The continental Atlas of tsetse and African animal trypanosomosis in Nigeria

Jill de Gier[#a1], Giuliano Cecchi[#*a], Massimo Paone[a], Peter Dede[b], Weining Zhao[a].

[a] Food and Agriculture Organization of the United Nations, Animal Production and Health Division, Rome, Italy

[b] Nigerian Institute for Trypanosomiasis Research, Kaduna, Nigeria

[1] Cambridgelaan 377, 3584 DB Utrecht, The Netherlands

[#] Contributed equally

*Corresponding author: Giuliano Cecchi (giuliano.cecchi@fao.org). Food and Agriculture Organization of the United Nations (FAO), Viale delle Terme di Caracalla, 00153, Rome, Italy.

Email addresses:

JDG: jill.degier@fao.org

GC: giuliano.cecchi@fao.org

MP: massimo.paone@fao.org

PD: dedepm@yahoo.co.uk

WZ: Weining.Zhao@fao.org

Abstract

Tsetse-transmitted trypanosomosis remains a major animal health problem in Nigeria, in a context where changes in land cover, climate and control interventions are modifying its epidemiological patterns. Evidence-based decision making for the progressive control of the disease requires spatially-explicit information on its occurrence and prevalence, as well as on the distribution and abundance of the tsetse vector. In the framework of the continental Atlas of tsetse and African animal trypanosomosis (AAT), a geo-referenced database was assembled for Nigeria, based on the systematic review of 133 scientific publications (period January 1990 - March 2019). The three main species of trypanosomes responsible for the disease (i.e. *Trypanosoma vivax*, *T. congolense* and *T. brucei*) were found to be widespread, thus posing a national-level problem. Their geographic distribution extends beyond the tsetse-infested belt, owing to the combined effect of animal movement and mechanical transmission by non-tsetse vectors. *T. simiae*, the major trypanosomal pathogen in pigs, *T. godfreyi* and the human-infective *T. brucei gambiense* were also reported. AAT was reported in a number of susceptible host species, including cattle, sheep, goats, pigs, camels, horses, donkeys and dogs, while no study on wildlife was identified. Estimates of prevalence are heavily influenced by the sensitivity of the diagnostic techniques, ranging from an average of 3.5% for blood films to 31.0% for molecular techniques. Two riverine tsetse species (i.e. *Glossina palpalis palpalis* and *G. tachinoides*) were found to have the broadest geographical range, as they were detected in all six geopolitical zones of Nigeria. By contrast, the distribution of savannah species (i.e. *G. morsitans submorsitans* and *G. longipalpis*) appears to be highly fragmented, and limited to protected areas. Very little information is available for forest species, with one single paper reporting on *G. fusca congolensis* and *G. nigrofusca nigrofusca* in the Niger Delta region. The future development of a national Atlas of tsetse and AAT, relying on both published and unpublished information, could improve on the present review and provide further epidemiological evidence for decision making.

Keywords

Nigeria; Tsetse; Trypanosomosis; GIS; Neglected Tropical Diseases.

Abbreviations

AAT: African animal trypanosomosis; BCT: buffy-coat technique; CATT: Card Agglutination Trypanosomiasis Test; FAO: Food and Agriculture Organization of the United Nations; GIS: Geographic Information Systems; GPS: Global Positioning System; HAT: Human African trypanosomosis; HCT: haematocrit centrifugation technique; LGA: Local Government Area; OIE: World Organisation for Animal Health; PAAT: Programme Against African Trypanosomosis; PCP: Progressive Control Pathway; PCR: polymerase chain reaction; SIT: sterile insect technique; WAD: West African Dwarf; WGS84: World Geodetic System 1984; WHO: World Health Organization.

Introduction

Tsetse-transmitted trypanosomosis is a severe vector-borne disease that affects both humans and animals in sub-Saharan Africa. The causative agents are flagellate protozoan parasites of the genus *Trypanosoma*, which are mainly transmitted by the bites of infected *Glossina* spp. (tsetse flies).

In ruminants, and in particular in cattle, African animal trypanosomosis (AAT) is predominantly caused by *Trypanosoma vivax*, *T. congolense* and *T. brucei* spp., while *T. simiae* is the main pathogen in pigs (Taylor and Authié, 2004). Infected animals present with intermittent fever, anaemia, decreased appetite, progressive loss of condition, decreased milk production, reduced fertility and increased mortality in affected herds (Desquesnes, 2018). The geographical distribution of AAT extends beyond the tsetse-infested belt, on account of mechanical transmission by other biting flies and animal movement (Ahmed et al., 2016; Hoare, 1947).

