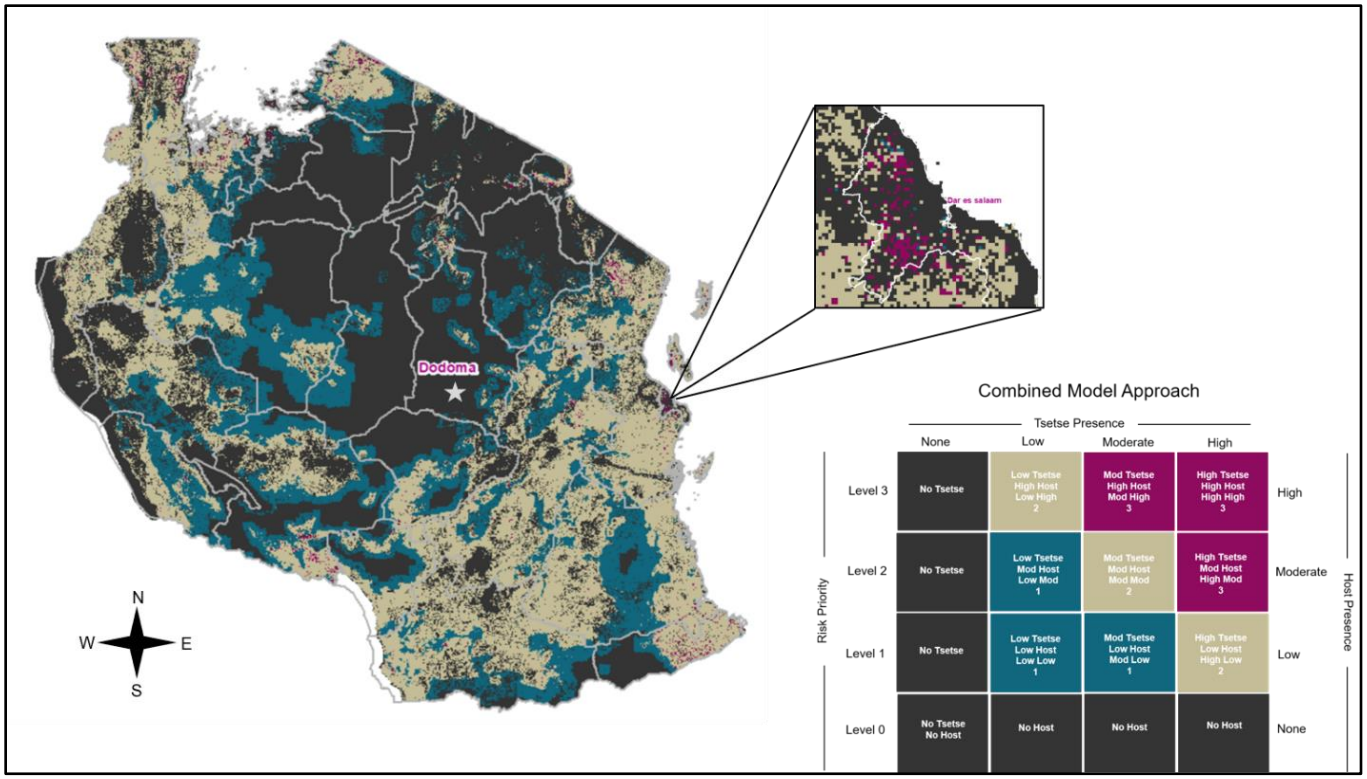


Figure 3. 19 Diagram of the Tanzania Combined Model Approach and a map of the model output. The inset map shows details of the Dar es Salaam, Tanzania area. The Combined Model Approach equally weights vector and host presence per pixel across the modeled area.

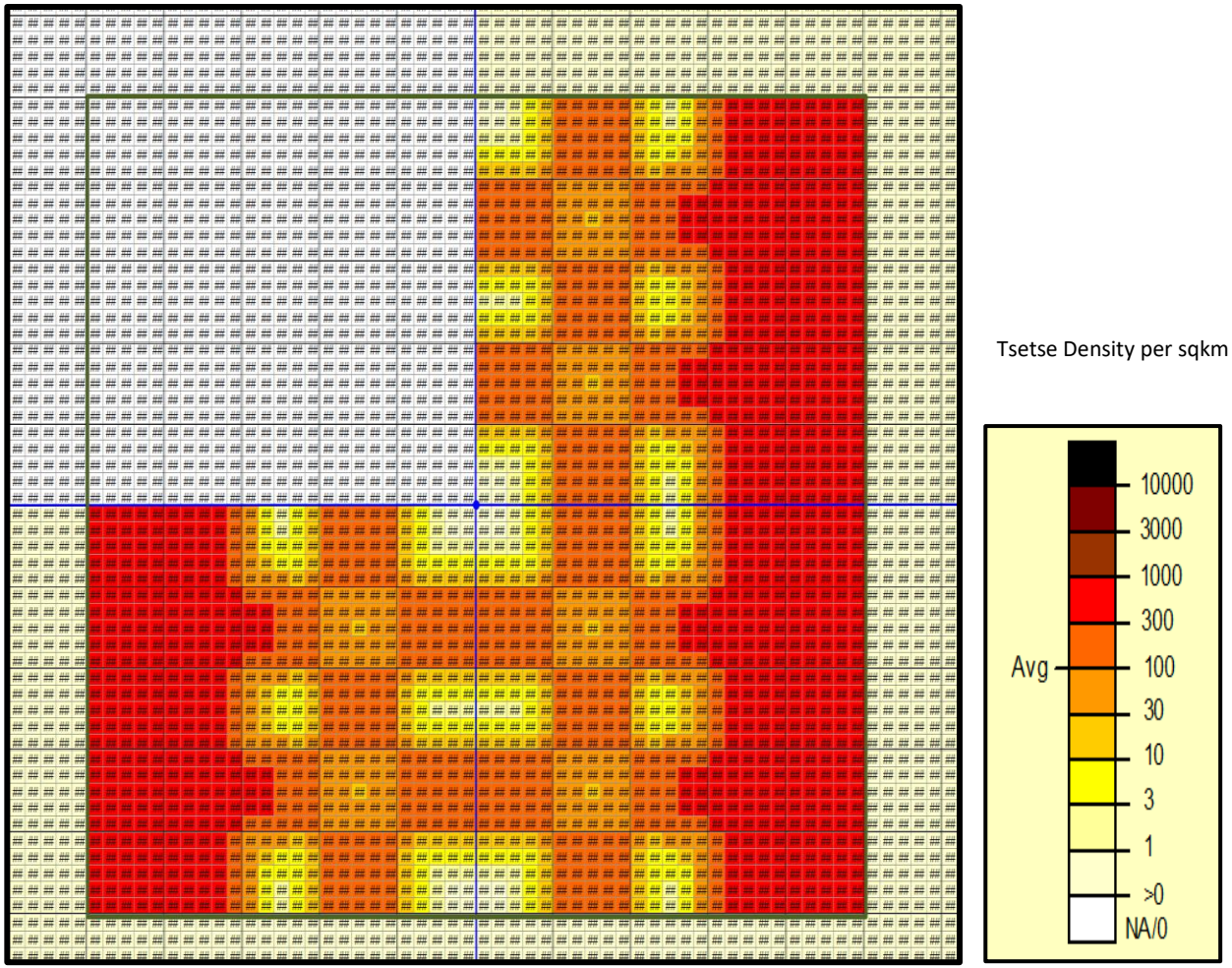


Figure 3. 20 Tsetse density of the woodland operational area after traditional control application. The bright red color on the map represents areas with high tsetse density within the operational zone that present a re-invasion threat. The areas where the red and orange colors meet represent places that are susceptible to re-invasion.

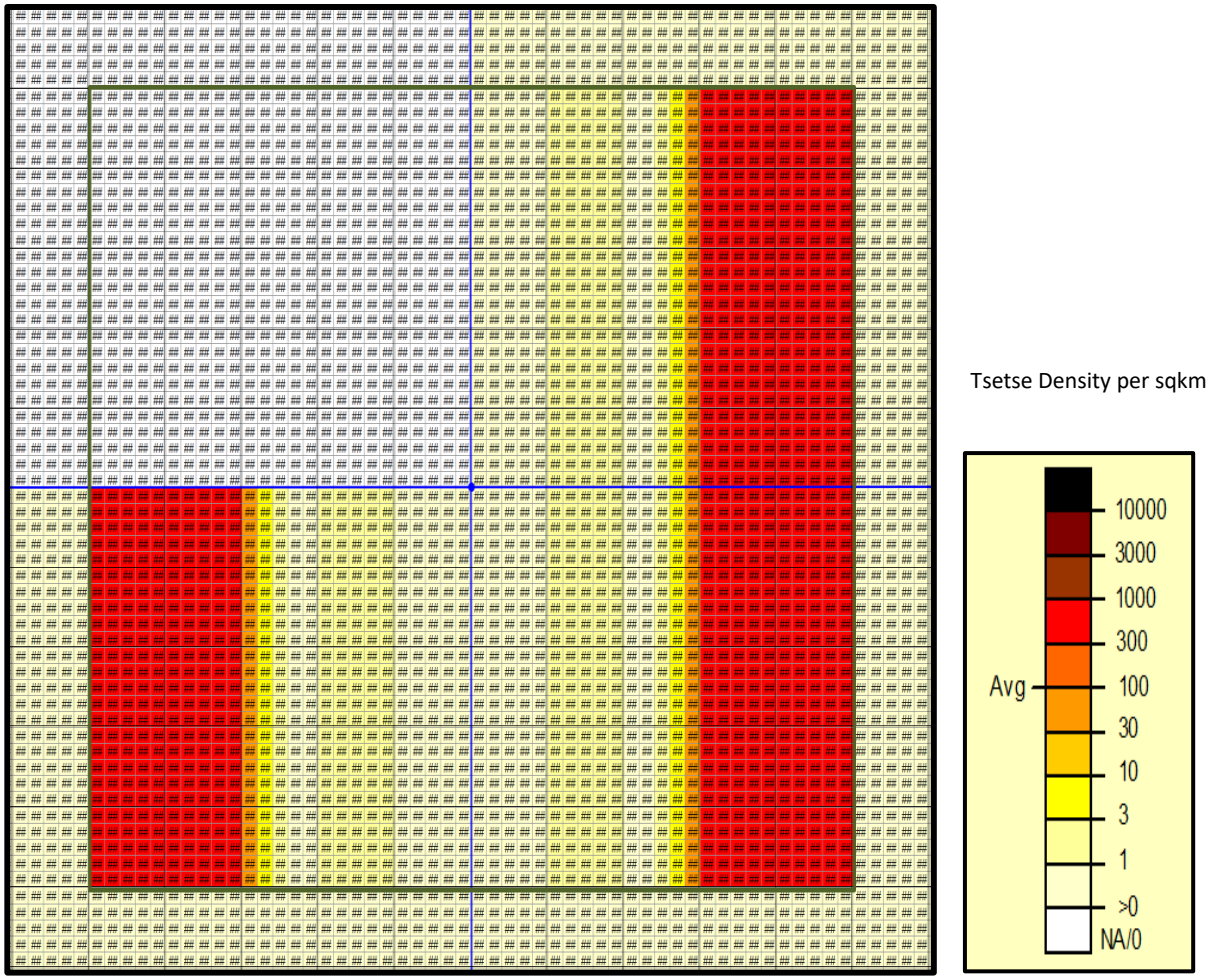


Figure 3. 21 Tsetse density of the woodland operational area after CANVAS method application. The bright red color on the map represents areas with high tsetse density within the operational zone that present a re-invasion threat. The areas where the red and orange colors meet represent places that are susceptible to re-invasion.

For the purpose of this dissertation, the CANVAS method has been applied to the same control extent as the traditional control. However, I argue that the application of CANVAS more broadly would be the ideal scenario and will have the biggest impact on knocking down tsetse populations to unrecoverable rates in some instances. Moreover, the hypothetical simulation environment can be altered to include natural barriers such as the "city/town" included in this simulation or other areas where control would be difficult to reach by foot. In such cases, the aerial applications, SAT, and SIT offer the best option for control of very remote areas.

Table 3.8 shows a day-by-day comparison of the traditional control scheme and the CANVAS method on the Woodland landscape. The results are in increments of 30 days beginning after Day 14. The density of tsetse at the start of the campaign in the woodland environment is 5,679 per km^2. At the end of all simulations, the tsetse density had been decreased, with the CANVAS method showing the greatest reductions (see Tables 3.8 and 3.9). Host risk was reduced in all cases over the course of the campaign, trailing the reduction in fly density. The graphs in Figure 22 below, demonstrated the downward trends in fly population numbers which correlate with the reduced risk of trypanosomiasis in hosts populations. Table 3.8 also shows gender response variations, for instance, female flies live longer than male flies (S. Leak 1999), the models show that female tsetse die at a slower rate too.

The graphs in Figure 3.22 below demonstrate the changes over time for fly density, from the start of the campaign (Day 1) to the end of the control campaign period (Day 216). The graphs delineate the population into two trendlines: (1) tsetse over 40 days old, and (2) tsetse of all ages. Tsetse over 40 days old are more likely to be infected with trypanosomes and therefore

more likely to infect hosts. Therefore, the density of mature flies over 40 days old are an important indicator for trypanosomiasis risk. The graph on the left shows the traditional control pattern applied to the Woodland operational area, and the graph on the right shows the Woodland operational area after the application of the CANVAS method.

At the start of both campaigns, the population of tsetse per sqkm over 40 days old hoovers around 2,000, and the population density for tsetse of all ages is roughly 6,000. The CANVAS method knocks down the fly population more rapidly than the traditional method in the first 50 days of the campaign. Although the control ran 216 days (P. McCord, Messina, and Fahey 2012) both graphs trend downwards, and level off near day 175 on the traditional graph and day 150 on the CANVAS graph. The trendlines remain flat until the end of the campaign, indicating that the maximum limit of the control's effectiveness was achieved around day 175 and 150, respectively. The implication of this observation is that the control campaign could be reduced by the remaining 41 days for the traditional control and 66 days for the CANVAS method, saving costs accrued for controlling the remaining days.

Table 3. 8 Tsetse Plan 2 simulation results: day-specific tsetse demographics and risk indices for the woodland area under traditional control and CANVAS applications.

Woodland Area Traditional Method														
Days	Average numbers of tsetse per sqkm							Avg % values in whole survey area				Risk Indices, Males & Females		
from	Adult Males		Adult Females		Males & Females		Pupae	% of adults of age>40			%Females	Cattle	Cattle	Humans
start	Age >40	All ages	Age>40	All ages	Age>40	All ages	All	Males	Females	Mal+Fem	in adults	ConViv	Brucei	Brucei
0	409.0	1898.2	1568.0	3780.81	1976.98	5679.05	5621.5	21.5	41.5	34.81	66.57	3901.4	190.2	158.5
1	397.1	1843.0	1521.1	3668.55	1918.17	5511.573	5615.3	21.5	41.5	34.80	66.56078	3901.4	190.2	158.5
14	316.3	1549.4	1188.1	2970.43	1504.48	4519.842	5176.9	20.4	40.0	33.29	65.71976	3005.7	146.6	122.2
30	285.0	1484.5	1028.6	2714.93	1313.60	4199.421	4251.0	19.2	37.9	31.28	64.65013	2635.6	131.4	109.5
60	269.2	1296.4	897.7	2358.78	1166.86	3655.172	3632.6	20.8	38.1	31.92	64.53258	2410.0	120.5	100.4
90	265.3	1201.4	844.7	2176.24	1110.00	3377.601	3323.9	22.1	38.8	32.86	64.43164	2249.8	111.6	93.0
120	252.9	1127.6	798.2	2043.66	1051.18	3171.248	3116.9	22.4	39.1	33.15	64.44336	2125.2	105.1	87.6
150	242.0	1070.3	763.1	1943.45	1005.10	3013.757	2958.4	22.6	39.3	33.35	64.48604	2026.0	100.1	83.4
180	232.6	1024.2	735.0	1864.17	967.54	2888.353	2833.9	22.7	39.4	33.50	64.54078	1946.2	96.0	80.0
210	224.4	986.4	712.1	1799.97	936.48	2786.384	2733.2	22.8	39.6	33.61	64.59865	1880.8	92.7	77.3
216	223.0	979.7	708.0	1788.59	930.95	2768.302	2715.3	22.8	39.6	33.63	64.60956	1869.1	92.1	76.8
Woodland Area CANVAS Method														
Days	Average numbers of tsetse per sqkm							Avg % values in whole survey area				Risk Indices, Males & Females		
from	Adults Males		Adult Females		Males & Females		Pupae	% of adults of age>40			%Females	Cattle	Cattle	Humans
start	Age >40	All ages	Age>40	All ages	Age>40	All ages	All	Males	Females	Mal+Fem	in adults	ConViv	Brucei	Brucei
0	409.0	1898.2	1568.0	3780.81	1976.98	5679.05	5621.5	21.5	41.5	34.81	66.57	3901.4	190.2	158.5
1	388.0	1801.8	1484.7	3582.77	1872.78	5384.567	5610.4	21.5	41.4	34.78	66.53781	3901.4	190.2	158.5
14	244.8	1285.9	908.2	2378.31	1152.99	3664.18	4839.3	19.0	38.2	31.47	64.90713	2334.1	114.0	95.0
30	192.2	1174.8	696.0	2026.14	888.15	3200.935	3280.0	16.4	34.3	27.75	63.29842	1804.2	92.0	76.7
60	171.6	870.7	601.1	1591.20	772.68	2461.945	2477.4	19.7	37.8	31.39	64.63167	1603.5	80.6	67.1
90	166.5	782.4	577.1	1463.09	743.59	2245.527	2216.7	21.3	39.4	33.11	65.15564	1497.1	74.1	61.8
120	160.2	736.3	560.0	1395.90	720.19	2132.169	2105.9	21.8	40.1	33.78	65.46854	1440.8	70.9	59.1
150	156.1	711.3	548.6	1357.10	704.68	2068.383	2041.5	21.9	40.4	34.07	65.61155	1404.9	69.0	57.5
180	153.3	695.8	540.2	1331.36	693.53	2027.187	2000.3	22.0	40.6	34.21	65.67535	1380.3	67.7	56.4
210	151.3	685.3	533.6	1312.68	684.94	1997.983	1971.2	22.1	40.7	34.28	65.70036	1362.1	66.7	55.6
216	151.0	683.6	532.5	1309.52	683.45	1993.112	1966.3	22.1	40.7	34.29	65.70243	1359.0	66.6	55.5

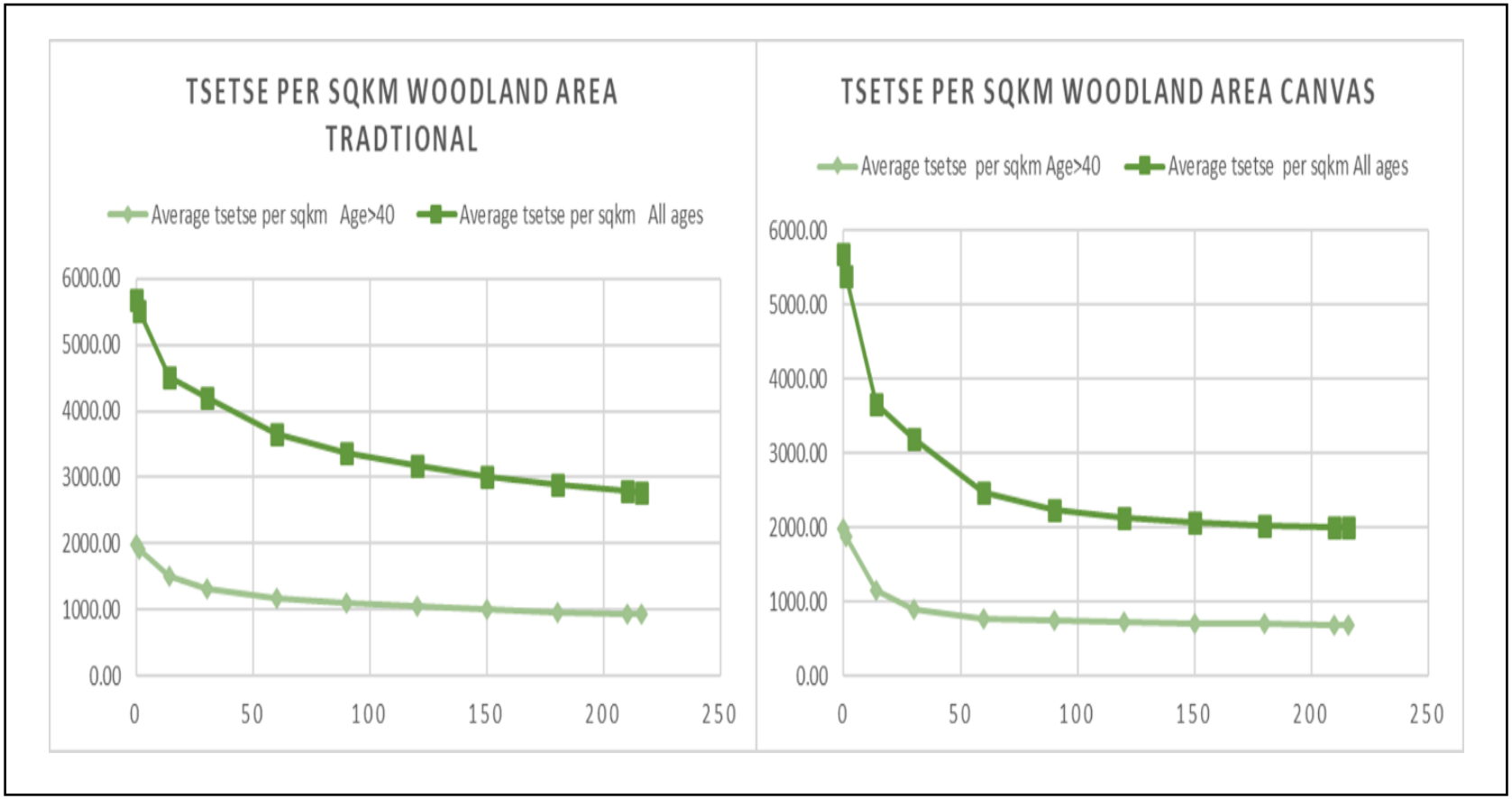


Figure 3. 22 Trends in tsetse population density in the woodland control operational area under traditional (left) and CANVAS (right) applications.