AAT has vast economic impacts in Nigeria. It is ranked as the second most important livestock disease in the country (Dede et al., 2007), and no fewer than 6 million cattle are estimated to be at risk (Cecchi and Mattioli, 2009), out of a cattle population that is presently estimated at 20 million. Trypanosomosis is a lethal disease, with severe direct impacts linked to reduced livestock productivity. Indirect impacts are associated with a reduced efficiency of draught animals for crop production and with challenges to the introduction of more productive but more susceptible livestock breeds (Swallow, 2000). AAT is also the cause of massive utilization of veterinary drugs in Nigeria, with dire issues of substandard medicines and drug resistance (Kingsley, 2015).

Human African trypanosomosis (HAT), also known as sleeping sickness, is the human form of the disease, and it is caused by two sub-species of *T. brucei*, namely *T. brucei gambiense* and *T. brucei rhodesiense*. The former occurs in western and central Africa, the latter in eastern and southern Africa (Büscher et al., 2017). These human-infective parasites can also affect animals, both livestock and wildlife, which can serve as reservoirs for HAT (WHO, 2013). In particular, the central role of animals in the epidemiology of rhodesiense HAT is well recognized (Franco et al., 2014), while for gambiense HAT this role is much less prominent and not yet fully understood (Büscher et al., 2018). Over the past ten years, only a few HAT cases have been reported in Nigeria (Delta State), and the risk of infection is considered low (Franco et al., 2018). However, these data should be interpreted with caution, because of the low intensity of surveillance activities (Franco et al., 2017).

Even though trypanosomosis can also be mechanically transmitted by such biting flies as *Tabanus* and *Stomoxys* spp., cyclical transmission is only due to tsetse flies. Based on their morphological characteristics and habitat requirements, *Glossina* species can be categorized into three groups: the fusca (forest) group, the palpalis (riverine) group and the morsitans (savannah) group. Overall, thirty-one different tsetse species and subspecies are recognised, of which eleven are found in Nigeria. These are *G. palpalis palpalis*, *G. tachinoides*, *G. pallicera pallicera* and *G. calliginea* (palpalis group), *G. morsitans submorsitans* and *G. longipalpis* (morsitans group), and *G. fusca congolensis*, *G. tabaniformis*, *G. nigrofusca nigrofusca*, *G. medicorum* and *G. haningtoni* (fusca group) (Moloo, 1993; Onyiah, 1995).

Nigeria has a surface area of approximately 924,000 km^2, and administratively, it is divided into 36 states and one Federal Capital Territory (FCT), where the capital Abuja is located. The states are clustered into six geopolitical zones (North-Central, North-East, North-West, South-South, South-East and South-West), and subdivided into Local Government Areas (LGAs) and districts. In the 1950s, about 70% of Nigeria landmass was estimated to be infested by tsetse flies (Jordan, 1961). Over the years, extensive efforts have been made to control and eliminate tsetse. Various techniques and tools were used, including aerial and ground spraying (MacLennan, 1967), the sterile insect technique (SIT) (Olandunmade et al., 1988), bush clearing (Glover, 1967), and trapping (Takken et al., 1986). In the 1960s and 70s, tsetse flies were eliminated from certain areas of northern Nigeria, in particular in Adamawa, Borno and Taraba states (Davies, 1964; MacLennan, 1968; Spielberger and Abdurrahim, 1971). However, due to financial constraints and the discontinuation of control measures (Koeman et al., 1978), some of these areas have been re-infested (Daniel et al., 1993; Dede et al., 2007; Karshima et al., 2011; Karshima et al., 2016c). Furthermore, tsetse flies were known to be absent from the Jos, Mambilla and Obudu plateaus (Ford, 1970; Iwuala and Ejezie, 1980; Onyiah et al., 1983a). Yet, recent studies have revealed a changed entomological situation in these areas, where *G. palpalis palpalis* and *G. tachinoides* were detected (Dede et al., 2005; Karshima et al., 2016c).

Beyond efforts to control the tsetse vector, direct control of AAT in Nigeria relies on disease surveillance, chemoprophylaxis and chemotherapy. However, a number of challenges beset AAT prevention and control. The most commonly used trypanocides [i.e. diminazene aceturate and isometamidium chloride (Anene et al., 2001)] are obsolete (Giordani et al., 2016) and expensive for farmers. Additionally, because of inadequate support from veterinary services, livestock keepers often treat their animals with less-than-recommended doses of trypanocides, counterfeited medicines or indigenous plants (Atawodi et al., 2002; Grace et al., 2009; Kingsley, 2015), which often results in antimicrobial resistance (Chitambo and Arakawa, 1991; Kalu, 1995). Another strategy to cope with AAT is the use of trypanotolerant breeds (e.g. N'Dama and Muturu cattle and West African Dwarf (WAD) sheep and goats). However, its adoption is constrained by the farmers' preference for more productive albeit trypanosusceptible breeds (e.g. Zebu cattle). Besides, trypanotolerant breeds, whilst able to resist the most severe effects of trypanosomal infection, can still represent a reservoir for other animals and humans (Grace et al., 2009; Onyiah, 1997).

Risk-based targeting of interventions is considered crucial for cost-effective disease control. This notion underpins the so-called Progressive Control Pathway (PCP), a step-wise methodology originally developed for the foot-and-mouth disease (Sumption et al., 2012), and subsequently adapted to other diseases including AAT (Diall et al., 2017). In Nigeria, comprehensive, national-level datasets on tsetse and AAT distribution are lacking, which constrains evidence-based disease control. In an effort to address this gap, we developed a geospatial database of AAT and tsetse in Nigeria. The study was conducted in the framework of the continental atlas of AAT and tsetse (Cecchi et al., 2015; Cecchi et al., 2014).

Materials and Methods

The methods developed by FAO for the continental Atlas of tsetse and AAT have previously been described in detail (Cecchi et al., 2015; Cecchi et al., 2014) and the present paper focuses on the implementation of the Nigerian component of the continental Atlas. The methodology is summarized here below.

Peer-reviewed scientific publications containing data on AAT occurrence, tsetse distribution or tsetse infection in Nigeria were identified, retrieved and stored in a digital repository. The papers were identified through systematic searches in PubMed Central (www.ncbi.nlm.nih.gov). The search terms used were: "Nigeria" and "trypanosomiasis/-osis", "animal", "bovine", "ruminant", "nagana", "tsetse" or "*Glossina*". The last search was executed on the 20 March 2019. In addition, the lists of references within the analysed articles were searched for possible supplementary published inputs.

Subsequently, specific pieces of information were extracted from the articles, harmonized and entered in a geo-spatial database. The database is structured into four components (i.e. tables), namely data sources, geographical data, epidemiological data (i.e. AAT) and entomological data (i.e. *Glossina*). Each data source was independently analysed by two persons. All details including author(s), title, year of publication, journal and publisher were recorded in the "Sources" table. Only papers containing epidemiological and/or entomological data collected in the field from January 1990 onwards were retained. Information on experimental infections and human infections were not considered. Infections with *T. evansi* (the aetiological agent of surra) were also excluded, as trypanosomal infections that are not cyclically transmissible by tsetse flies are not presently included in the FAO continental atlas of tsetse and AAT.

The epidemiological table captures information on AAT, including period of sampling, host species and breed, husbandry system, sample size, parasite species and subspecies, number of infections (including mixed infections), prevalence, diagnostic methods and whether the sampling strategy was random or not. Information on the possible presence of tsetse control (e.g. insecticide treated targets or insecticide treated cattle) and trypanosomosis control actions (i.e. chemotherapy or chemoprophylaxis) was also recorded if available.
Entomological information on tsetse distribution and tsetse infection is recorded into two separate tables. The first, devoted to tsetse distribution, includes the survey period, type and number of traps used, odour attractants, duration of trapping (in days), absence/presence and number of flies and their apparent density (i.e. flies/trap/day). Information on the possible presence of tsetse control is also recorded if available. The second entomological table, dedicated to tsetse infection, records sampling strategy for tsetse examination (e.g. either all tsetse caught during trapping, non-teneral flies only or a random sub-sample thereof), number and species of flies examined, examination methods, trypanosome sub-genus, species and subspecies and infection rates. Information on the occurrence of other biting flies (e.g. *Stomoxys*, *Chrysops* and *Tabanus* spp.) is recorded in notes.
To map the available epidemiological and entomological data, geographic locations as reported in the papers were referenced in terms of latitude and longitude (decimal degrees on WGS84 datum). Publically available repositories (e.g. GEOnet gazetteer, Google Maps, Google Earth) provided the geographic coordinates, or they were estimated by means of other Geographic Information Systems (GIS) layers. Global Positioning System (GPS) coordinates were very rarely available from the analysed papers. In addition to the geographic coordinates, the geographical table also includes the location name, country name and the names of the sub-national administrative units (i.e. state, LGA and district). Also, the surface of the area covered by the survey is recorded according to six broad categories (i.e. ≤ 10 km^2, > 10 and ≤ 25 km^2, > 25 and ≤ 100 km^2, > 100 and ≤ 500 km^2, > 500 and ≤ 1,000 km^2, and > 1,000 and ≤ 10,000 km^2).