The second set of scenarios took place on the SMART landscape environment outlined in Table 3.6. The control application from Figure 3.13 (left) was run on the resulting vegetation pattern (see Figure 3.12 left). In the SMART landscape environment Q2 has the most suitable vegetation type for tsetse (see Table 3.5), which means higher initial fly density in the area. Figure 3.23 shows the SMART landscape operational area after the traditional control application. The legend to the right of the figure shows the tsetse population density and can be used to examine the post control results for figures 3.23-3.24.

The outcomes in Figure 3.23 show moderate reductions in tsetse populations density in Q3, evidenced by the mostly yellow to white hues in the grid squares. The control effect degrades closer to the inner borders of Q3, as signified by the orange and red hues in those areas. As the colors transition from white to yellow to the darker more saturated shades of oranges, reds, brown and black it denotes high tsetse density in each pixel which represents 1 sqkm. Contrastingly, the areas in Q2 and Q4 show minimal control, reflected by the sustained high density tsetse population post control, demonstrated by the dark red to red brown shaded areas. The areas at the center of the operational landscape experienced a moderate to high control effect, despite receiving no direct control application. This phenomenon illustrates the "free rider" notion that many smallholder farmers find upsetting when practicing control

Table 3.9 shows a day-by-day comparison of the traditional control and the CANVAS method applied to the SMART landscape from the beginning to the end of the campaign. The results are in increments of 30 days beginning after Day 14. The density of tsetse at the start of the campaigns in the SMART environment is 2,288 per km^2. At the end of the campaign, the tsetse

density declined in both models, with the CANVAS method showing the greatest reductions (see Tables 3.8 and 3.9). Host risk was reduced in all cases over the course of the campaign, trailing the reduction in fly density. The graphs in Figure 3.22 and 3.25, illustrate the differences between the two control application models. Both the outcomes also demonstrate reductions in the fly population and subsequent trypanosomiasis risk reductions to host populations. Neither model achieved a zero fly level, the implications of residual fly populations is that over time with the ecological and environmental conditions, species proliferation is likely, and resurgence is a possibility.

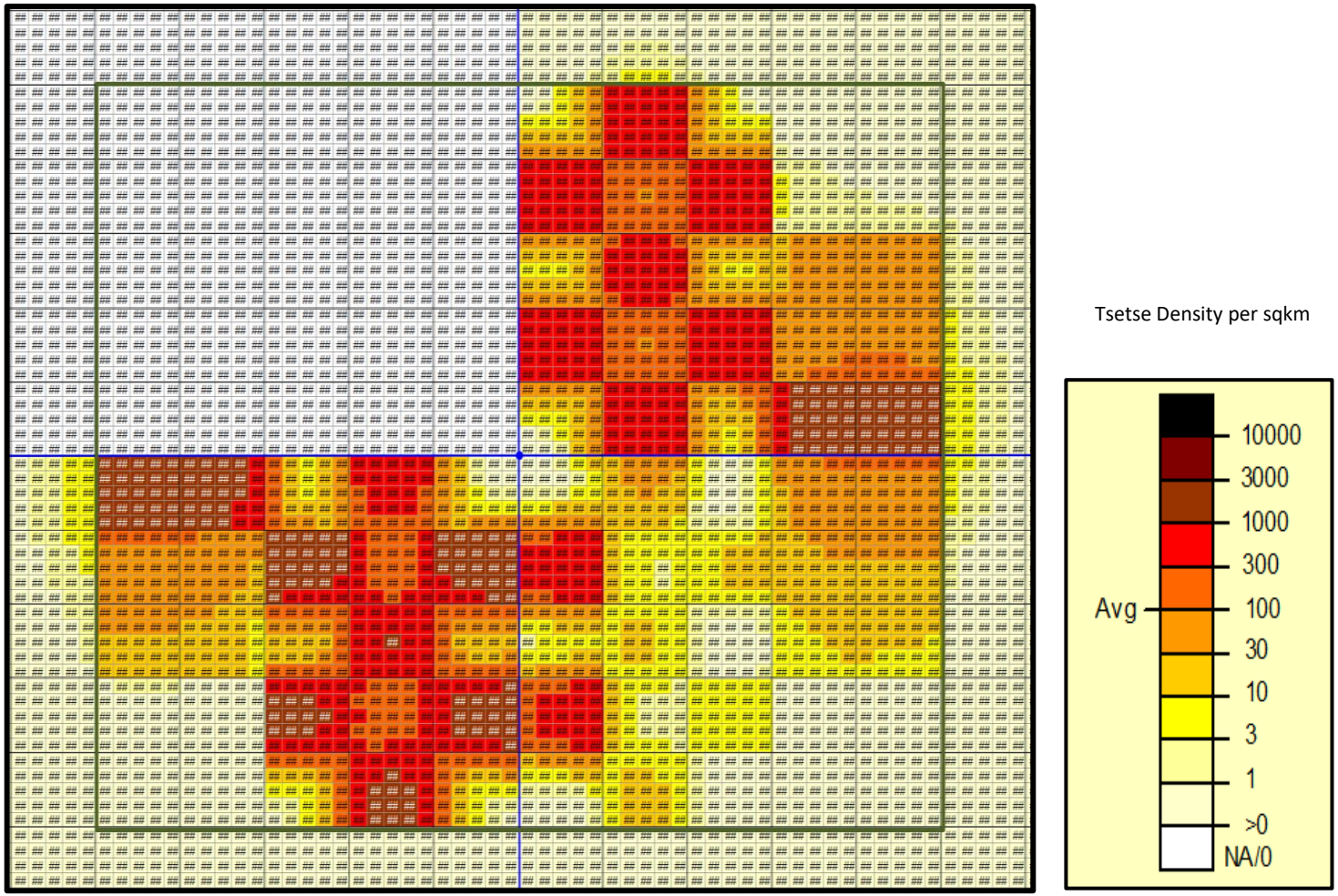


Figure 3. 23 Tsetse density on the SMART risk-scape operational area after traditional control application. The bright red color on the map represents areas with high tsetse density within the operational zone that present a re-invasion threat. The areas where the red and orange colors meet represent places that are susceptible to re-invasion.

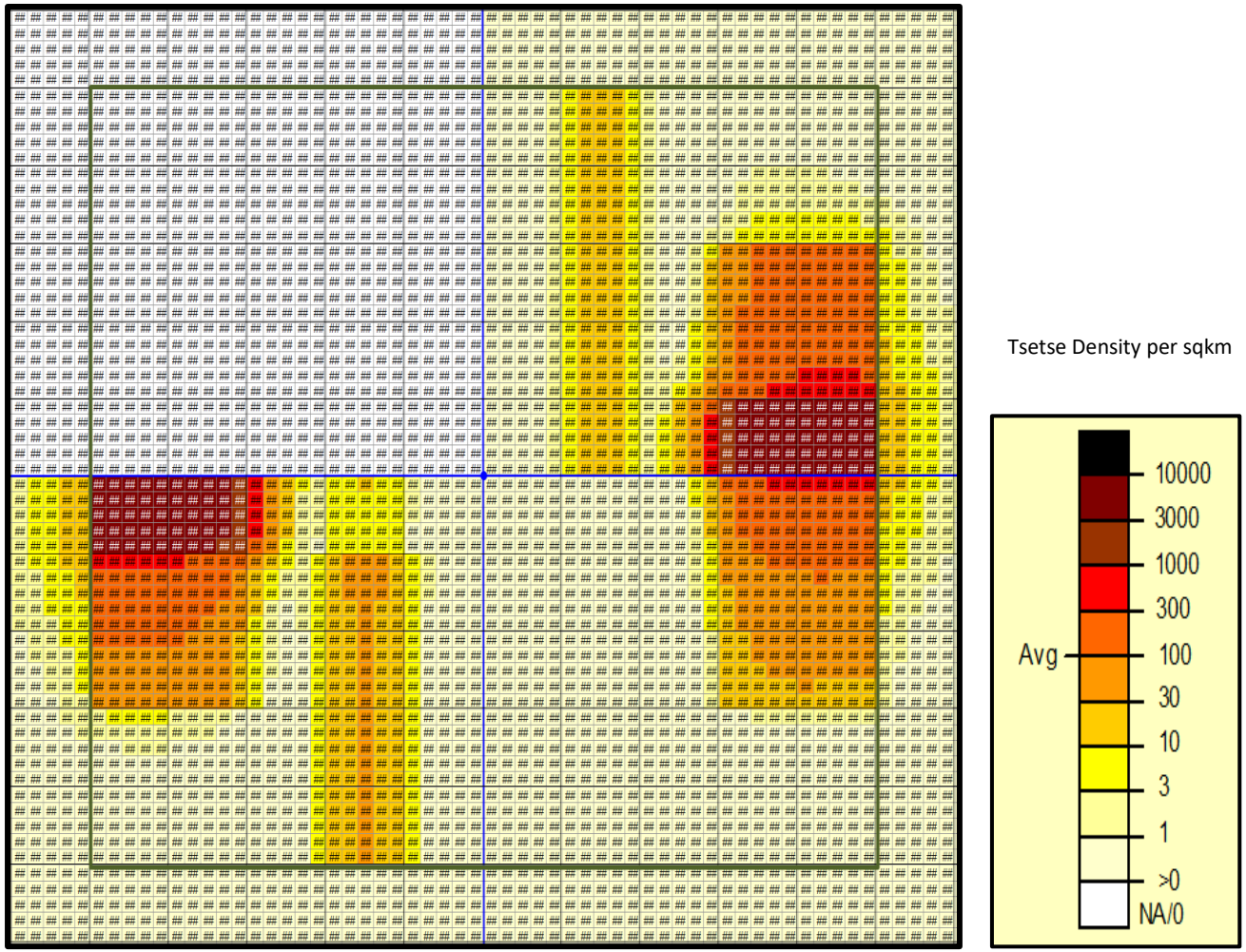


Figure 3. 24 Tsetse density on the SMART risk-scape operational area after CANVAS control application. The bright red color on the map represents areas with high tsetse density within the operational zone that present a re-invasion threat. The areas where the red and orange colors meet represent places that are susceptible to re-invasion.

Table 3. 9 Tsetse Plan 2 simulation results: day-specific tsetse demographics and risk indices for the SMART landscape under traditional control and CANVAS applications.

SMART Landscape Traditional														
Days	Average numbers of tsetse per sqkm							Avg % values in whole survey area				Risk Indices, Males & Females		
from	Adults Males		Adult Females		Males & Females		Pupae	% of adults of age>40			%Females	Cattle	Cattle	Humans
start	Age >40	All ages	Age>40	All ages	Age>40	All ages	All	Males	Females	Mal+Fem	in adults	ConViv	Brucei	Brucei
0	164.1	769.7	623.9	1519.23	787.96	2288.95	2271.2	21.3	41.1	34.42	66.37	2466.3	120.8	101.7
1	156.9	736.1	596.1	1452.05	753.03	2188.178	2267.5	21.3	41.1	34.41	66.35902	2466.3	120.8	101.7
14	108.1	556.8	400.1	1036.14	508.19	1592.916	2003.5	19.4	38.6	31.90	65.04681	1626.8	79.7	67.3
30	89.6	517.1	309.8	889.12	399.37	1406.222	1450.2	17.3	34.8	28.40	63.22727	1296.7	66.0	55.8
60	80.3	405.3	239.1	686.48	319.43	1091.791	1092.8	19.8	34.8	29.26	62.87678	1104.4	56.5	47.8
90	77.6	351.1	210.8	586.13	288.39	937.2732	920.8	22.1	36.0	30.77	62.53563	968.4	48.9	41.5
120	70.5	309.5	186.1	513.74	256.52	823.2753	806.6	22.8	36.2	31.16	62.40219	862.8	43.4	36.8
150	64.2	277.3	167.4	459.18	231.58	736.4645	719.5	23.2	36.5	31.44	62.34968	778.5	39.1	33.2
180	58.8	251.3	152.5	416.07	211.26	667.3807	651.1	23.4	36.7	31.65	62.34382	710.7	35.6	30.2
210	54.1	230.0	140.4	381.18	194.46	611.1967	595.8	23.5	36.8	31.82	62.36642	655.0	32.8	27.9
216	53.2	226.2	138.2	375.00	191.46	601.2262	585.9	23.5	36.9	31.85	62.37195	645.1	32.3	27.4
SMART Landscape CANVAS														
Days	Average numbers of tsetse per sqkm							Avg % values in whole survey area				Risk Indices, Males & Females		
from	Adults Males		Adult Females		Males & Females		Pupae	% of adults of age>40			%Females	Cattle	Cattle	Humans
start	Age >40	All ages	Age>40	All ages	Age>40	All ages	all	Males	Females	Mal+Fem	in adults	ConViv	Brucei	Brucei
0	164.1	769.7	623.9	1519.23	787.96	2288.95	2271.2	21.3	41.1	34.42	66.37	2466.3	120.8	101.7
1	151.1	709.4	573.1	1397.03	724.21	2106.455	2264.4	21.3	41.0	34.38	66.32129	2466.3	120.8	101.7
14	63.4	388.1	226.4	663.46	289.73	1051.593	1790.1	16.3	34.1	27.55	63.09116	1006.3	49.4	41.9
30	32.8	320.6	109.2	463.76	142.06	784.373	844.5	10.2	23.5	18.11	59.12495	546.4	30.1	25.7
60	21.9	143.9	67.7	227.72	89.60	371.5985	394.8	15.2	29.7	24.11	61.28201	397.5	21.1	18.1
90	19.2	101.8	60.0	172.65	79.24	274.4218	272.5	18.9	34.8	28.88	62.91261	328.9	16.8	14.5
120	16.9	83.2	55.8	148.95	72.69	232.117	231.5	20.4	37.4	31.31	64.16859	300.3	15.0	13.0
150	15.7	75.0	53.5	138.14	69.19	213.0874	212.1	21.0	38.7	32.47	64.82577	285.1	14.2	12.3
180	15.1	70.8	52.1	132.42	67.16	203.2423	202.3	21.3	39.3	33.05	65.15163	276.3	13.7	11.8
210	14.7	68.5	51.1	128.97	65.80	197.4931	196.5	21.4	39.6	33.32	65.3042	270.5	13.4	11.6
216	14.6	68.2	51.0	128.44	65.57	196.6255	195.7	21.4	39.7	33.35	65.32219	269.5	13.3	11.5

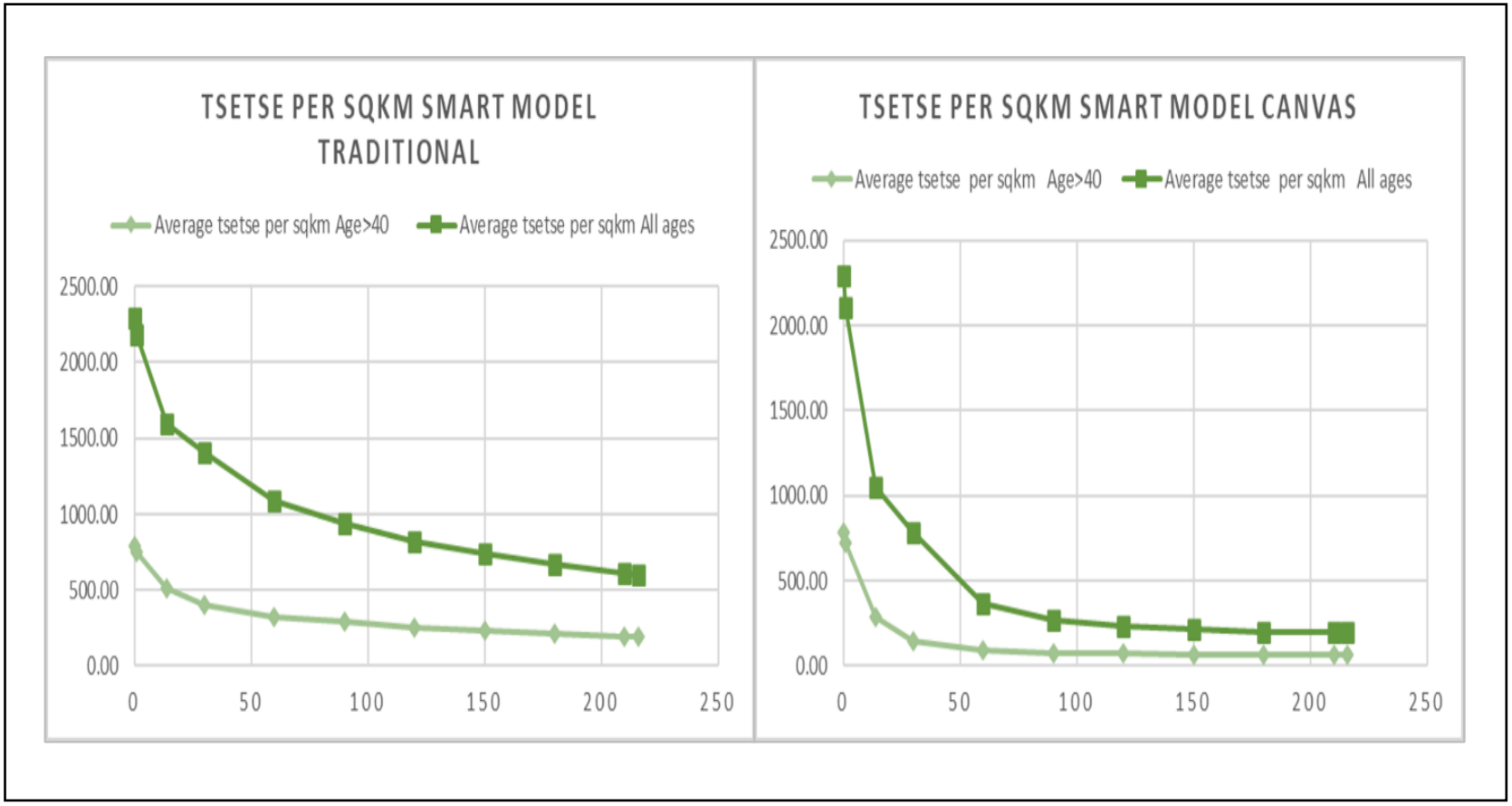


Figure 3. 25 Trends in tsetse population density in the CANVAS control operational area under SMART (left) and CANVAS (right) applications.

3.7 LIMITATIONS

The three datasets used in the risk models: (1) google earth engine tsetse ecological distribution, (2) LandScan global human population distributions, and (3) grazing areas as well as the scenario data in the Tsetse Plan 2 model simulator, are modeled data and have not been validated on the ground for accuracy. While models can be informative, the use of simulated data in a controlled environment, without the benefit of ground truthing, cannot be interpreted as exact. Models are a good estimate of conditions on the ground. However, in some instances ground truthing is not feasible or possible, therefore modeled data is our best estimate to explore some phenomenon. Moreover, there are degrees of uncertainty introduced with the linking of data and models in a GIS environment, and while there are geoprocessing techniques to transform data files such as projections, resampling and reclassification to correct the errors, some may remain when scaling (Burrough 1996). Further the spatial resolution of the data files used were not a one-to-one match, primarily along the edges but can occur elsewhere as well. Despite resampling, small variances may impact the alignment of the data points in space which may cause an overlay issue.