Results

A total of 133 scientific papers containing spatially-explicit information on the occurrence of AAT, tsetse and their trypanosomal infection were identified and processed. In particular, 114 papers provided information on AAT distribution (Supplementary file S1), 38 on tsetse distribution (Supplementary file S2) and 26 on tsetse trypanosomal infection (Supplementary file S3). The breakdown of papers by publication period is provided in Table 1, which shows that more than half the papers were published in the last ten years. Table 2 summarizes the availability of published surveys and the reported presence of AAT, tsetse flies and tsetse trypanosomal infection for the different states in Nigeria.

Table 1 Number of papers containing spatially-explicit information on the occurrence of AAT, tsetse and their trypanosomal infection by publication year.

Years of publication	Number of papers
1990 - 1994	11
1995 - 1999	11
2000 - 2004	15
2005 - 2009	22
2010 - 2014	36
2015 – 2019*	38

* Up to 20 March

Table 2 Availability of published surveys on, and reported presence of, African animal trypanosomosis, tsetse flies and tsetse trypanosomal infection in Nigeria. Published surveys, and the related reported presence, refer to peer-reviewed scientific papers (Supplementary file S1, Supplementary file S2 and Supplementary file S3). Period of data collection: January 1990 – March 2019.

Geopolitical zone	State	African animal trypanosomosis		Tsetse flies		Tsetse trypanosomal infection	
		Published surveys	Reported presence	Published surveys	Reported presence	Published surveys	Reported presence
North West	Jigawa	×	×	×			
	Kaduna	×	×	×	×	×	×
	Kano	×	×	×	×	×	
	Katsina	×	×				
	Kebbi	×	×	×	×	×	×
	Sokoto	×	×				
	Zamfara						
North East	Adamawa	×	×				
	Bauchi	×	×	×	×	×	×
	Borno	×	×	×			
	Gombe	×	×	×			
	Taraba	×	×	×	×	×	×
	Yobe						
North Central	Benue	×	×	×	×	×	
	Kogi	×	×	×	×	×	
	Kwara	×	×	×	×		
	Nasarawa	×	×	×	×	×	×
	Niger	×	×	×	×	×	×
	Plateau	×	×	×	×	×	×
	Federal Capital Territory						
South West	Ekiti	×	×				
	Lagos	×	×				
	Ogun	×	×	×	×	×	×
	Ondo	×	×	×			
	Osun	×	×				
	Oyo	×	×	×	×	×	×
South East	Abia	×	×	×	×	×	×
	Anambra	×	×				
	Ebonyi	×	×				
	Enugu	×	×				
	Imo	×	×				
South South	Akwa Ibom	×	×	×	×		
	Bayelsa			×	×		
	Cross River	×	×	×	×		
	Rivers			×	×		
	Delta			×	×	×	×
	Edo			×			

Figure 1 summarizes the results of the Atlas in terms of reported occurrence of AAT and tsetse flies. Regarding the disease, the map includes all locations where AAT was detected, regardless of animal species, trypanosome species and diagnostic method. Regarding the geographical distribution of tsetse flies, Figure 1 shows the locations of reported detection, regardless of the tsetse species. Surveys reporting on the absence of detection of AAT or tsetse are not shown in Figure 1.