The grazing land data is an aggregate of MODIS grasslands and savanna classes. For this study, grazing land was used as a proxy for animal distribution across sub-Saharan Africa. Combining the landcover classes in this manner may overestimate the animal distributions which are more confined on the ground. Additionally, the modeled data indicates that animal distributions are stationary, but livestock mobility and herd movements occur frequently, following seasonality trends (Turner and Schlecht 2019). The innumerable amount of livestock and wild game animals make accurate counts difficult. Estimates using modeled livestock distributions and livestock

censuses provide ex ante approximations of the domestic animal distributions (Robinson et al. 2014; Cumming et al. 2015). However, wild animal estimations are more difficult to obtain. In the absence of official counts and actual numbers, modeled distributions such as was used in the risk area study serve as adequate proxies.

It is widely accepted that development such as that in urban areas drives out tsetse due to the inadequate vegetation and other environmental characteristics. However, with the proper ecological conditions, tsetse can exist in atypical locations. These atypical locations challenge the model's ability to accurately predict the location of habitats and falsely classifying locations as unsuitable, that may contain isolated tsetse populations. The Sequential Aerial Technique (SAT) and the Sterile Insect Technique (SIT) approaches were not analyzed in this study.

Additionally, SIT is not a control operation option in the TP2 program. However, they are important in the tsetse control equation especially for reaching remote, isolated populations that cannot be reached by foot. Model outcomes are great guides but can be improved through the addition of first-hand observations for example, local narratives. The models are great guides to demonstrate risk determinants across space but should not be considered the complete picture.

3.8 CONCLUSIONS

The objective of this chapter was to explore tsetse and trypanosomiasis risk from multiple dimensions. Examining the determinants of risk contextualized the micro and macro level factors that create risk vulnerabilities for people and animals of sub-Saharan Africa. Through

modeled approaches, at-risk areas were identified across both case study countries. Locating the areas at-risk allows better control strategy planning. The SMART models provide a way to investigate the risk/hazard dynamic comprehensively through the lens of vector presence, human and animal host presence, and through the multicriteria combined model.

Each model's results illustrated that risk is not a continuous phenomenon across space but is predicated by environment and ecological conditions and are rather peppered throughout the landscape. McCord 2011 states, "streaming from limited financial resources is the need to prioritize which areas within a country would yield the greatest benefits from control". The Simulated Models of Areas at Risk for Trypanosomiasis (SMART), created for this dissertation, provide a scalable, multidimension method by which countries can make such determinations.

The central hypothesis for this study argues that a coordinated, simultaneous, and scalable control strategy will improve outcome efficacy across space and time**.** The hypothesis was tested using the CANVAS Method demonstrated in the Tsetse Plan 2 simulation environment on the woodland and SMART landscapes in section 3.6.5. The results of the comparative analysis between the traditional control application and the CANVAS method provide evidence that simultaneous control applications, strengthen the control effect on the operational area. Further the compounded effect of control diffuses outside the operational area.

Moreover, the results indicate that the closer interval pattern of the CANVAS method intensifies the dose strength of control throughout the operational area. The stronger dose strength of the control application increased the rate of decline among tsetse populations as

indicated by the resulting day-specific tsetse demographic graphs. The rapid decline of the tsetse palpalis fuscipes population in the simulations means that the maximum control effect was reached faster in the CANVAS method than the traditional control application suggesting that shorter lengths of control campaigns might be possible. Additionally, the CANVAS method can be scaled for small or large operational areas and the application is generalizable to different environments and vectors in addition to tsetse flies. The findings support my central hypothesis.

The models jointly allowed the investigation into whether a two-step trypanosomiasis risk reduction framework such as the SMART models and the CANVAS method combination improves control systems. The SMART model provides a scalable and generalizable characterization of the risk-scape which allows localized and area-wide planning of control strategies. The CANVAS method demonstrates that concentrated control strategies regardless to the intensity of the control, offer the best opportunity to suppress tsetse populations opening the way for elimination. While there are a multitude of factors that drive the differences of control outcomes, informational awareness of the full breadth and depth of risk improve intervention planning and increase the likelihood of program success.

Scalable risk and control modeling approaches such as those presented in this study will benefit researchers, practitioners, and planning agencies seeking to develop tsetse and trypanosomiasis control initiatives. The two-step framework provides information and insights that could be useful in the preplanning and intervention feasibility phase. The CANVAS method contributes to sustained reduction of fly populations and addresses reinvasion susceptibility.

Lastly, while unnecessary, species elimination is likely if tsetse populations become unrecoverable. Despite being the only vector that transmits African trypanosomiasis at the risk to humans and animals, there is no other known function of tsetse, therefore eradication will not create an ecological consequence. The only effect is a reduction in biodiversity if tsetse species are lost.

TOWARDS A STAKEHOLDER DRIVEN FRAMEWORK FOR TSETSE AND TRYPANOSOMIASIS CONTROL: A PARTICIPATORY POLICY DEVELOPMENT APPROACH

4.1 INTRODUCTION

Tsetse and African trypanosomiasis mitigation and control in sub-Saharan Africa (SSA) is an inherently human-environment and policy-based problem, requiring multiscale interdisciplinary approaches to manage. African trypanosomiasis is a parasitic illness acquired by the bite of trypanosome carrying tsetse fly. Endemic to 36 countries in SSA, African trypanosomiasis is one of several major neglected tropical diseases. There are many species of tsetse; however only 12 are linked to the transmission of trypanosomiasis infections in humans and animals. The infections manifest in three forms: chronic West African trypanosomiasis, athroponotically derived from trypanosome T.b. gambiense with a three-year life expectancy, acute East African trypanosomiasis from zoonotic trypanosome T.b. rhodesiense with a six-month life expectancy and Nagana in domesticated cattle and wildlife.

The entire region of SSA has been negatively impacted by tsetse and trypanosomiasis (Ford 1971; Alsan 2015b; Mahamat 2015a), through reduced work productivity and agriculture production, concomitant lagging development, and public health burdens. Underdevelopment, poverty, and failure for many villages to thrive is correlated to the presence of tsetse and trypanosomiasis (Grant 2014; Grant, Anderson, and Machila 2015a). Control was frequently a national policy with centralized governance, financing, regulation, and some success. The shift towards local control and stewardship provoked differential access to resources, corruption, and reduced compliance (Grant 2014). Disparities in control protocols and efficacy allowed

tsetse populations to recover and often exacerbated the disease. Current control policies remain top-down strategies (Hargrove, Torr, and Kindness 2003) with limited success. One barrier is the lack of collective support and participation. Long-term sustainability of control programs depends on multiscale cooperation, (Swallow and Woudyalew 1994; Kamuanga et al. 2001; Rogers, Hendrickx, and Slingenbergh 1994) especially by stakeholders including regional officials and locally respected leaders (World Health Organization (WHO) 2017a; Mahamat 2015a). Local engagement among expert and non-expert stakeholders is a fundamental predictor of success of disease control programs in Africa (Mlozi et al. 2006; Kotlyar 2010).

Over the past decade reducing the prevalence and disease burden of sleeping sickness has become a global public health priority. To spur research and support in this area, in 2012, the World Health Organization set a target date of 2020 for the elimination of human African trypanosomiasis as a public health problem and 2030 for the eradication of the tsetse fly. However, little consensus exists among researchers, policymakers and stakeholders on which interventions are the most efficient and feasible for long-term sustained results (Keating et al. 2015; Wamwiri and Changasi 2016a; Mahamat 2015a). Contrary to WHO's reluctance towards broad-based control strategies; the lack of coordinated, generalizable wide area applications, unified and standardized control protocols and policies developed with input from stakeholders across scales will continue to hinder progress towards tsetse and trypanosomiasis suppression and elimination (Aksoy et al. 2017; Scoones 2000; Grant, Anderson, and Machila 2015a).

Further complicating control and eradication success are policies created with little input from local leaders and residents with situational knowledge of the environment and disease system.

Overwhelmingly, inaction around control and eradication ultimately sustain tsetse and trypanosomiasis indefinitely and impede the achievement of the elimination target goal (Scoones 2000; Grant 2014). Through an environmental science and policy lens, the following questions surrounding the policies of tsetse and trypanosomiasis will be examined: (1) what would a global policy for tsetse and trypanosomiasis risk reduction and control require to be successful (2) how is success measured and, (3) who would be the major stakeholders and what agencies would need to be involved.

4.2 BACKGROUND

Tsetse and trypanosomiasis policies have a long history of tragedy, controversy, and inadequacy stemming from fundamental breakdowns in societal contracts. A disease of antiquity, trypanosomiasis has existed in ancient foci for millennia (Lambrecht 1964; Kohagne Tongue et al. 2011; Cattand and De Raadt 1991). The outbreaks of human and animal African trypanosomiasis are largely the results of environmental disruptions triggering an upset to the ecological balance of mammal and fly interactions (Bursell 1980; Waller 1990; Hargrove 2003).

Although past failures have plagued control programs, policy and practice, historical perspectives continue to inform the current tsetse and trypanosomiasis policy, mitigation and suppression landscape (Bouyer, Seck, and Sall 2013; Solano et al. 2010). The difficulties to control tsetse and trypanosomiasis are broad and complex. Participation at the national, regional, and local levels across the tsetse belts are required to make progress towards suppression and elimination (Okello, Welburn, and Smith 2014).

Conventional policy construction philosophies undertaken by WHO and other global and

national agencies often omit local voices (Kimbell and Bailey 2017; Sindato, Kimbita, and Kibona 2008; Grant 2014). This tradition perpetuates a hierarchy which marginalizes stakeholders at lower scales (Kimbell and Bailey 2017; Junginger 2017). Collective involvement and contributions are important indicators of the success of disease control programs in Africa (Mlozi et al. 2006; Kotlyar 2010; Quick 2018). Thinking about the process is important not only regarding intervention effectiveness but the process of policy development and whose voice matters (Machila, Anderson, and Grant 2016; Anna Okello, Welburn, and Smith 2015; World Health Organization (WHO) 2017b). Although the World Health Organization and others support community participation in theory, the development and implementation of tsetse and trypanosomiasis control and eradication programs and policies have historically been planned at the global and national levels (Sindato, Kimbita, and Kibona 2008; Mahamat 2015a).

The programmatic management and decision-making have traditionally been the responsibility of central governments, non-governmental organizations, and public-private partnerships (Fèvre et al. 2008; Simarro, Diarra, and Ruiz-Postigo 2011; Waiswa and Wangoola 2019). The top-down structure of the abovementioned practices, creates barriers to participation for local people during the planning and development process (Sindato, Kimbita, and Kibona 2008; Menon 2011; Percoma et al. 2018). Providing opportunities for inclusive engagement reduces structural inequity, increases the likelihood of acceptance during implementation, creates buy-in, builds social capital, are more culturally competent, and encourages good stewardship of the projects among community members (Kovacic et al. 2013a; Rutto et al. 2013; Song and Yin 2010). Additionally, idea generation and innovation are enriched by the inclusion of diverse voices which enhance program design and captures nuanced dynamics on the ground that

might otherwise be missed (Brocklesby, Hobley, and Scott-Villiers 2010; Junginger 2017).

While it is rare for input and decisions regarding tsetse control to be derived at the local level (Mulumba Kamuanga 2003; Mahamat 2015a), the long-term sustainability of control and eradication programs depends on local commitment and acceptance (Swallow and Woudyalew 1994; Kamuanga et al. 2001; Rogers, Hendrickx, and Slingenbergh 1994). The lack of policies developed with input from stakeholders across all strata will continue to hinder progress towards trypanosomiasis elimination and may explain the lack of efficacious outcomes regionally (Aksoy et al. 2017; Scoones 2000; Grant, Anderson, and Machila 2015a).

The policy analysis and subsequent participatory policy development for tsetse control and eradication addresses these concerns through (1) the inclusion of local voices, (2) equitable opportunities for participation in the policy, and intervention development among expert and non-expert stakeholders.

4.3 Analytical Policy Framework for Tsetse and Trypanosomiasis Control

This paper follows a modified version of the Centers for Disease Control and Prevention's POLARIS policy framework with an analysis of tsetse and trypanosomiasis control policies. POLARIS is a systematic five phase policy framework that includes: (1) problem identification, (2) policy analysis, (3) strategy and policy development, (4) policy enactment and, (5) policy implementation, with stakeholder engagement and education at its core (CDC 2013). POLARIS is a step-by-step policy development framework. The process helps to define the issue, identify risk factors, survey best practices, and conduct an environmental scan to determine the best

policy options for the proposed problem and the community. While several other health policy analysis tools exist, POLARIS is stakeholder-centered with opportunities for engagement, education, and contributions. The POLARIS framework offers functional and operational considerations are for prioritizing policies. For the purpose of this dissertation only the first three phases of POLARIS will be undertaken as depicted in Figure 4.1, suggestions for the final two phases will be provided in Discussion section. A policy analysis is an important retrospective evaluation step which can help determine the efficacy and areas of opportunities of past and present intervention strategies (Canela-cacho et al. 2000). Prospectively, analyzing policies can assist with the planning of future programs and validate recommendations for adjustments to prior procedures (Walt et al. 2008). Differential levels of success and sustainability have plagued tsetse and trypanosomiasis control (Grant 2014; Scoones 2000), suggesting that evaluation of on-going programs would be beneficial.

Phase one of the framework is **problem identification**. In this stage the fundamental concern is characterized, and a problem statement and potential outcomes are developed. After defining the problem, a **policy analysis** of past and present tsetse and trypanosomiasis control programs literature from Chapter 2 was conducted. The final phase is the **strategy and policy development** stage. After outlining the problem and grounding strengths and weaknesses through the context of existing policies, identifying, and describing what an alternative tsetse and trypanosomiasis policy needs to be successful is the next step. To do this, data were collected to support participatory policy development using the Political, Economic, Socio-cultural, and Technological (PEST) analysis and stakeholder narratives.

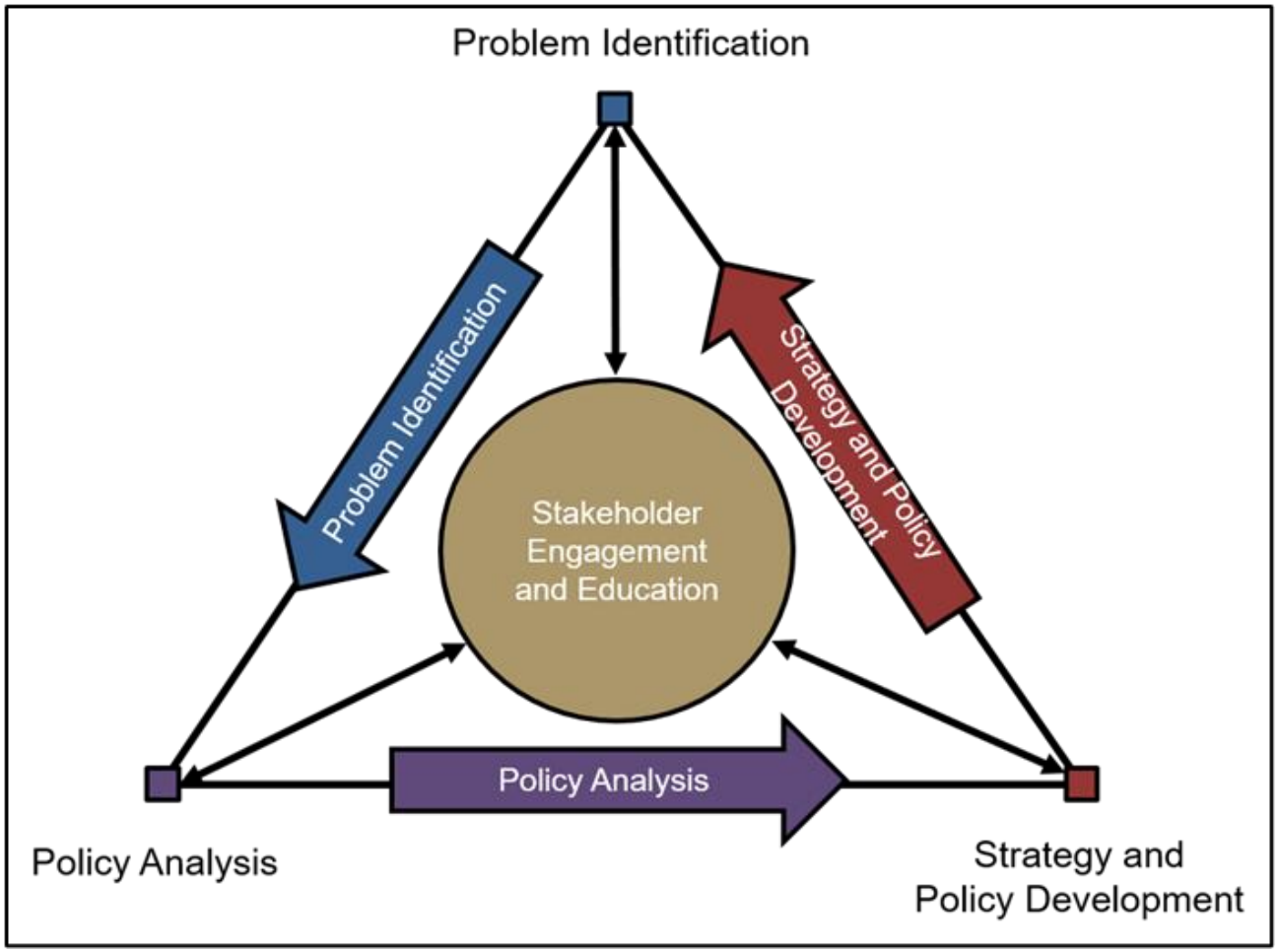


Figure 4. 1 Conceptual Diagram Adapted from Centers for Disease Control POLARIS Policy Framework.

4.4 PHASE 1: PROBLEM IDENTIFICATION

A critical barrier to the long term success of tsetse and trypanosomiasis control programs is limited participation, including local voices in policy construction and community buy-in. Novel approaches to policy development are necessary to advance science and solve prolonged and persistent disease systems. Co-creating policy with members of the groups who will benefit most or those who will be affected most by the policy, is a more inclusive approach to policy development which improves the overall outcome of the policy and strengthens acceptance among local communities(Mlozi et al. 2006; Kotlyar 2010). Creating policy interventions with limited external collaboration reduces the likelihood of widespread application, effectiveness, or sustainability (Kimbell and Bailey 2017).

For years, local participation in tsetse control strategies have been identified as a key factor in program success. In the April 1997 proceedings for a joint symposium for African animal trypanosomiasis, both the International Atomic Energy Agency (IAEA) and Food and Agricultural Organization (FAO) espoused that “control should be participatory” (IAEA and FAO 1997; Gerber et al. 2008; P. H. Clausen et al. 2010). In 2004, Dransfield and Brightwell concluded that top down trypanosomiasis control policies fail to account for “community needs and priorities”(Dransfield and Brightwell 2004). Additionally, emphasizing that community-based approaches provide engagement opportunities for local people, which foster a sense of ownership and increase the likelihood of program sustainability (Dransfield and Brightwell 2004). Further, Dransfield contends that policies derived by international agencies often follow traditional static methods, which fail to account for on the ground dynamics of both tsetse and human populations, illuminating the importance of local knowledge (Brightwell et al. 2001;

Dransfield and Brightwell 2004; Kovacic et al. 2013a).

Efforts to galvanize community support have waned in recent years, due to the perceived reduction in reported trypanosomiasis cases across sub-Saharan Africa. Despite the downward trend, “advocacy in endemic areas should continue to be maintained and sleeping sickness should retain its high priority with health policy makers and planners” (Simarro, Jannin, and Cattand 2008). The sentiment expressed by Simarro et al. 2008, is reinforced by practitioners who are actively running tsetse control programs and working with communities to identify ways to include them in the process (Mlozi et al. 2006; Gunn et al. 2018). Additionally, people on the ground have an intimate understanding of the environment which is a valuable asset for policy making and compliance and their voices must be included in policy development (Ellis and Mdoe 2003; Davis et al. 2019).

Mahamat’s 2015 *How to Succeed a Tsetse Eradication Project* (Mahamat 2015b), attests to the lack of community input and informational awareness in tsetse control policies. For example, during the April 2017 WHO meeting on sleeping sickness, several requests arose, including participant’s desire for WHO to improve its communications and opportunities to contribute, specifically, to non-expert persons and local communities (World Health Organization (WHO) 2017a). Although WHO recognizes the importance of community support and buy-in, and openly acknowledge this as a shortcoming in their policy development process, little has changed with their input solicitation protocols (Mahamat 2015a). Mboera et al. 2007 and others assert there are knowledge gaps within endemic and nonendemic populations about the

vector and the disease, highlighting poor community sensitization, awareness, and buy-in deficits (Mboera et al. 2007). Other scholars cite these factors as fundamental indicators of deficient cooperation and implementation, which inhibit the long-term success of tsetse control programs (Kovacic et al. 2013b; Wangoola et al. 2019). Capacity building relies heavily upon awareness and inclusion in the decision-making process (Lambrechts et al. 2009; Standley et al. 2019; Ramirez 2017). Although there is sufficient evidence to support the inclusion of local voices in tsetse control policy development, barriers to participation persists.

4.5 PHASE 2: POLICY ANALYSIS

The **policy analysis** will examine the four overarching policies of control and eradication: (1) population displacement, (2) land development, (3) vector control, and (4) trypanosomiasis treatment, surveying areas of opportunity and best practices.

4.5.1 Population Displacement Policies

Ford's ecological hypothesis argues that ancient African civilizations were aware of and successfully lived with tsetse (Ford 1971). Historical documents attribute the co-existence to local knowledge that allowed Africans to navigate the environment. For example, the development of villages far removed from tsetse-prone areas, the diversion of the Nile River to alter its flow path to avoid tsetse habitats, bush clearing, and the expansion of villages kept tsetse populations and trypanosomiasis outbreaks controlled (Steverding 2008b). The onset of colonialism brought out many tensions both sociocultural, and environmental (Isenberg and Nash 2014; Petri 2012). Most notably, the modification of settlement patterns in Sub-Saharan Africa by the forced removal of Africans from ancestral lands, and then more subtlety during

Pax Britannica (Ford 1971). The period touted by colonial administrators as an opportunity to reduce inter-tribal conflict, relaxed the long-held cultural requirements of African people to stay within the boundaries of land owned by relatives (Willett 1963). Pax Britannica encouraged migration over the continent, creating alternative settlement patterns that reduced population density in traditional encampments, and developed sparse homesteads in the bush, both actions amplified host-fly contact and increased the risk of epidemics (Grébaut et al. 2004).

While Pax Britannica incorporated a broader over-arching population displacement policy, some colonial occupied countries in Africa adopted similar and often harsher removal practices to control tsetse and trypanosomiasis. Henry Hesketh Bell, Colonial Governor of Uganda, issued radical mandates to restrict, isolate, and evacuate Ugandans from the shores of Lake Victoria (Headrick 2014; Queen 1911) and far from any known tsetse habitats. Ugandans living on small fishing islands along the coast were not allowed to return to the mainland, nor was anyone allowed to sell or possess fish (Headrick 2014). Lake Victoria served as a primary source of the food supply in Uganda and its shoreline had the right conditions to be a suitable tsetse habitat (Johnson 1929a). However, the actions by Bell not only supplanted countless Ugandans, it created a negative feedback loop: the abandoned lands were then taken over by bush which provided appropriate environmental conditions for tsetse proliferation and spurred more sleeping sickness infections among African and colonial settlers (Van Den Berghe and Lambrecht 1963).

Continent wide, colonial land occupation policies created bifurcated land holding systems that stripped lands from Africans and displaced families (Wolmer 2005). The system granted

possession of perceived prime lands to colonialists, relegating Africans to marginal lands in remote rural areas, often in close proximity to tsetse habitats (Giblin 1990; Ford 1971). It could be argued that Colonial Administrators were less familiar with the African environmental landscape and therefore through intentional population relocation policies, inadvertently placed Africans at risk for tsetse exposure (Hoppe 2003).

Refugees and population displacement in Africa continue to threaten the lives of migrating people by increasing their exposure risk to tsetse (Armstrong 1991). Political unrest and instability have caused displaced people throughout sub-Saharan Africa creating a disease control concern, among other issues (Bayar and Aral 2019). Violent conflicts such as those in the Democratic Republic of the Congo created fragmented and segregated populations and people fleeing warring areas with trypanosomiasis increases the risk of trypanosome transference to tsetse populations in new areas (Tong et al. 2011; Berrang-Ford, Lundine, and Breau 2011).

4.5.2 Land Development Policies

The economics of agriculture and land development in Africa was among many drivers behind colonization of the continent (Langley 1994). Land expropriation for agricultural intensification programs became widespread under colonial rule (Muriuki et al. 2005). The changes in land development and husbandry procedures towards more intense production systems, while viewed as public good policies by imperial leaders, dramatically altered the environment and the ensuing bush clearing operations encroached on tsetse habitats (Okello, Welburn, and Smith 2014).

The number of outbreaks and subsequent human and animal trypanosomiasis epidemics are closely related to territory advancement and environmental alterations during the colonial period (Macaulay 1942). Colonial battles for preeminence, contests for space and land ownership battles, promoted land abandonment and bush expansion (Armstrong 1991). Mineral mining projects and railway development further enlarged colonial territories and increased the probability of human and animal host interactions with tsetse (Dumett 1985). Prevailing attitudes around tsetse and trypanosomiasis both past and present, center on development as the critical component to reduce the presence of the fly (Alsan 2015c). While the development-control argument is valid, development in the case of the occupation of Africa was also the catalyst for several epidemics (Anderson et al. 2015b). Additionally, African population growth resulted in agricultural land expansion and movement into marginal areas frequently unsuitable for the high-intensity agriculture necessary to reduce tsetse habitat.

Post-colonial land grabs and corporate development have continued to create pressure on the land throughout sub-Saharan Africa. The energy and mineral richness of the African continent has attracted interests from many governments and multilateral companies (Armstrong and Blackmore 2017). Most notably, China and Korea have been dominant investors in agriculture, trade, and land improvement projects at the subnational level (Alden 2005; Hwang 2014). International Development Bank's ancillary support of African nations have also aided in land growth and expansion across the continent.(Cemea 1988; World Bank Group 2019; Scholte 2012). African national investor, Dangote Group has also gained preeminence in the race for commercial land projects in Africa (Akinyoade and Uche 2018). The collective pressure of development has constrained crop cultivation and animal husbandry expansion for smallholder

farmers, who are unable to compete economically with industrial operations (Reid et al. 1997; Salmon et al. 2018). Equally, internal pressures including population growth, unenforced land tenure rights, armed conflict, and transnational transhumance, have increased demands on the land forcing grazing further into the bush into tsetse habitats (Pokou et al. 2010; Fratkin 1997; Luizza 2016).

4.5.3 Tsetse Control Policies

Tsetse control has varied widely over the years: the inconsistency of methods is influenced by a number of factors encompassing: the prevailing attitudes of the time, the leadership, the country or region of control and the targeted tsetse species. There remains much debate among the tsetse control communities about which strategy is most effective.

4.5.3.1 Traps and Targets

The first documented tsetse control efforts occurred on the island of Principe in 1910 (Leak 1999). The two-step control program required the killing of wild pigs and dogs to reduce host availability and then placing black sticky traps on the backs of plantation workers while they were in the field (Ndegwa and Mihok 1999). Both steps had significant environmental and human health consequences. Tsetse are k-strategist vectors with low fecundity, meaning they reproduce slowly, therefore, small isolated populations can be managed with non-mechanical techniques (Gooding and Krafsur 2005). In the 1940s hand nets were giving to workers to catch tsetse throughout the bush of Kenya (Morris 1961). Traps and targets with both human and animal baits were attempted. Traps and targets are species specific, driven by the tsetse group being controlled (Malele 2011), examples of the different traps and targets can be found in **Appendix C**. The standalone odor baited traps, targets and impregnated screens used in

conjunction with pyrethroid insecticides were the most successful (Doyle, Moloo, and Borowy 1984) for non-isolated tsetse populations (Shaw et al. 2013).

DDT was extremely effective as a pour-on insecticide for cattle (Cox 2004). Although successful at killing and eradicating tsetse, the harmful environmental consequences of DDT made its use impractical (Douthwaite and Matthiessen 1985). The use of DDT was replaced with synthetic pyrethroids in the form of pour-on, spray-on and foot dips for cattle (Hadaway et al. 1977). Sequential aerosol technique (SAT) is a plane distributed insecticide spraying method (A. J. Armstrong and Blackmore 2017). This process was employed to control isolated tsetse populations in hard to reach areas (Vreysen et al. 2013). Due to associated costs, the SAT method is not widely used (Alexandra Shaw 2018). Insecticides though effective have unintended environmental consequences including the extermination of non-target, beneficial insects like honey bees (Fiedler 1950; Ross, Wiley, and Sons 1994).

4.5.3.2 Bush Clearing

Environment altering approaches in the form of large scale bush clearing was used widely throughout sub-Saharan Africa. Partial bush clearing was the practice of chopping down or burning shrubs and thickets but leaving the true forest intact (Seed 2001). Discriminative bush clearing is a comprehensive vegetation removal method from areas critical to tsetse survival (Goodier 1961). Selective clearance removed the specific foliage of tsetse's dry season habitats (Unruh 1993). Partial clearance removes undergrowth and low hanging branches of tsetse frequented vegetation (Lloyd, Johnson, and Rawson 1927). Effective in knocking down fly populations, bush clearing caused unintended ecological and environmental consequences

including changes to the microclimate and food availability (Haussmann, Kalwij, and Bezuidenhout 2016). The large scale removal of shrubs and bushes caused soil erosion, downstream effects in the water supply and quality, and habitat fragmentation for wildlife (Sedda et al. 2010; Mweempwa et al. 2015). Additionally, unmaintained cleared areas increased reinvasion susceptibility (Van Den Bossche et al. 2001).

4.5.3.3 Game Culling

Animal hosts are a vital part of the tsetse life cycle and the trypanosomiasis disease system. Hosts are both the transmitter and receiver of trypanosomes and the primary source of the blood meal for tsetse (Beschin et al. 2014). The loss of the primary food source causes increased starvation rates among the fly (Hamilton 1911). Even a minor reduction in animal host availability causes severe consequences for tsetse populations (Hall et al. 1984). Game hunting was accidentally discovered to be an effective way to control fly populations (Vale and Cumming 1976). After the rinderpest epidemic, large scale game animal removal operations became the dominant choice for tsetse management (Gargallo 2009). Initial programs included the indiscriminate elimination of all wild animal hosts. The later process was more selective and only targeted wild animals that were staples in the tsetse diet (Simo et al. 2008). Lasting until the 1960s, mass game kill-offs was a flawed and ecologically irresponsible philosophy as some wild animals such as elephants, are natural environmental cultivators and help control the balance vegetation (Armstrong and Blackmore 2017; Pringle 1990). Furthermore, tsetse would switch primary meal source in response to selective game killing rendering the expected eradication of the fly unfulfilled (Leak 1999). Game culling like bush clearing was a failed

enterprise, conservationists argued that these practices upset the balance of nature and caused numerous environmental consequences (Adams and McShane 1996).

4.5.3.4 Biological Control

Mechanical and environmental control management programs have yet to succeed in the eradication of tsetse. Lack of sustained reductions in fly populations and overwhelmingly negative environmental impacts have led to the abandonment of some practices. Traps, targets, and insecticide treatment of cattle are among the landmark control programs that continue to be used today (Simarro, Jannin, and Cattand 2008). These approaches have been joined by biological control efforts including symbiont cycle disruptors and genetic modifications (Jacob et al. 2017; Aksoy 2003). Biological controls which use the anatomical structures and physiological functions of the tsetse reduce viability of larvae formation and shorten its life expectancy (Sassera et al. 2013; Menon et al. 2016a). For instance, tsetse exist on symbiotic bonds throughout its life cycle (Doudoumis et al. 2013; Heller 2011). Pathology testing that explores the traits and physiological characteristics of each tsetse group has led to discoveries that Wolbachia infections interrupt the symbiotic relationship between tsetse and Wigglesworthia bacteria and thus causes sterility in the fly (Doudoumis et al. 2017).

Sterile insect technique introduces lab reared irradiated male tsetse into wild fly populations (Hoppenheit et al. 2013; Hoy 2019). Female tsetse mate once in their lifetime the use of SIT as a control method increases mating competitions between sterile and wild male flies (Menjeta et al. 2004). Females that mate with sterile males will not produce viable larvae (Hoy 2013). SIT is not a method that can be used alone, it requires a prior control application to knock down the

tsetse population which provides the sterilized males adequate opportunity to mate with wild females (Pagendam et al. 2018). SIT has few environmental consequences, the primary one being its successful application can result in the loss of biodiversity from eradication of tsetse (Nagel and Peveling 2005). Predatory ants feed on tsetse pupae in the ground before they emerge (Rennison and Smith 1961). Similarly, wasp, robber flies and other arthropods feed on adult tsetse, however none of the predators cause the population reductions necessary to control tsetse and therefore are not effective management strategies (Knipling 1972). Photos from the SIT program in Senegal can be found in **Appendix C**.

4.5.3.5 Trypanosomiasis Diagnosis and Treatment Policies

Early diagnosis and treatment of trypanosomiasis includes invasive procedures and toxic chemicals. Early stages of sleeping sickness in humans was detected by swollen lymph nodes in the neck, known as Winterbottom's sign (Willett 1963; Lutumba, Matovu, and Boelaert 2016). Africans suspected of having sleeping sickness were placed in segregation camps and underwent intense exams (Hoppe 2003).

Lumbar punctures were used to detect trypanosomes in the central nervous system; some Africans underwent multiple spinal taps for testing and treatment (Byrd 1973). Treatments consist of trypanocidal drugs and chemotherapeutics. The first trypanocidal drug, atoxyl, a derivative of organic arsenic, was discovered in 1905 (Nieuwenhove 1999). Medicinally, atoxyl required multiple courses of treatment, was only mildly effective and had toxic and sometimes lethal side effects (Ross and Thomson 1910).

In 1919 tryparsamide was determined to have trypanocidal properties with a lower level of toxicity (Sharma and Anand 1997; Davey 1948). However, by the 1950's Lomidine became the primary medicinal prophylaxis against sleeping sickness infections. Large scale mandatory public health vaccination programs using Lomidine were conducted in several countries. The use of Lomidine was deeply controversial and severely unethical co (Lachenal 2017; Newman 2018). The lyrics of the song below translated from the Eton language chronicle the Lomidine drug trial and treatment of Cameroonian natives in the 1950s:

> The shot against sleeping sickness brought me so many problems
>
> The shot against sleeping sickness hurt me so…
>
> They pricked me in the head…
>
> They pricked me in the neck…
>
> They pricked me in the back…
>
> When they go lower
>
> Excrement wants to leave me
>
> Urine even wants to spurt
>
> And still, they want to send me to draw water
>
> If I try to slow my step
>
> The policeman hits me on the head with a stick
>
> - From the personal collection of Hubert Mvogo's Family (qtd. In M. Lachenal 96)

It is clear that the use of Lomidine in the colonies was a major source of pain and suffering among the Africans inoculated with the medicine (Webel 2013), along with many other colonial

edicts. Reports of exploding abscesses, gas gangrene, swift and often gruesome deaths were documented by European doctors seeking to treat and prevent trypanosomiasis (Webel 2019). Lomidine became so compromised that the name had to be change to pentamidine (Lachenal 2017). Although its use was briefly discontinued in Africa, it is still registered for the treatment of active trypanosomiasis infections and HIV/AIDS on the continent (Barrett et al. 2007). Presently, the drug treatment regimen for trypanosomiasis consists of pentamidine, suramin, melarsoprol, and eflornithine (Giordani, Mwenechanya, and Barrett 2014; J. Franco, Scarone, and Comini 2018). Treatment depends upon the stage of disease, and efficacy of treatment remains variable (Lutumba, Matovu, and Boelaert 2016; Priotto et al. 2009). The trypanosome changes its protein sheet frequently which prevents adequate vaccine development (Onyilagha et al. 2017) and a cure is still being pursued (Lejon et al. 2008; Schoijet, Sternlieb, and Alonso 2019). In such cases where prophylaxis and curative treatment are not available, risk reduction and limiting exposure to pathogens becomes critical.

4.6 PHASE 3: STRATEGY AND POLICY DEVELOPMENT

Historically, tsetse and trypanosomiasis control policies were top-down edicts, sometimes ruthlessly imposed on African countries and civilizations (MacKenzie 2017). The practice of creating policy at agencies and institutions far removed from the target communities continues today (Jordan 2012). Programs and policies designed by 'experts' can fail to capture nuanced details from local situated knowledge impacting policy effectiveness (Haraway 1988; Mclafferty 2010; Corbett and Keller 2005). The absence of the local input might explain the lack of efficacious outcomes in the battle against tsetse and trypanosomiasis (Brightwell et al. 2001). While it is rare for input to be derived at the local level, the long-term sustainability of control

and eradication programs depends on buy-in at every scale (Swallow and Woudyalew 1994; Mugalla 2001; Mulumba Kamuanga et al. 2001). Participatory policy development provides an opportunity to co-create programs and strategies with those most likely to benefit from or most likely to be constrained by new programs and policies (Corbett and Keller 2005). A multiscale policy construction approach using stakeholder narratives has the ability to generate buy-in from the groups who will be most impacted.

A small-scale pilot study was developed and conducted to explore and examine perceptions of tsetse and trypanosomiasis control policies. This study was fundamentally based on the strategy and policy development phase of the POLARIS framework, the stakeholder narrative approach developed by Grant et al. 2015 (Grant, Anderson, and Machila 2015a), and the Political Economic Socio-cultural and Technological analysis (Herman 2013; Friesner 2014). Stakeholder identification is the centerpiece of the strategy and policy development phase. Following the example of Grant et al. 2015, the target sample size of 20 was selected (Grant, Anderson, and Machila 2015b). Employing a combination of sampling methods including: (1) purposeful sampling of subject matter experts, (2) convenience sampling of respondents at specific sites, and (3) snowball sampling for respondents with practical and demonstrated knowledge of tsetse and trypanosomiasis control was distributed to colleagues of the targeted participants (Allsop and Saks 2007; Creswell 2014), a diverse list of 18 respondents were identified to participate in the study (see table 4.1 and 4.2).

Using a qualitative methods concurrent study design (Creswell 2014), a combination of semi-structured interviews and the Political Economic Socio-cultural and Technological (PEST)

analysis was administered to study participants. The interviews and PEST analysis were conducted in-person or virtually using either Zoom or Skype. The interview consisted of 16 questions (see Figure 4.2) on tsetse and trypanosomiasis control and eradication policies and a 12 question PEST analysis (see Figure 4.3). All interviews were recorded, and comprehensive notes were taken to accompany the recordings. The interviews were transcribed, evaluated and aggregated according to emerging themes (Grant, Anderson, and Machila 2015a). The resulting stakeholder narratives and PEST analysis

The PEST analysis is a heuristic to examine new policy and program options such as the CANVAS method from Chapter 3. The PEST matrix allows stakeholders to participate in the construction and evaluation of potential policy options across four core areas (1) political feasibility, (2) economic trade-offs, (3) social equity and inclusion of interests groups across all scales, and (4) a technological survey (Friesner 2014). Pairing the PEST Analysis (Herman 2013; Ho 2014) with the stakeholder narrative approach employed by Grant et al. (Grant, Anderson, and Machila 2015a), will aid in participatory policy development and prioritizing potential policy options for tsetse and trypanosomiasis abatement.

Table 4. 1 Stratification of respondents who participated in the stakeholder interviews.

Stakeholder Groups Interviewed							
Industry and Country	Development	International	Regional	Local	Ag Ext	A/H Health	Academics
West Africa	1			1	1	3	2
East Africa			1	1		1	1
Other	1	2				1	2
Total	2	2	1	2	1	5	5

Table 4. 2 Stratification of stakeholders who participated in the PEST analysis.

Stakeholder Group PEST Analysis Respondents					
Industry	Regional	Local	Ag Ext	A/H Health	Academics
West Africa		1	1	3	2
East Africa	1	1		1	1
Other				1	
Total	1	2	1	5	3

Interview Questions

1) How long have you been working in tsetse control?
2) What type of tsetse control programs have you been involved with?
    a. Past
    b. Current/Active
3) What barriers have you faced implementing control strategies (i.e. political, resource and technological)?
4) Which agencies have/are supervising the past/present control programs you have been involved with? What different agencies are funding the control efforts?
5) How have policies helped or hurt tsetse control efforts in your district/regionally/nationally?
6) What type of resources do you feel would help with tsetse control?
7) Do you think coordinated PanAfrican supervision of tsetse control would work?
8) Which tsetse control strategy do you feel is the most optimal approach with the greatest chance of sustainable results?
9) What's your opinion on local governance of and local participation in control efforts?
10) How do you feel about the level of administrative support and assistance received from your local government, regional government etc for control efforts?
11) What's your opinion on current control programs?
12) Do you feel control information is shared widely and effectively between the districts/regionally/nationally (i.e. best practice, successes, failures)
13) How do you feel about the WHO's target elimination of trypanosomiasis as a public health concern by 2020 and the eradication of tsetse by 2030? Do you think the goal will be reached why/why not?
14) Have your programs achieved success in control? Explain.
15) In your opinion what components would a good policy for T&T control require to achieve long-term success
16) What are the most significant or common tsetse control program errors you have seen/made

Figure 4. 2 The list of interview questions on tsetse and trypanosomiasis control asked of each study participant.

Potential Policy Options	**Stakeholders Chart**						
Q1. Do Nothing/Maintain the status quo							
Q2. Strengthen tsetse control policies							
Q3. Increase resource availability							
Q4. Improve control programs through innovation and technology							
Q5. Increase use of traps/targets and other low-tech options							
Q6. Improve trap/target maintenance through incentives							
Q7. Encourage the use of cattle pour-on or dip pesticides							
Q8. Increase the use of SIT hi-tech							
Q9. Encourage use of combined suppression/elimination hi-low tech control throughout the tsetse belt regions							
Q10. Encourage use of SIT through cost breaks and funding							
Q11. Discourage use of pesticides due to environmental concerns							
Q12. Any other option suggestion							
Interest Groups	Development Agencies	Regional Agencies	Agriculture Workers	Conservation Groups	Local Leadership	Animal and Human Health Practitioners	Academics

Figure 4. 3 Sample Political Economic Social and Technological Analysis Matrix chart for stakeholders to identify potential policy options.

4.6.1 Stakeholder narratives interviews

Several schools of thought exist surrounding tsetse and trypanosomiasis abatement. Expert and stakeholder opinions on the subject vary widely. The analytical policy framework of this chapter provides an opportunity to examine tsetse and trypanosomiasis control from multiple angles. The voices of stakeholders are an important attribute to the discussion over suppression and elimination of tsetse (Sundin, Andersson, and Watt 2018). Stakeholder narratives are an important technique to capture their experiences, keen insights, and prevailing attitudes in the tsetse control and eradication debates. Policy development is often a closed processed driven by the values and beliefs of the architects, seldom constructed from the perspective of those they will impact.

Multisectoral stakeholder narratives offer a way to shape policy that is inclusive of voices often marginalized in the process (Grant, Anderson, and Machila 2015b; Quick 2018). The respondents who participated in this project represent international, regional, and local agencies, development banks, agriculture, animal and human health fields, and academia (Table 4.1). Most respondents have been working on tsetse and trypanosomiasis research for over 15 years. While all agree that control is important the approach varies based on interest, world view and school of thought. The respondents participated in a semi-structured interview consisting of the 16 questions outlined in Figure 4.2. Three dominant narratives emerged from the interviews, **barriers to control**, **resource availability**, and **One Health**.

4.6.1.1 Barriers to Control Narrative

The barriers to control narrative implies that although abatement programs are implemented, practitioners have faced resistance in different forms that impacted programmatic effectiveness. Control program challenges differ throughout the tsetse belts of sub-Saharan Africa and are due to different factors. The interviewees expressed that control programs face barriers despite widespread knowledge of the threat that tsetse and trypanosomiasis pose to animal and human health.

Logistics and technical issues, baseline data collection, and importing key program components from other countries and regions are some of the barriers we face. These issues impact the effectiveness of programs producing suboptimal results.

(respondent)

Collaborations across countries can be difficult, but it is the only way to we are going to solve the tsetse problem long-term. We need to work with neighboring countries, but they are not always able to practice control which creates setbacks for our efforts, especially along the border. Resurgence happens when you cannot finish the job.

(respondent)

Finances are a major hindrance. National leadership changes have led to budget cuts of tsetse and trypanosomiasis control resulting in inconsistent programming, long-term planning is not possible.

(respondent)

the main barriers are not politics they are financial. Most money for tsetse control programs come from international funders, but national governments have to give more money to control. If the international funds go away, control programs also go away. It is a limiting factor an unfavorable dynamic for control practitioners. But then when there is government money there are strings and other issues.

(respondent)

Space is the issue. Once tsetse is gone there will be no space left for smallholder farmers to grow and expand their operations because big developers have bought the land. It is hard to motivate farmers to participate in control programs when the odds of improving their personal situation is unlikely. The reluctance influence program outcomes.

(respondent)

It is difficult to change the habits of those in rural communities even when you increase their awareness of trypanosomiasis. They have lived there their entire life and you cannot prevent them from going to areas of the forest for grazing or water. Women unintentionally expose babies when they fetch water in tsetse areas, although they are aware of the risk, there is often no alternative. Until tsetse are eradicated or behavior change is achieved trypanosomiasis will be a concern.

(respondent)

The biggest threat to human African trypanosomiasis control is misdiagnosis and poor treatment outcomes. Sleeping sickness is overly misdiagnosed and underreported. Most treatment facilities misdiagnose sleeping sickness as malaria be malaria is a cheaper disease to treat in Africa. The early stage sleeping sickness symptoms are similar to those of malaria, but providers do not perform the key diagnostic tests. Sleeping sickness can only be diagnosed with microscope after a lumbar puncture. In order to understand the true burden of trypanosomiasis in African communities, we must stop automatically assuming it is malaria.

(respondent)

4.6.1.2 Resource Availability Narrative

Resources are often a source of concern for tsetse and trypanosomiasis control programs. The resource availability narrative suggests that without adequate resource allocation control programs are at risk of premature termination and any benefits of control is unlikely to be sustained. Some interviewees advise that tsetse control resources are treated as a local public good and access to control resources is only afforded to communities in specific locations. For resource poor people in remote rural areas access to control mechanisms such as impregnated traps and targets or pour-on treatment for cattle is an improbability. It was suggested that a pooling of resources for tsetse control would provide a more equitable distributions and expand the benefit catchment area.

Without money we are unable to hire more technicians, without more technicians we are unable to serve the areas in an ideal capacity. The quality of programs depends on personnel, robust staff is necessary.

(respondent)

For some countries with limited resources, eradication is not possible. Especially those countries with forest tsetse located in areas that are difficult to reach on foot. The only options for remote isolated tsetse populations are cost exorbitant strategies such as aerial spraying of pesticides and sterile male flies. This is an impractical option for poor countries. with the shifting support of politicians

(respondent)

Good cars are needed to transport teams to control areas, good tools are needed to build the traps and targets and to replace traps and targets if they are stolen. These things cost money, even a minimal amount of money for these items can be quite expensive for already shrinking budgets for tsetse control.

(respondent)

Some counterfeit trypanocidal drugs have entered the market often cheaper than authentic medication for animal treatments. For countries with limited resources they may be fooled into purchasing these counterfeits due to costs. This could have disastrous consequences on the

livestock industry if these diseased cattle are sold. The financial burden is the biggest barrier to success.

(respondent)

To win the war against tsetse will require multiple control strategies deployed simultaneously. With so many other issues facing their populations, many African nations are unable to allocate adequate resources for one control program, making the possibility of multiple control deployments unlikely.

(respondent)

Land use and land cover change will help with the natural reduction of fly populations without other inputs; however, development most often occurs in cities before the rural areas and even more so before the remote rural areas. Tsetse is in the rural and remote rural areas and resources do not flow freely in rural regions of Africa even though development in these areas could help drive out the fly.

(respondent)

4.6.1.3 One Health Narrative

The One Health narrative emerged as many interviewees answered question number 15: In your opinion, what components would a good policy for T&T control require to achieve long-term success? One Health is a global, national, or local collaborative approach that recognizes

the interdependence between human, animal, and ecosystem health. One Health's foundation is built on the notion that a whole approach to the complex health problems require multidisciplinary strategies and multisectoral inputs to address. The One Health approach is well suited for the tsetse and trypanosomiasis control debate both the animal health and public health concerns can be addressed simultaneously.

One Health is offering the opportunity for us to really work together and address this issue of tsetse and trypanosomiasis. If the program is well coordinated, we could finally be successful eliminating tsetse.

(respondent)

*If we learn from past mistakes, we can build better programs. One Health is an ideal method. T*he *many environmental, community, animal health, human health, entomological, and chemical considerations that require expertise. Bringing us all together will help generate support and understanding and unify to eliminate the fly.*

(respondent)

*One Health would encourage teamwork and support training of locals. Bringing in locals will bridge awareness of programs, help with community sensitization, and improve overall program quality because what they learn they will take back to their communitie*s.

(respondent)

There should be a PATTEC coordinator with an office and personnel available in all countries. Sometimes this is not possible because the regional office in some countries is not always staffed. Tsetse and trypanosomiasis need dedicated control coordinators. One Health teams in endemic countries could be the link to fill the support deficit.

(respondent)

Politicians shift their support which makes them unreliable partners in the fight against tsetse. All tsetse endemic countries need to sing the same song when it comes to control. Where animals are sick the people are sick also, these are not two separate matters and we must treat them jointly. We need the same policy from the African Union and the same strategy on the ground, a continental agreement to bind each county to a commitment towards control. We need a body to oversee the commitment and collaborative teams to do the work efficiently. One Health can offer new hope for the fight against tsetse.

(respondent)

4.6.2 Political Economic Socio-cultural Technological (PEST) Analysis

The PEST Analysis supports a participatory approach to policy development using a decision and prioritization matrix. There were 18 informants for this study and 12 participated in the PEST analysis. The stratification of respondents for the PEST analysis is as follows: one respondent from the Pan African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) a regional

agency, one agriculture extension worker, two locally elected leaders, five animal and human health practitioners, and three research academics. The informants are a diverse group of men and women across multiple scales and industries (Table 4.1).

The PEST analysis consisted of two steps. The first step required the participant to respond yes or no to the potential policy option (Table 4.2). The responses receive a numerical equivalent where, yes = 1 and no = 0. Questions with a yes/no response was given partial credit of .5. The second allowed the respondent to elaborate on any response to the matrix. The sum of the individual responses range, from 0 – 12. The questions with the highest response are bolded and shaded in blue see Table 4.3. Readily apparent are the potential policies that received a score of 12, meaning that all respondents answered yes to **Q2**, **Q3**, **Q4**, and **Q9**. The corresponding questions for the four policy options with unanimous responses are chronicled here. A full list of all the policy options can be found in Table 4.2.

Question 2 – *strengthen tsetse control policies*, **Question 3** – *increase resources available*, **Question 4** – *improve control programs through innovations and technology*, and **Question 9** – *encourage use of combined suppression/elimination hi-low tech control throughout the tsetse belt regions*. Other emerging themes surround pesticide use: only 3.5 respondents agreed that discouraging the use of pesticides in **Q11** was a viable policy option, juxtaposed to **Q7** in which encouraging the use of pesticide treated cattle was widely approved. While the numerical answers were interesting, the insights during step two, the elaboration phase provided additional noteworthy insights.

Table 4. 3 Table of individual responses from the cumulative PEST matrix tabulation.

PEST Analysis Responses	
Question Number	Sum of Responses
Q1	0
Q2	**12**
Q3	**12**
Q4	**12**
Q5	10.5
Q6	9.5
Q7	10
Q8	10.5
Q9	**12**
Q10	8.5
Q11	3.5
Q12 – write in question	varied responses

For example, the response to **Question 1** included the following declaration, “improvements are always needed, we must always innovate”. **Question 3** about resource availability included the comment, “capacity building, renovations and research”. The additional response for **Question 4** suggests a need to include global positioning systems (GPS) and tiny targets in tsetse control programs. While the majority were in favor of the use of traps and targets in **Question 5**, it was suggested that these should be coupled with some high technology options. Additional insights were offered about **Question 5**, interface areas such as the Serengeti use traps and targets, pour-on insecticides are not allowed in the Serengeti National Park. **Question 6** asked about incentivizing programs and one of the respondents said, “if sleeping sickness is significant in an area, you do not need to incentivize the people, participation is area dependent”. This perspective implies that in endemic areas with active trypanosomiasis cases, community sensitization is automatic meaning awareness and buy-in is predicated on the level of risk to residents.

Question 7 surrounding pesticides garnered the following additional response, “with dips the measurement isn’t precise, and the dip can be disposed of improperly and can cause environmental concerns”. It was also advised that pesticide use programs should be regulated at the national level. **Question 10** was the source of great debate as most respondents had additional comments surrounding the use of the sterile insect technique (SIT). Responses included, “where would funding for the program come from”, “in areas where SIT is practical this is a good option, but not in areas where SIT is not practical”, and “may not work for African countries, the money will be used for other things”, when asked to elaborate the respondent

advised if the funding was provided for SIT those in charge would make decisions to use the money elsewhere and not necessarily for a SIT program.

Question 11 also received varied of responses requesting the judicious use of pesticides, approach dependent responses, encouraging the use of pour-on application instead of aerial spraying. Some respondents specifically warned against the use of pesticides citing "environmental concerns" requesting use only when "following the restrictions". One respondent proclaimed, "what about the burden of disease on human health should take precedent over the environment". **Question 12** was a write-in policy option and the responses provided keen insights for potential policy options. More than half the participants responded to **Q12** the answers consisted of, requests to "address trypanosomiasis treatment issues", move towards a "One Health concept" to address tsetse and trypanosomiasis control, "increase the availability of data and dedicated PATTEC personnel to support each country's programs".

There was also a call for "a combined African program to eliminate tsetse". This respondent was asked to elaborate advised that a unified approach with a simultaneous application would encourage countries to work together across their borders to defeat tsetse. The response illuminated the possibility for approaches such as the CANVAS method from Chapter 3 to offer sustainable option for tsetse control. Some respondents also requested, "tsetse control in animal health should have a high priority in university entomology program curriculum". Lastly, pesticides once again entered the debate from a respondent who advised, "pesticides should be strictly controlled, lab reared flies were more sensitive to pesticides so their use has negative impacts on SIT program", and proclaimed, "every program should include a veterinary

professional on the team", this supports the previous comment in support of a One Health approach to tsetse and trypanosomiasis control.

Aggregating all responses to the PEST analysis yielded the following results on the completed matrix (Table 4.4). The aggregate outcomes and the individual outcomes align with most favorable responses for **Q2**, **Q3**, **Q4** and **Q9** indicated in bold on the chart below. However, when examining the collective responses across interest groups, there is a clear divide between the Regional Agencies and the Agriculture Workers in **Q6-Q8**. In **Q6**, the Regional Agencies felt incentives will create tensions within the communities, while the Agriculture Extension Workers felt incentives would help them improve maintenance participation. Likewise, for **Q7**, the Regional Agencies felt the increase in counterfeit pesticides, which have no impact on pest reduction, render an unstable enterprise and with no way to distinguish authentic products from counterfeit ones they should be avoided altogether. The Agriculture Extension Workers support the use of pesticides, understanding the potential setbacks from counterfeit products. Regarding **Q8** - the Regional Agencies feel SIT is too expensive to encourage its use widely as it would bankrupt poor countries. However, the Agriculture Extension Workers felt the use of SIT would benefit control and eliminate theft of materials such as the fabric on traps and targets. Understanding these dynamics and philosophical differences could be useful in policy development. Similarly, in **Q5-Q7**, among the Local Leadership, Animal and Human Health Practitioners and Academics there is a gradient pattern in the responses. The PEST matrix is an effective way to illustrate the nuanced details in responses that might not be apparent with a standard development tools.

Potential Policy Options	**Stakeholders Chart**						
Q1. Do Nothing/Maintain the status quo		-	-		-	-	-
Q2. Strengthen tsetse control policies		+	+		+	+	+
Q3. Increase resource availability		+	+		+	+	+
Q4. Improve control programs through innovation and technology		+	+		+	+	+
Q5. Increase use of traps/targets and other low-tech options		+	+		+	-/+	-
Q6. Improve trap/target maintenance through incentives		-	+		+	-/+	-
Q7. Encourage the use of cattle pour-on or dip pesticides		-	+		-/+	+	-/+
Q8. Increase the use of SIT hi-tech		-	+		+	+	-/+
Q9. Encourage use of combined suppression/elimination hi-low tech control throughout the tsetse belt regions		+	+		+	+	+
Q10. Encourage use of SIT through cost breaks and funding		+	+		+	-/+	+
Q11. Discourage use of pesticides due to environmental concerns		-	-		-/+	-	-/+
Q12. Any other option suggestion		+	+		+	+	+
Interest Groups	Development Agencies	Regional Agencies	Agriculture Workers	Conservation Groups	Local Leadership	Animal and Human Health Practitioners	Academics

Figure 4. 4 Cumulative PEST Matrix Stakeholders Chart with most supported policy options.

4.7 DISCUSSION

While most agree that tsetse and trypanosomiasis is a problem in terms of its impact on animal and human health and the economic impact on endemic countries, none of the prior policy approaches have generated sustainable solutions, beyond the island of Zanzibar, which was certified tsetse free by the World Health Organization (Hargrove 2005; Vreysen et al. 1998). The environmental, ecological, biological, and public health science is well chronicled and widely known. If the science of tsetse and trypanosomiasis is sound, the remaining opportunity area is policy. Tsetse and trypanosomiasis policies have been fundamentally flawed from the onset, especially how the policies have been created and enacted. One impediment with policy development is the lack of local participation in the construction and development phase. Participatory policy development is one way to address this deficit, include marginalized voices and create more just policies.

Additionally, there are pockets of opposition from conservationists who consider the presence of tsetse key to preserving the natural environment in Africa. While the eradication of tsetse would not create an ecological vacuum and there is no known purpose for tsetse from a 'circle of life' perspective, the loss would be to the biodiversity of insect vectors on the continent. Tsetse impacts all aspects of life for those in at-risk areas: work productivity, agriculture, development, and the public health system. Sustained suppression or elimination of the fly could stimulate poverty alleviation. Controlling the fly could have implications on multiple systems across sub-Saharan Africa and alleviate poverty in endemic countries.

The study offered a multiscale interdisciplinary approach to policy analysis and development through the POLARIS framework, stakeholder narratives, and the PEST analysis. The outcomes highlight potential policy options for consideration including: (1) strengthen tsetse control policies, (2) increase social and material resource availability, (3) improve control programs through innovation and technology, and (4) encourage the use of combined suppress and elimination approaches including high and low technology options. The responses to the PEST analysis further reveal philosophical differences between groups, for instance, the participants representing Regional Agencies and Agriculture Extension Workers had dissenting responses for Q6-Q8 in section 4.6.2.

However, the main limitations of this study were that the full POLARIS framework could not be utilized. The Policy enactment and Policy Implementation phases were not conducted and therefore it cannot be known if (1) the selected policy options would receive administrative approval, (2) whether broader audiences would have been receptive to the policy options, nor (3) what implementation across the regions and nations would entail. Future directions in this work with tsetse and trypanosomiasis should include the full POLARIS policy development protocol.

The limited number of participants would prevent the pilot study findings from being regionally generalizable. However, the quality of the feedback and the diverse backgrounds, perspectives and local situated knowledge enriched the study outcomes and can serve as a protype guiding more comprehensive studies in this area. Marshall et al. 2013 conducted a study of 83 qualitative studies and found no justification for specific sample size, and argued

that sample size in qualitative research is "arbitrary and thus inconsequential" (Marshall et al. 2013). Marshall further offered that quality of the interview, more so than, quantity, has a more substantial impact on qualitative studies (Marshall et al. 2013). In *Sample Size and Grounded Theory*, Thomson argues that interview sample sizes range from 5-350 with an average of 31. Additionally, Thomson asserts that theoretical saturation is reached between 10-30 interviews. Theoretical saturation means that no new insights are gained from additional interviews. The 18 interviews conducted during this study fall within the range for average interview sample size and the theoretical saturation range (Thomson 2011).

An important caveat in participatory policy development in Africa is formal access to local populations. The challenges include patriarchal barriers to some groups, distrust of researchers and non-community members, and language barriers, among others (Lee, Sulaiman-Hill, and Thompson 2014; Conradie et al. 2018). In the case of farmers, who would be most impacted by animal trypanosomiasis, it is especially difficult to garner their trust. Therefore, agriculture extension workers and other locally supported leaders may be the most prudent targets to capture the perceptions and prevailing attitudes among this group. In this study three participants: two local agency representatives and one agriculture extension workers represented the voice of the farmers in the community. Although only the respondent representing the farmers was interviewed, the interview was conducted in an open forum that included the farmers. The respondent would converse with and seek consensus from the farmers before responding to each interview question or answering the PEST analysis. While were not represented numerically in the sample, they were adequately represented in the responses. Additionally, their contributions to the PEST analysis of potential policy options,

would lead to better acceptance if the policy were enacted and implemented in their area. Community sensitization during policy implementation, is an area of opportunity with disease control programs in Africa. Participatory policy development processes such as the ones employed in this study, builds coalition, and generates buy-in during the development stage. Buy-in from local participants can have a positive impact on programmatic implementation and long-term sustainable (Kimbell and Bailey 2017; Sindato, Kimbita, and Kibona 2008; Grant 2014).

Lastly, WHO set a target date of 2020 for the elimination of T.b. gambiense derived human African trypanosomiasis as a public health concern; while I applaud WHO's ambition, there existed no consensus among the research and practitioner communities about the best approach for elimination. With no logical path forward the target elimination could not be reached. The host population for T.b. rhodesiense derived human African trypanosomiasis varies so widely that elimination of that disease variant is unlikely. Additionally, WHO set a target date of 2030 for the eradication of tsetse fly, as noted in section 4.6.1., there have been consistent budgetary cuts to control programs, a severe shortage of personnel, and an overwhelming lack of resources for these efforts. If the 2030 date is to be reached, rethinking of support is going to be required.

5. GENERAL CONCLUSIONS

The studies of this dissertation largely conducted at the population and landscape scale, use modeling, mapping, and participatory policy development to examine tsetse and African trypanosomiasis from a multiscalar risk reduction and control perspective over space and time.

Chapter 2 (Study 1) conducted a meta-analysis on tsetse and trypanosomiasis control literature over the last 122 years, from 1898 – 2020. The study aimed to investigate whether a meta-analysis of tsetse and trypanosomiasis literature could offer new insights into control efforts, if there have been shifts in control priorities over time, and what drivers influence research topic trends. The study concluded that research priorities are influenced by the dynamics of publication trends and journals influence patterns and practice, including the abundance of literature thus creating trends in dominant thoughts and perspectives.

Chapter 3 (Study 2) characterized the tsetse and trypanosomiasis risk landscape for Senegal and Tanzania and demonstrated control strategies in a simulated environment. Study 2 explored how identifying areas at-risk for trypanosomiasis would strengthen control strategy development, if risk varies across space, and will a two-step trypanosomiasis risk reduction framework improve control systems. The findings of the study illustrated that risk is not a continuous phenomenon across space but is predicated by environment and ecological conditions and has a peppered pattern throughout the landscape. Additionally, the CANVAS method demonstrated that simultaneous control applications increase the dose strength and

enhance the control effect on the operational area and provides some level of protection to uncontrolled areas.

Chapter 4 (Study 3) developed a stakeholder driven policy framework for tsetse and trypanosomiasis control. Study 3 explored what a global policy for tsetse and trypanosomiasis risk reduction and control requires to be successful, how success is measured, who would be the major stakeholders, and what agencies would need to be involved. The outcomes of the PEST analysis conducted in Study 3, highlight potential policy options for consideration including: (1) strengthen tsetse control policies, (2) increase social and material resource availability, (3) improve control programs through innovation and technology, and (4) encourage the use of combined suppress and elimination approaches including high and low technology options.

This dissertation offers a comprehensive, spatial-temporal examination of tsetse and trypanosomiasis control and risk reduction from multiple yet linked perspectives. The analyses begin with the broad regional perspective of sub-Saharan African, then scales down to explore the national risk and control landscapes of Senegal and Tanzania, culminating with multisectoral individual perspectives highlighting local voices.

5.1 REFLECTIONS

In the "Dialectics of Nature" (1883), Frederick Engels wrote,

> Man alone has succeeded in impressing his stamp on nature, not only by shifting the plant and animal world from one place to another, but also by so altering the

> aspect and climate of his dwelling place, and even the plants and animals themselves, that the consequences of his activity can disappear only with the general extinction of the terrestrial globe.

The quote by Engels (Engels 1883), captures the entire African environmental history and the legacy of tsetse and trypanosomiasis on the continent. To put this quote into perspective, a non-colonized Africa would have naturally endured extensive population growth, conflicts, famine, and outward expansions (Hochkirch et al. 2018a; Muriuki et al. 2005; John Ford 1979).

Those activities and processes would have organically resulted in some form of environmental degradation and introduced some level of disease into the populations, but the nature and type of disease cannot be known (Hausner 1992). It can however be argued that no other process or enterprise would have left the lasting imprint of disease and environmental trauma on the African landscape as colonialism (Hoppe 2003; Isenberg and Nash 2014). The literature of tsetse and trypanosomiasis emphasizes, that prior to colonialism, the inhabitants of Africa were able to avoid tsetse and minimize trypanosomiasis outbreaks (Headrick 2014; Ford 1971). Their local knowledge of the environment allowed them to circumvent known tsetse habitats and reduce risk of the disease to their populations and livestock (Bado 1996).

The political ecology of colonialism in Africa argues that European colonizers drastically changed the demographic and environmental landscape, as well as the social order (Wallman, Wells, and Rivera-Collazo 2018). The combination of these shifts created, " structural violence" (Farmer 1996) and a legacy of "violent ecologies" (Robbins 2012), global inequity, marginalization, stigmatization, and the unjust treatment of the African people, which persists

today (Bulhan 2015). Additionally, the economic imperative of the colonial agricultural production system led to rapid expansions, further into the bush and territory in close proximity to tsetse habitats (Ofori-Amoah 2019). In the Principles of Political Economy, John Stuart Mill wrote "the logical conclusion of unlimited growth is the destruction of the environment and a reduction of the quality of life" (Mill 1848). The artifacts of colonialism in the story of tsetse and trypanosomiasis are undeniable, many of the systems govern and shape how tsetse and trypanosomiasis control are practiced today. After some 130 years of research in this area, humankind is still contending with conquering the fly and curing the disease.

It is widely accepted that the environmental and ecological factors of the tsetse vector are known (Langley 1994; Carpenter 1920) and the science of the disease system (Steverding 2016), screening and treatments (P. P. Simarro et al. 2012; Veerle Lejon, Jacobs, and Simarro 2013) have been well studied. However, the policies that govern tsetse and trypanosomiasis remain largely top-down processes constructed at agencies and institutions far removed from the communities they will impact (Menon 2011; Mahamat 2015a). In Chapter 4, I argue that that the remaining vulnerability is policy and the lack of equitable participation of policy construction and development are responsible for ineffective tsetse and trypanosomiasis control, leading to suboptimal acceptance and enactment on the ground (Kovacic et al. 2013a; Wangoola et al. 2019; Jakob Zinsstag et al. 2015).

5.2 THE CONTINUING DEBATE OVER TSETSE CONTROL

Tsetse and trypanosomiasis control have rested on three dominant philosophies: (1) suppress tsetse fly populations, (2) eradicate the tsetse fly, and (3) preserve the tsetse fly.

5.2.1 The vector control philosophy

The vector control philosophy seeks to suppress the population to levels where the threat to hosts are minimal. Vector control is the most cost effective (Yang et al. 2017; P. F. McCord et al. 2012; Kristjanson et al. 1999) of the philosophies, and some argue it is the swiftest (Hocking, Lamerton, and Lewis 1963). However, it may require an unending number of control applications (Alonso, Engels, and Reeder 2017; Juarez et al. 2018). Tsetse are k-strategist vectors therefore population regeneration is not a vulnerability for this philosophy (Lin, Devisser, and Messina 2015). Additionally, the vector philosophy also considers the loss of biodiversity if tsetse species were eradicated (Hochkirch et al. 2018b).

5.2.2 The vector elimination philosophy

The eradication of tsetse contrasts with the vector control philosophy in that eradication seeks species removal and extinction. Tsetse is evolutionarily unique with adaptative behaviors and features that make species eradication an ethical consideration (Jérémy Bouyer et al. 2019). Several countries have succeeded in eliminating tsetse species locally including, Zanzibar, Botswana, and Namibia (Mahamat 2015b). Tsetse eradication does not threaten the “circle of life” as no predator is known to feed solely on tsetse (Jérémy Bouyer et al. 2019). The main consideration of tsetse eradication is the technique of elimination.

Some methods, such as the sequential aerosol technique (SAT) can impact non-target organisms (Koeman et al. 1978; R. J. Douthwaite 1992), although the effects have been found to be minimal. The sterile insect technique (SIT), has been found to be environmentally benign with no non-target species interaction (E. S. Krafsur 1998; Kariit 2013) . Vector elimination is the

most expensive of the tsetse control options which make wide-scale use unlikely (Anaman et al. 1994; G. A. Vale and Torr 2005; F. Bouyer et al. 2014b). Incidentally, tsetse eradication strategies are a two-step process requiring prior vector control to reduce the fly populations.

5.2.3 The vector conservation philosophy

This philosophy has a tsetse preservationist theme. Those who subscribe to the vector conservation philosophy believe that tsetse help to maintain the natural environments of Africa, which is in direct conflict with those of the vector control and vector elimination philosophies (Wilson et al. 1963; Anderson et al. 2015a). To this end, they advocate for the preservation of tsetse flies, especially around national parks, where livestock incursions pose threats to protected areas (Grant, Anderson, and Machila 2015b). Tsetse conservationists typically opt for policies of inaction and do not support either the vector control or elimination philosophy (Machila, Anderson, and Grant 2016; Scoones 2014).

The debate over tsetse and trypanosomiasis control is deeply rooted in philosophical differences. Though unlikely to be resolved in the near future, this dissertation serves as a bridge to understanding these concepts and demonstrate how philosophical entrenchment may be a factor in the failure may be the long term success of tsetse control. Understanding the three philosophical positions can inform policy development and the exploration of knew philosophies for tsetse and trypanosomiasis control.

5.3 FUTURE DIRECTIONS – CONSIDERATIONS FOR CLIMATE CHANGE

Climate change and global warming could have a profound impact on tsetse habitats throughout sub-Saharan Africa (J. P. Messina et al. 2012). The shifts in climatic conditions could naturally shrink some habitats and expand others. Areas prone to soil erosion, land degradation, and desertification are susceptible to even the slightest change in climate (FAO 2006). Warming temperatures could expand such areas along the western coast of Africa in countries such as Senegal. As seen in Chapter 3 tsetse habitats are most abundant in southern Senegal. Much of Senegal is unsuitable for tsetse due to the lack of appropriate vegetation, temperature, and humidity (Peter Van den Bossche et al. 2010). As warming occurs, the unsuitable areas could expand naturally and eliminate tsetse species from this country. In contrast, global warming could cause present-day drier, unsuitable environments such as the Horn of Africa to become suitable (Dodge and Messina 2018).

Predicted increases in precipitation for coastal East Africa could contribute to increasing wetness in the area, higher relative humidity, and vegetation cover thus making tsetse species proliferation probable (Kimaro, Toribio, and Mor 2017). Changes in temperature and precipitation are expected over the coming decade. Knowing the environment is dynamic, it is important to develop policies that will be adaptive to changes in tsetse habitat due to climate change.

5.4 FINAL THOUGHTS

As I write this dissertation in the midst of the COVID-19 pandemic of 2020, several interesting realizations and parallels come to mind. Throughout human history, there have been germs, diseases, and viruses that present an imminent threat to human life. With centuries of experience and a wealth of history from which to learn, disease control programs and agencies worldwide remain inadequately prepared to deal with large scale epidemics.

Further, humankind has remained largely reactionary in the face of disease control and elimination. Although the diseases are etiologically, spatially, and temporally different, human African trypanosomiasis of the 19th and 20th centuries, and COVID-19 during the 21st century, the responses and initial assumptions have remained regrettably the same – to stigmatize and otherize. In both cases, political will, ideologies, and tribalism have driven behaviors and decisions resulting in disparate outcomes to the populations and across the landscape. Additionally, both have been plagued by inconsistent messaging, lack of informational awareness, institutional barriers to participation, and access to screening.

Complex and complicated issues such as these require adequate leadership, interdisciplinary approaches, and inputs derived across all scales to inform policy and generate the best control strategies and interventions. Risk reduction and mitigating exposure coupled with inclusive and participatory policy development are the most prudent approach and serve and reinforce justification for this dissertation.

APPENDICES

APPENDIX A

Bibliometric Analysis – Publications Trends Over the Decades by Search Topic

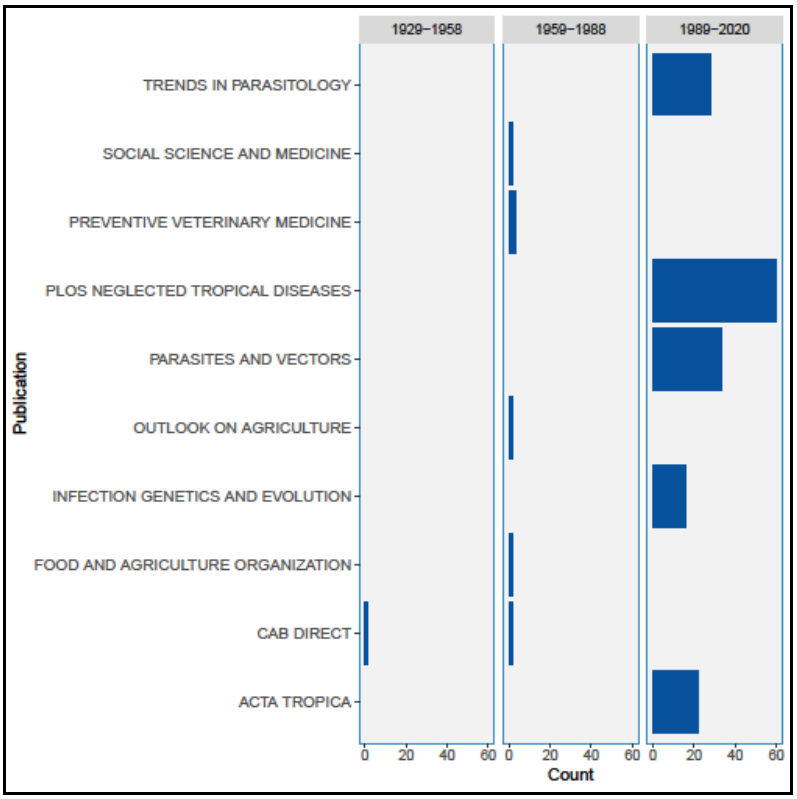


Figure 6. 1 Journals with the highest publications on African animal trypanosomiasis control.

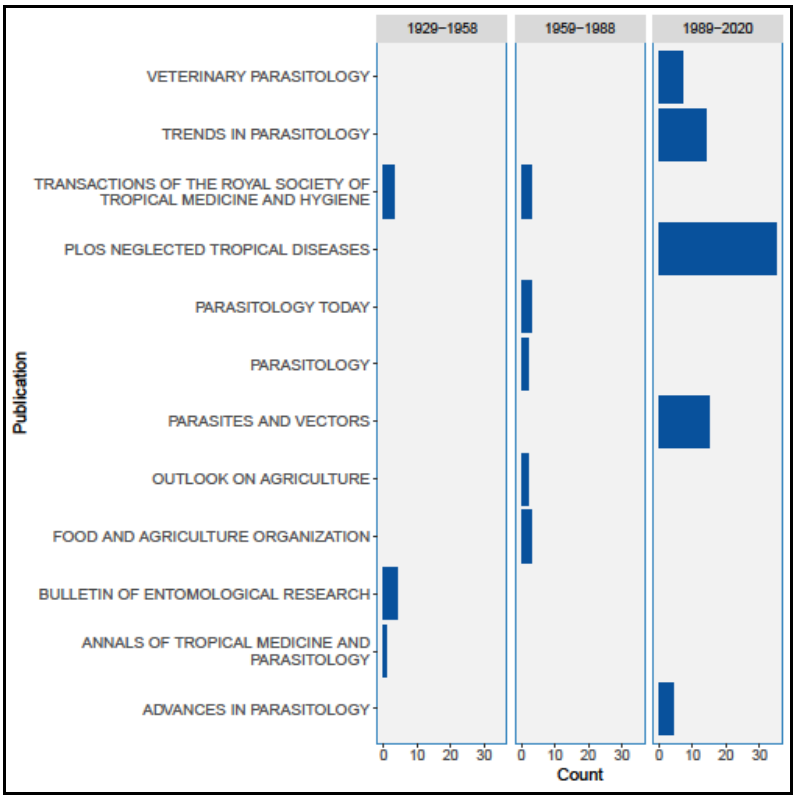


Figure 6. 2 Journals with the highest publications on African animal trypanosomiasis eradication.

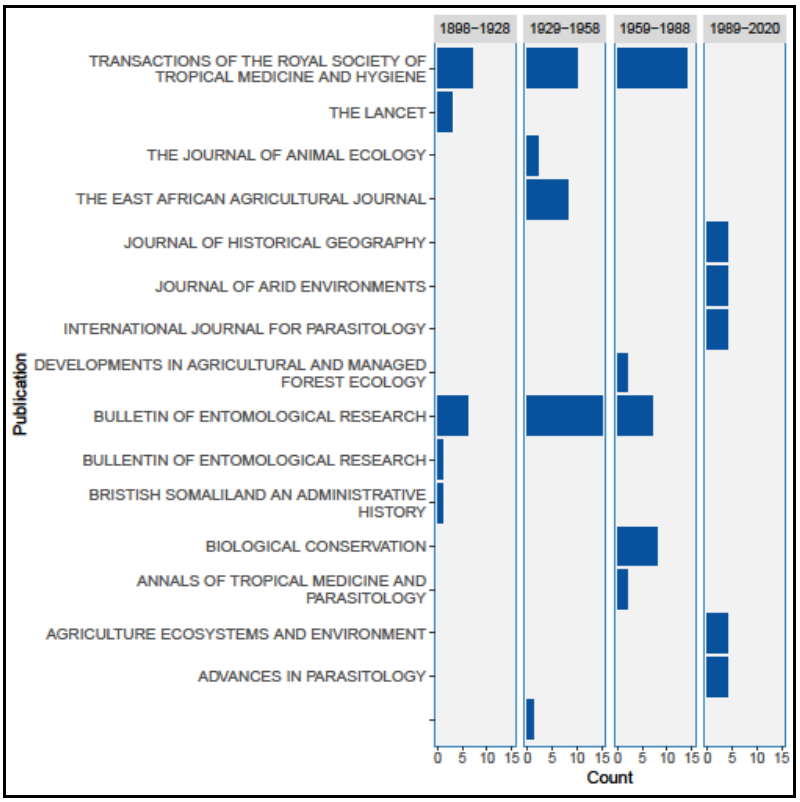


Figure 6. 3 Journals with the highest publications on bush clearing.

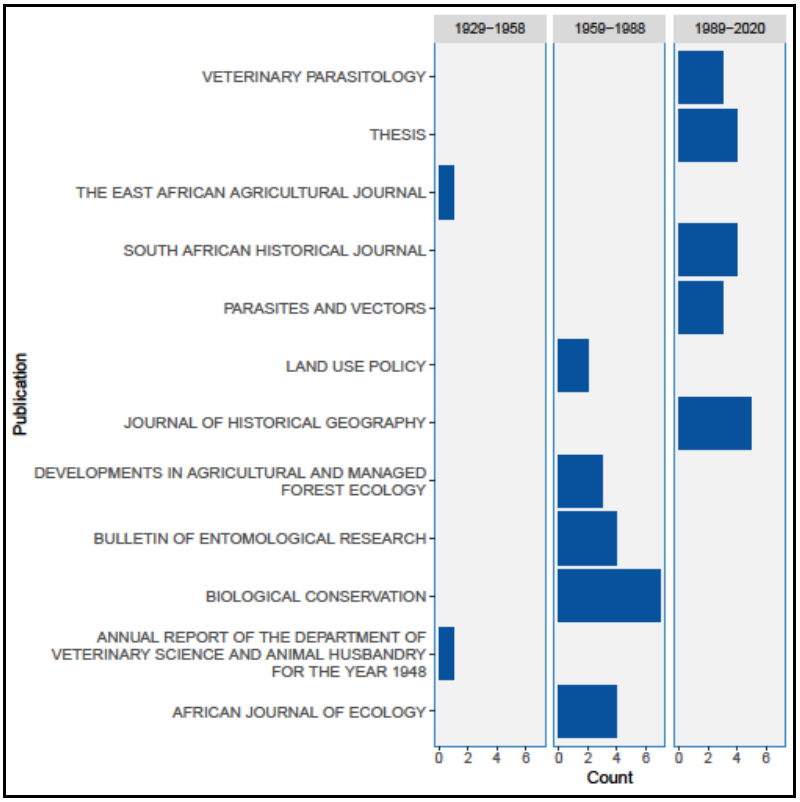


Figure 6. 4 Journals with the highest publications on game culling.

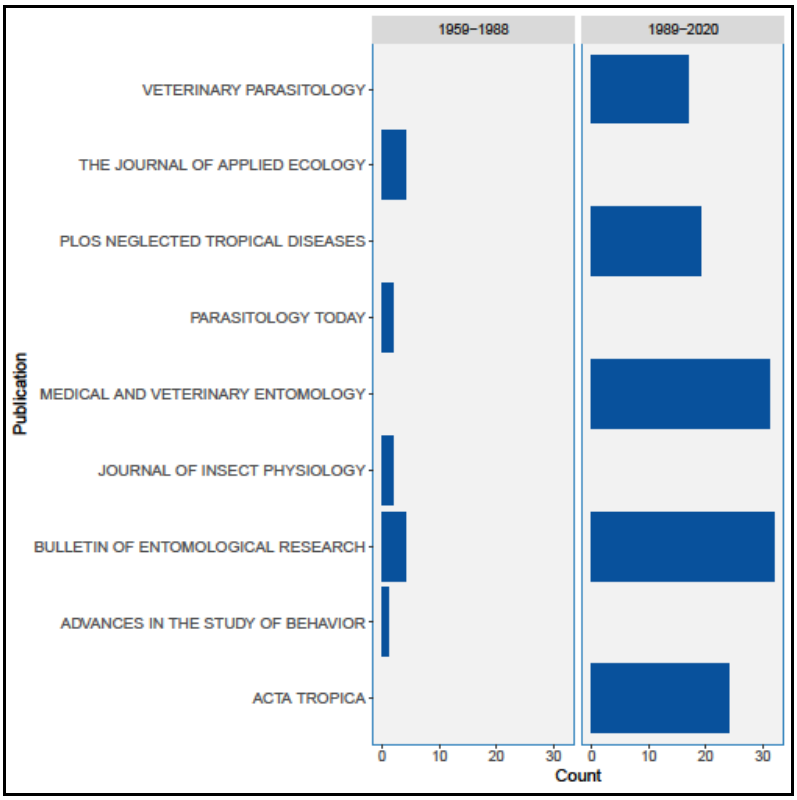


Figure 6. 5 Journals with the highest publications on tsetse control targets.

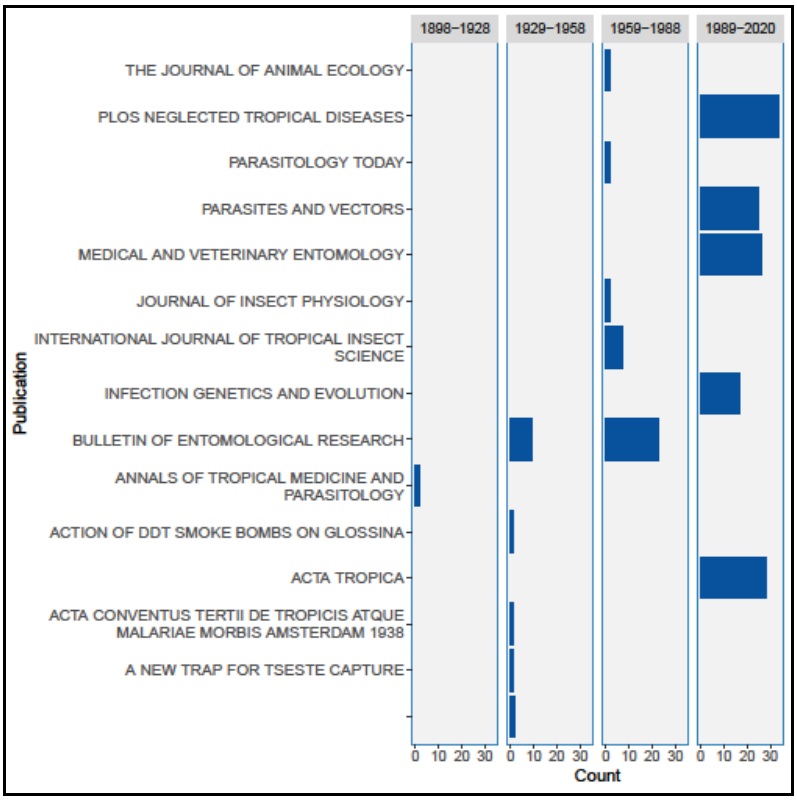


Figure 6. 6 Journals with the highest publications on tsetse control traps.

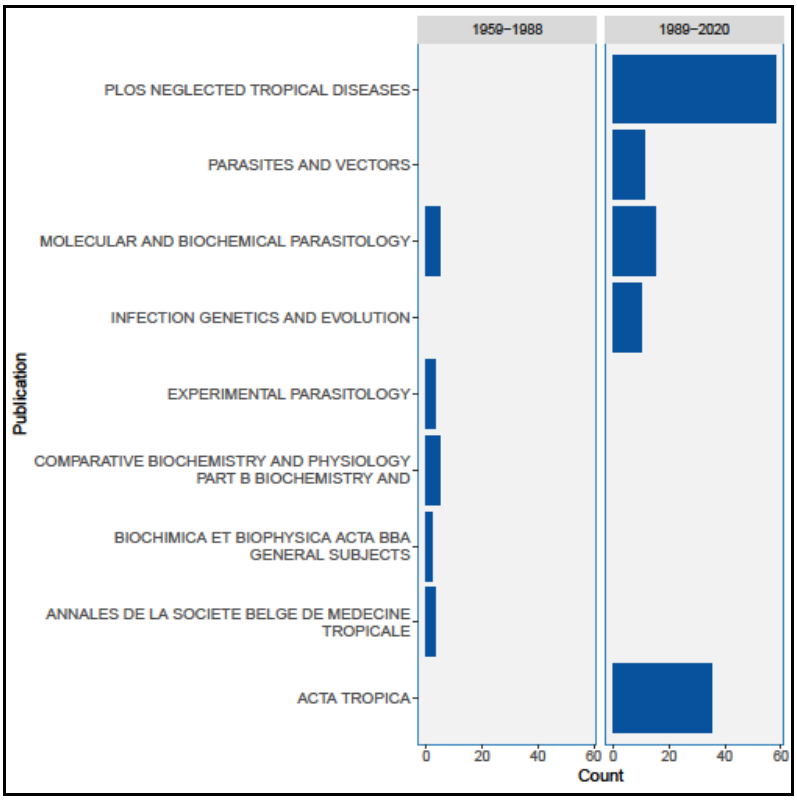


Figure 6. 7 Journals with the highest publications on T.b. gambiense.

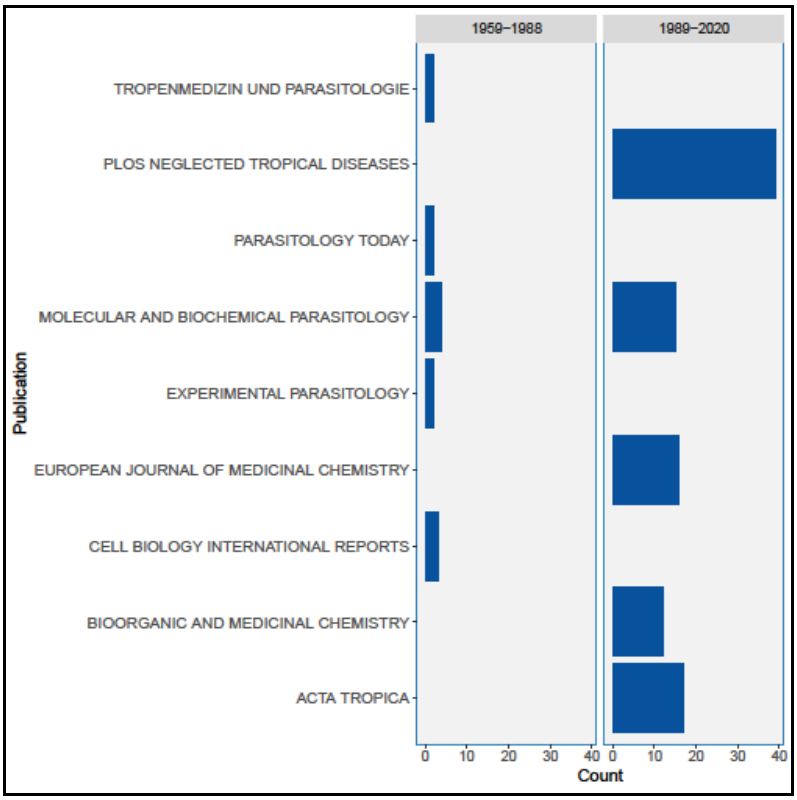


Figure 6. 8 Journals with the highest publications on T.b. rhodesiense.

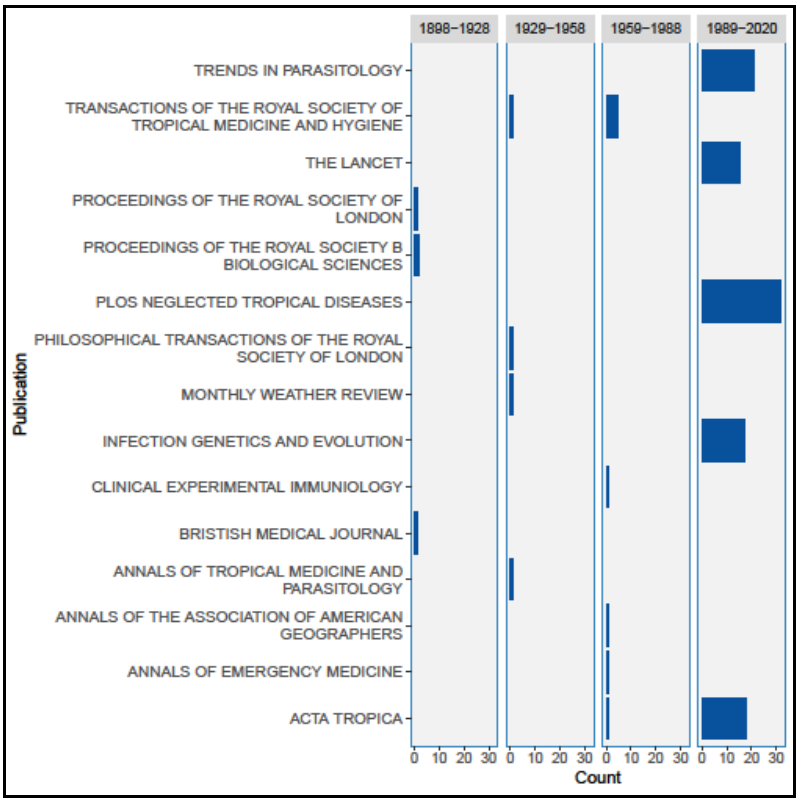


Figure 6. 9 Journals with the highest publications on human African trypanosomiasis.

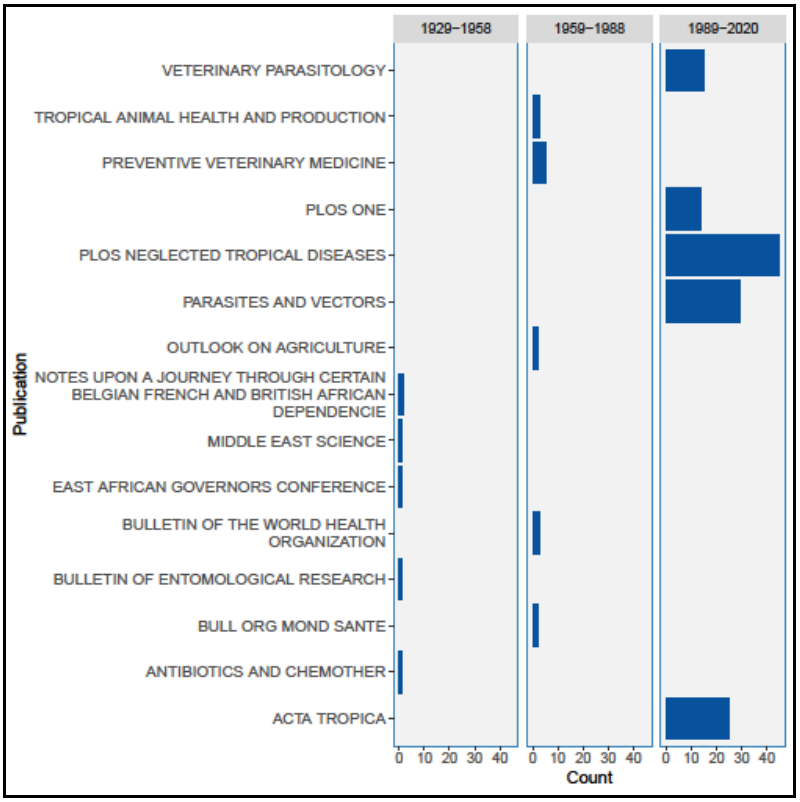


Figure 6. 10 Journals with the highest publications on human African trypanosomiasis control.

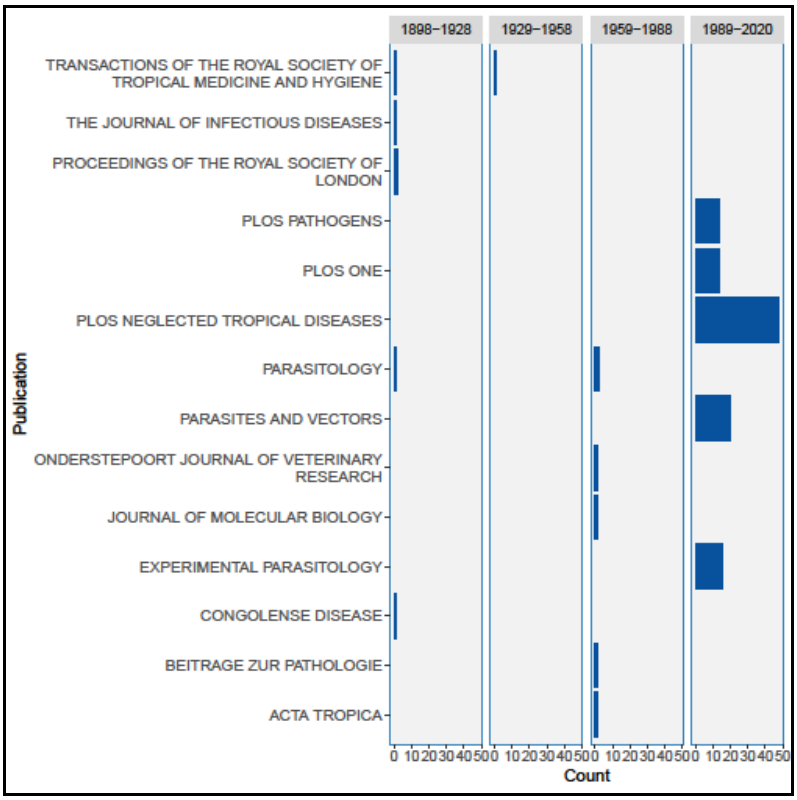


Figure 6. 11 Journals with the highest publications on Nagana.

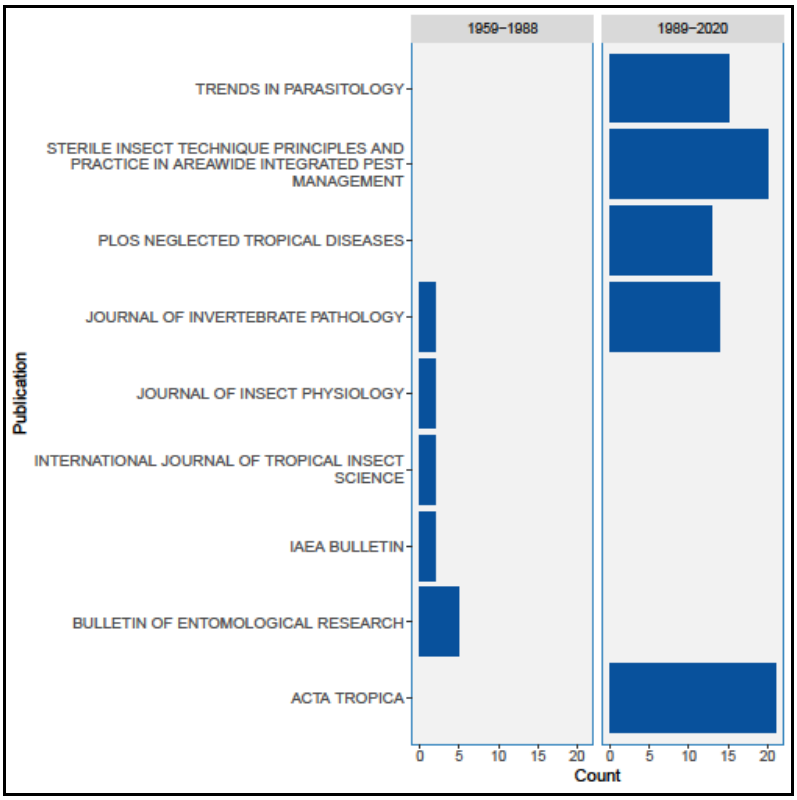


Figure 6. 12 Journals with the highest publications on sterile insect technique.

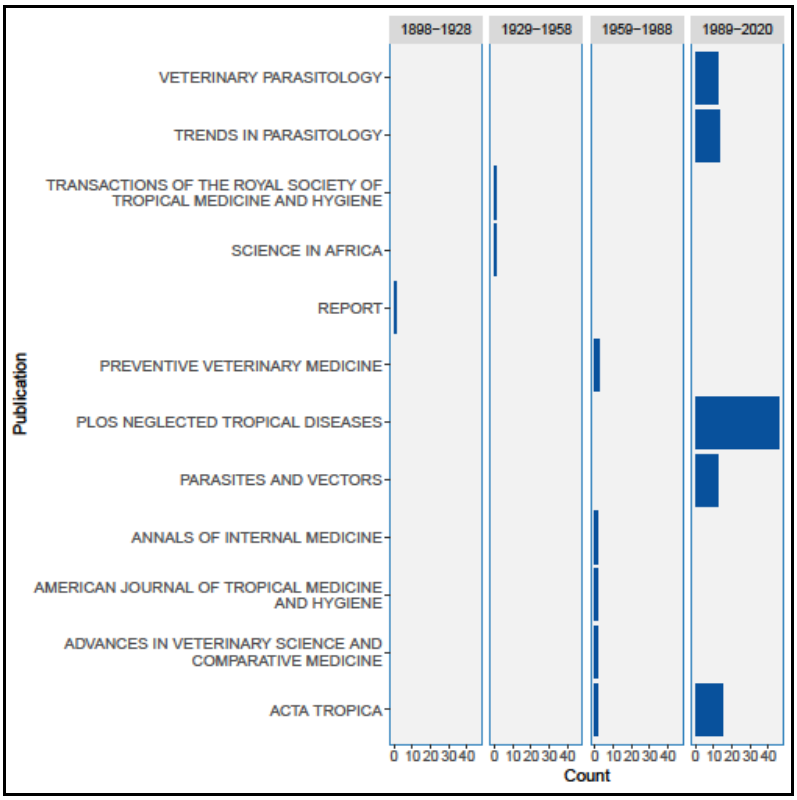


Figure 6. 13 Journals with the highest publications on trypanosomiasis prevention.

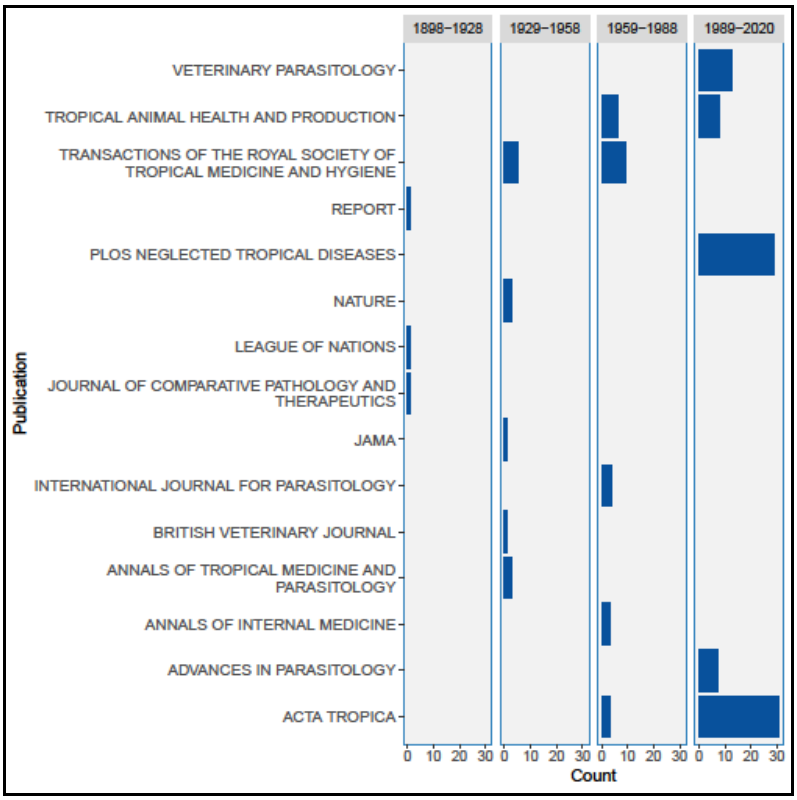


Figure 6. 14 Journals with the highest publications on trypanosomiasis prophylaxis.

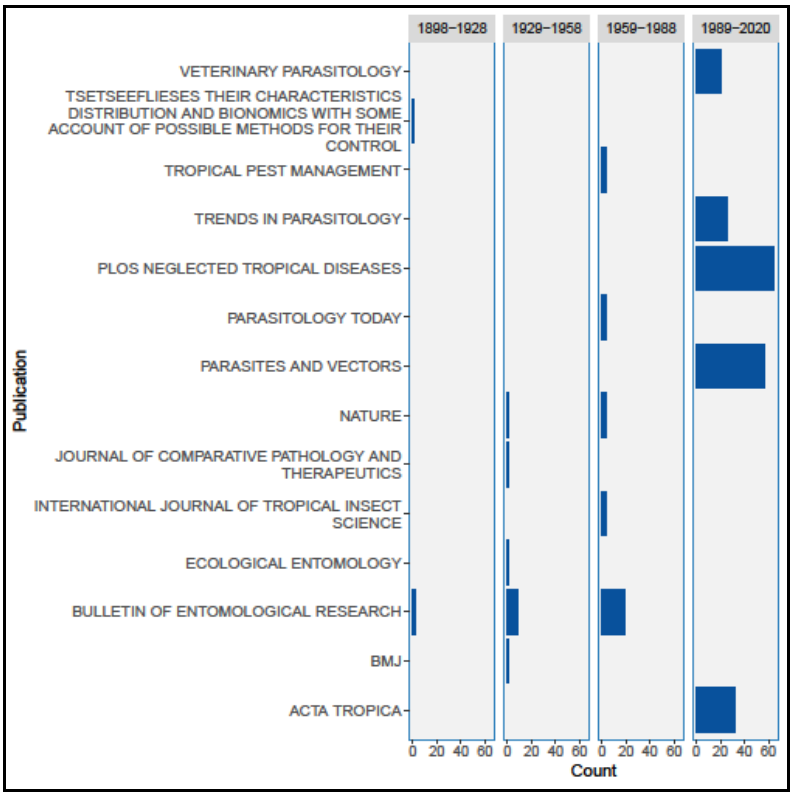


Figure 6. 15 Journals with the highest publications on tsetse control.

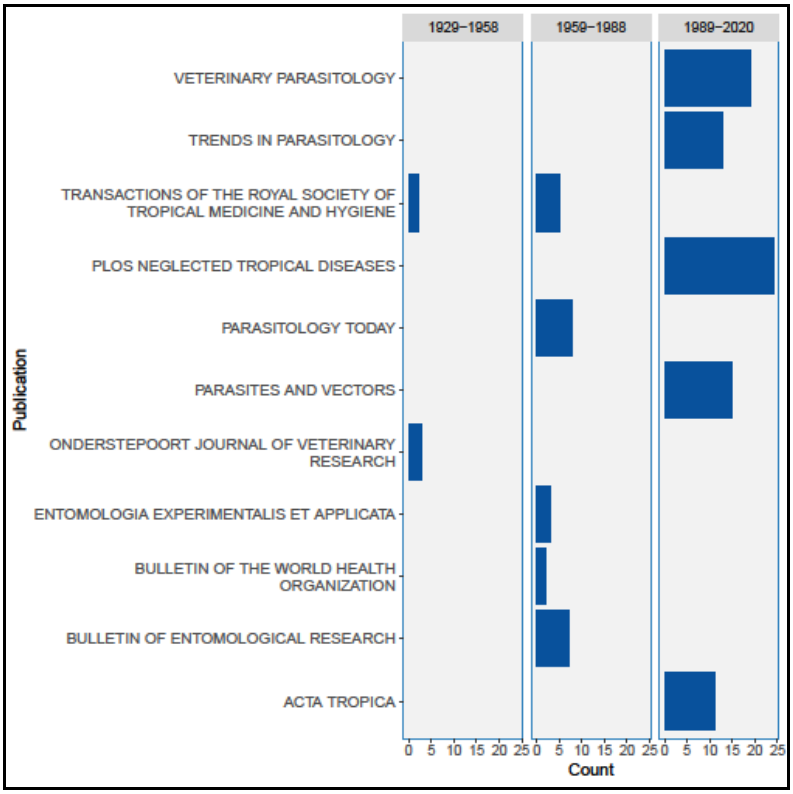


Figure 6. 16 Journals with the highest publications on tsetse eradication.

APPENDIX B

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Institution name	Michigan State University
Expected presentation date	Jun 2020
Portions	distribution of east and west african sleeping sickness in sub-Saharan Africa
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APPENDIX C

Traditional and CANVAS Method Control Application Results

Figure 7. 1 Tsetse per sqkm pre-control application in SMART landscape.

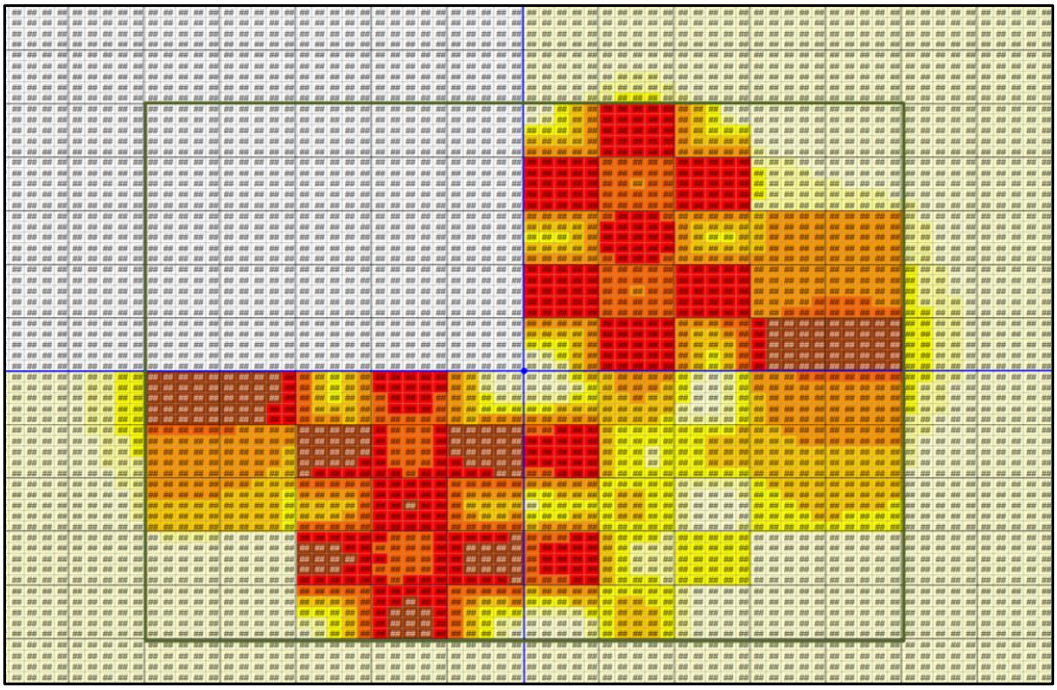

Figure 7. 2 Tsetse per sqkm post-control application in SMART landscape.

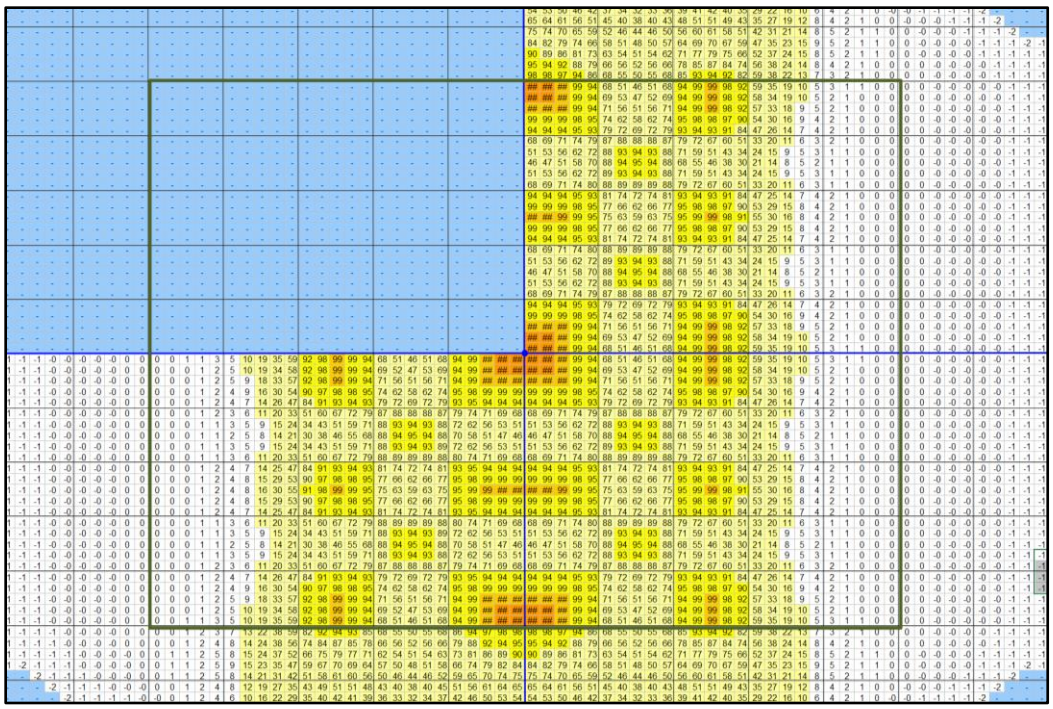

Figure 7. 3 Cattle risk for T.b. brucei infections post-traditional control on the woodland area.

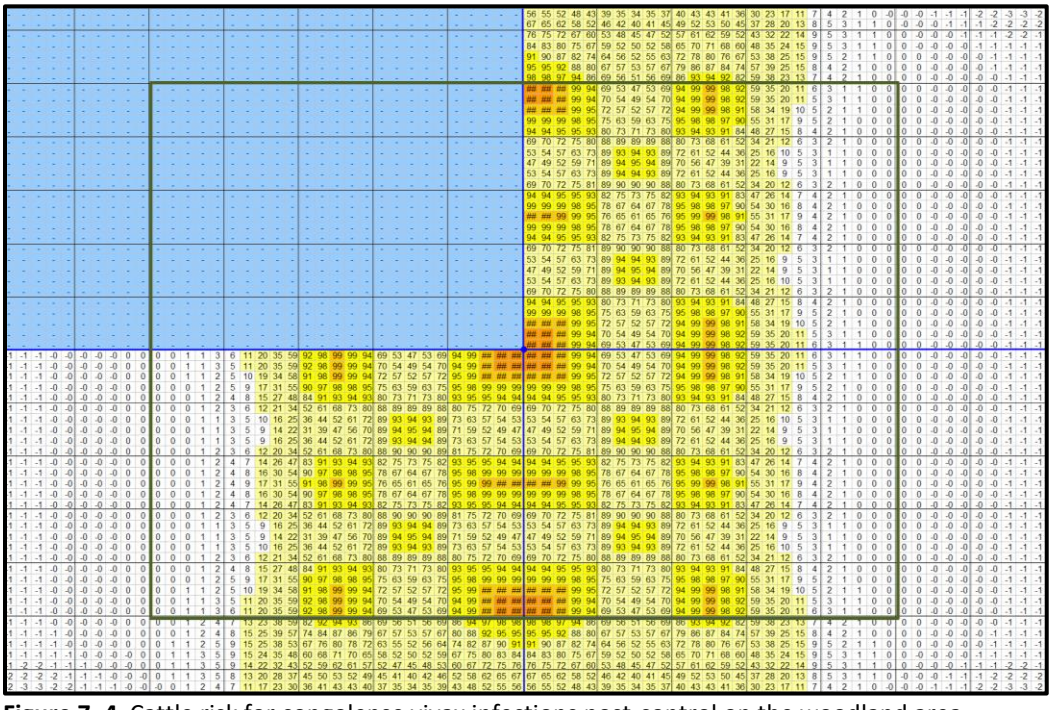

Figure 7. 4 Cattle risk for congolense vivax infections post-control on the woodland area.

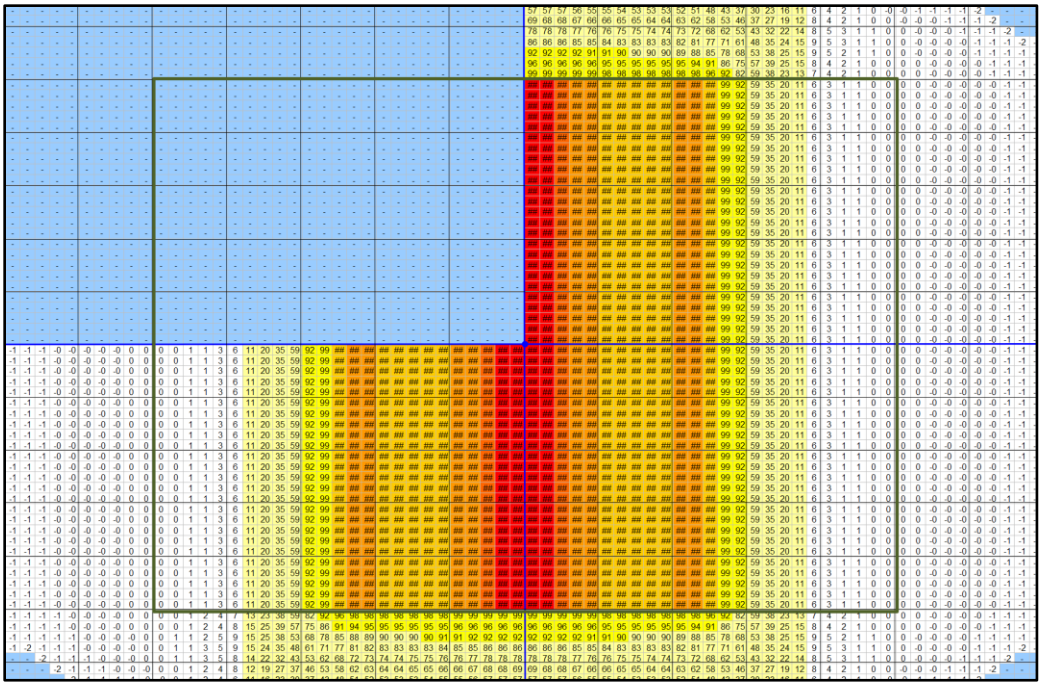

Figure 7. 5 Cattle risk for T.b. brucei infections post- CANVAS control on the woodland landscape.

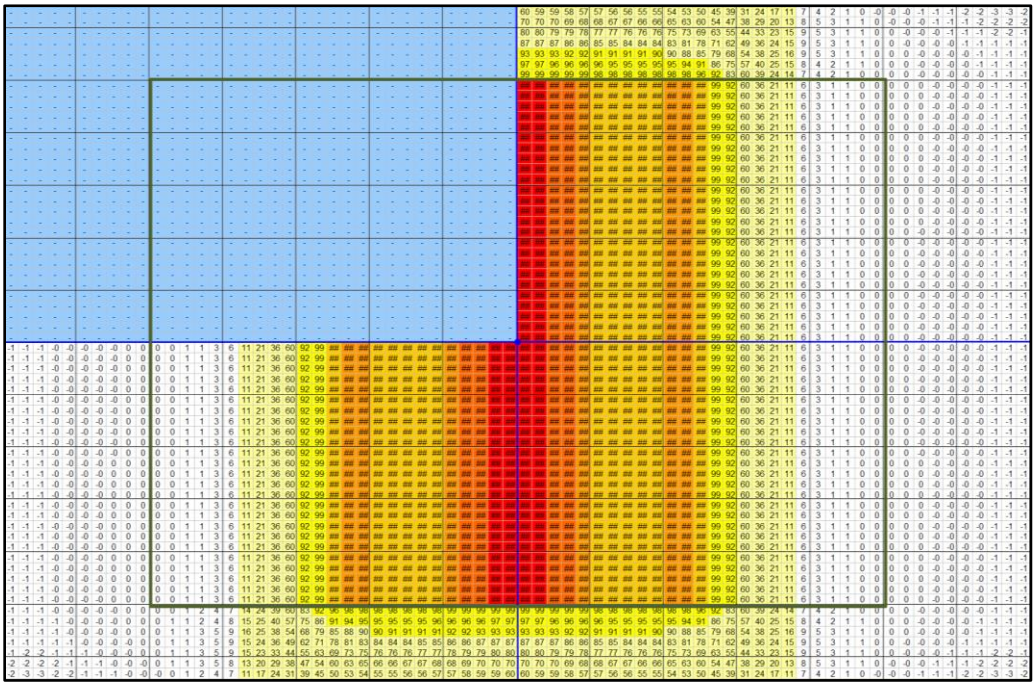

Figure 7. 6 Cattle risk for congolense vivax infections post- CANVAS control on the woodland landscape.

APPENDIX D

Field Observation Documents and Various Control Method Images

Table 7. 1 Field environmental data collection form.

	Site/Country#		**Date:**	**Time:**
	Coordinate (X) Lat:	**Coordinate (Y) Long:**	**Coordinate (Z) Height:**	**Base Camp Folder Name:**
	Land Use (how the land is used):			**Photos Taken:**
	Land Cover (physical land type):			**Tsetse Species:**
	Control Area Only or Active Tsetse Habitat:			**Tsetse Present:**
	Habitat Description (savannah, river, forest):			**Traps Present:**
	Habitat Climate Characteristics (humid, arid, wet):			**Day Temp:**
	Land Cover of Surrounding Area (with distance):			**Night Temp:**
	Notes:			

Figure 7. 7 Tsetse control Ngu trap.

Figure 7. 8 Tsetse control H trap.

Figure 7. 9 Tsetse control Vavoua trap.

Figure 7. 10 Tsetse control screen.

Figure 7. 11 Tsetse control Nzi trap.

Figure 7. 12 Tsetse control biconical trap.

Figure 7. 13 Tsetse control pyramidal monitoring trap

Figure 7. 14 Tsetse control mobile target.

Figure 7. 15 Shipment of Glossina gambiense palpalis pupae for the sterile insect technique.

Figure 7. 16 Glossina gambiense palpalis pupae being separated from sawdust for transport.

Figure 7. 17 Sterile male tsetse pupae separated in petri dishes for the luminescent sand application.

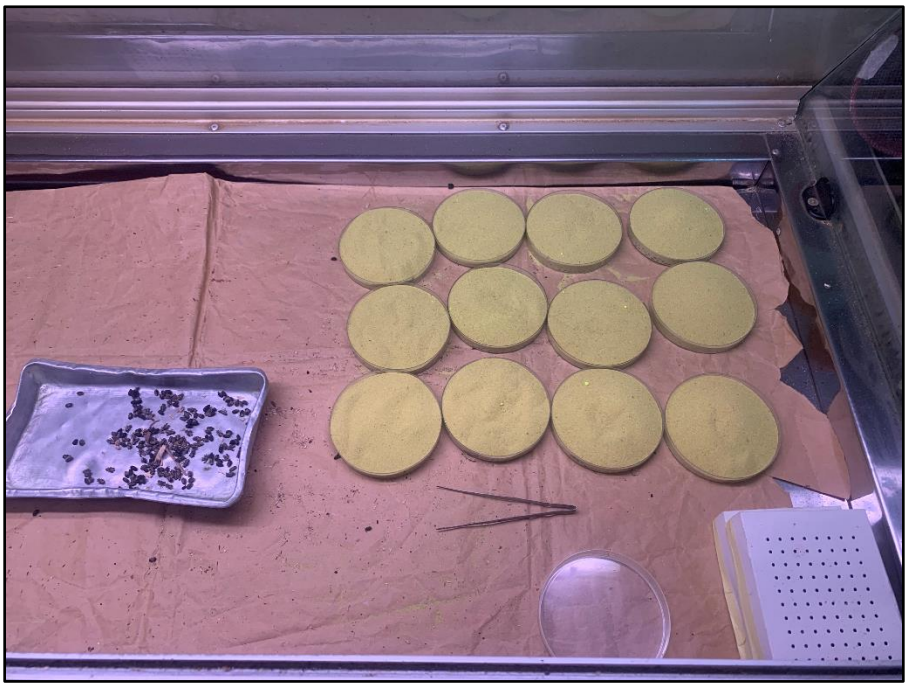

Figure 7. 18 Sterile male tsetse pupae covered with luminescent sand.

Figure 7. 19 Sterile male pupae in emergence cage.

Figure 7. 20 Emerged sterile male tsetse in feeding cages during first blood meal.

Figure 7. 21 Emerged sterile male tsetse in transport boxes for ground and aerial release.

Figure 7. 22 Gyrocopter used to release sterile male tsetse through control area.

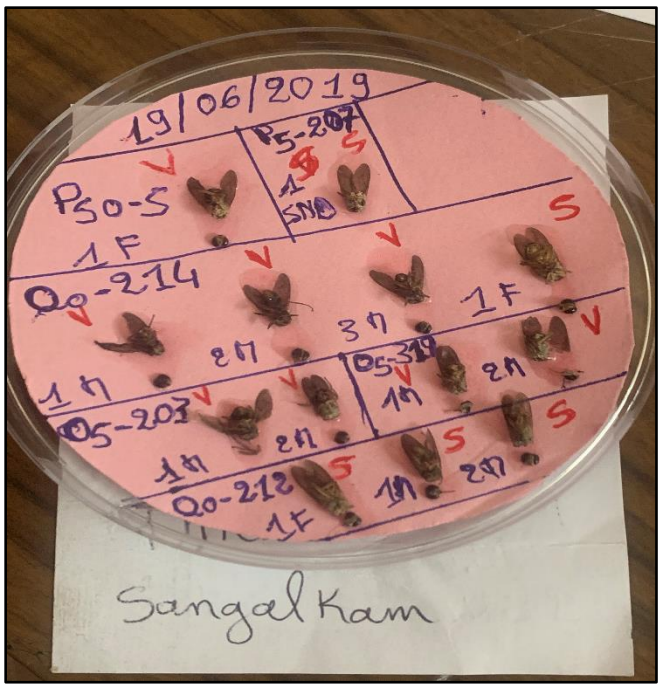

Figure 7. 23 Sterile and wild tsetse caught in monitoring traps.

Figure 7. 24 Sterile male tsetse signified by the presence of the luminescent sand torso (left), head (right).

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