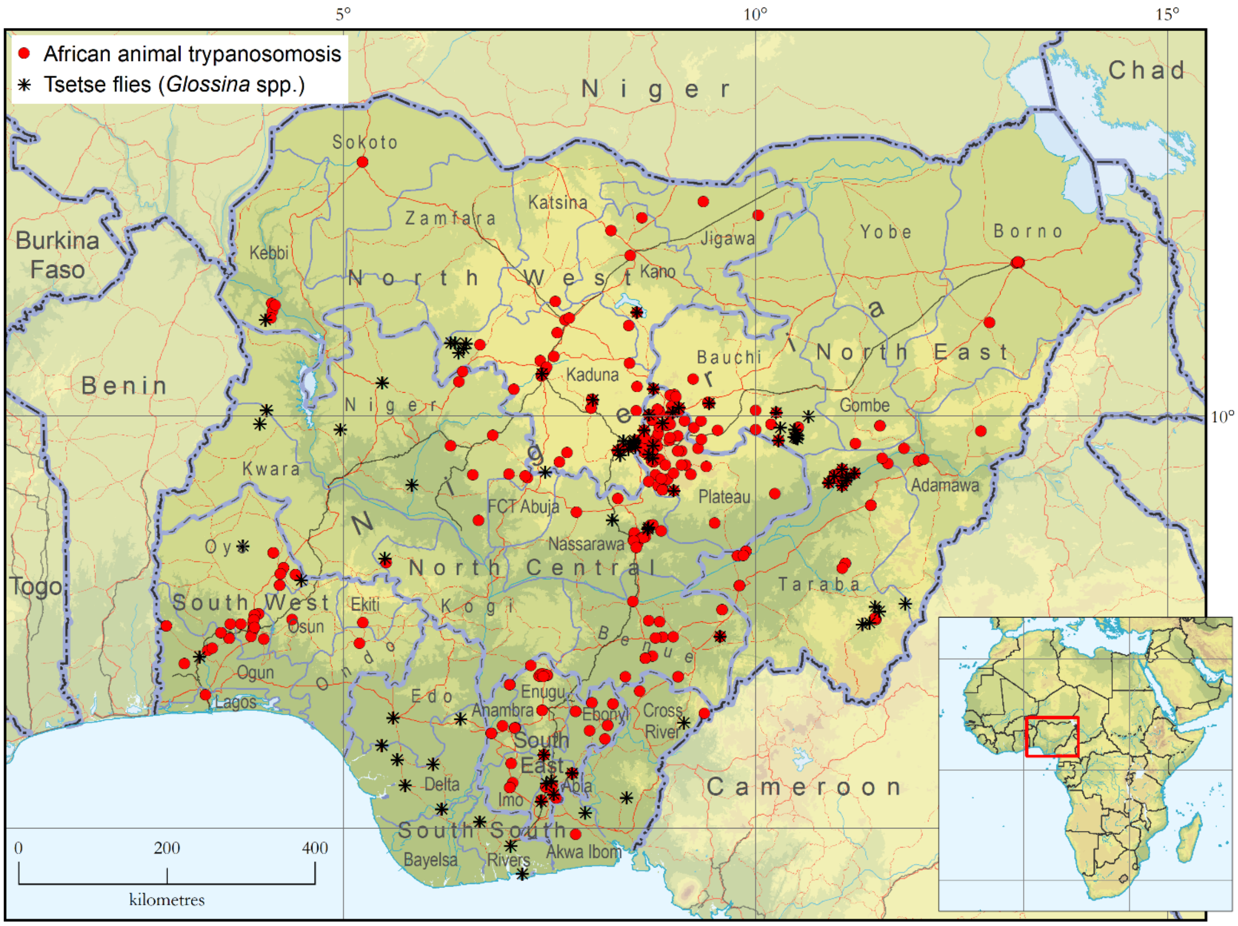

Figure 1 Occurrence of African animal trypanosomosis and tsetse flies (Genus: *Glossina*) in Nigeria. Reporting period: January 1990 – March 2019. Data were extracted from peer-reviewed scientific papers (Supplementary file S1 and Supplementary file S2).

As regards the mapping component of the exercise, a high level of completeness was achieved, with geographical coordinates having been identified for 94% of the reported locations.

African animal trypanosomosis distribution

Regarding the AAT component, the database includes a total of 506 surveys, corresponding to 335 different geographic locations in 31 of the 36 states in Nigeria (Table 2). A total of approximately 124,000 domestic animals were reported to have been tested, of which approximately 53.1% cattle, 39.5% sheep and goats, 6.1% pigs, 0.9% horses, 0.3% camels, <0.01% donkeys and <0.01% dogs. No study on trypanosomal infection in wildlife was identified. Five species of trypanosomes causing AAT were reported to be present in Nigeria: *T. vivax*, *T. congolense*, *T. brucei*, *T. simiae* and *T. godfreyi*.

Figure 2 shows the confirmed presence (or absence of detection) of the three most common trypanosome species (i.e. *T. vivax*, *T. congolense* and *T. brucei*) as determined by the three main diagnostic methods: blood films [i.e. wet smears and thick and thin smears (Eisler et al., 2004)], concentration techniques [i.e. haematocrit centrifugation technique (HCT) (Woo, 1970) and buffy-coat technique (BCT) (Murray et al., 1977)], and PCR, including both species-specific PCR (Artama et al., 1992; Katakura et al., 1997; Masake et al., 1997; Masiga et al., 1992; Morlais et al., 2001; Sloof et al., 1983) and multi-species PCR (Njiru et al., 2005).

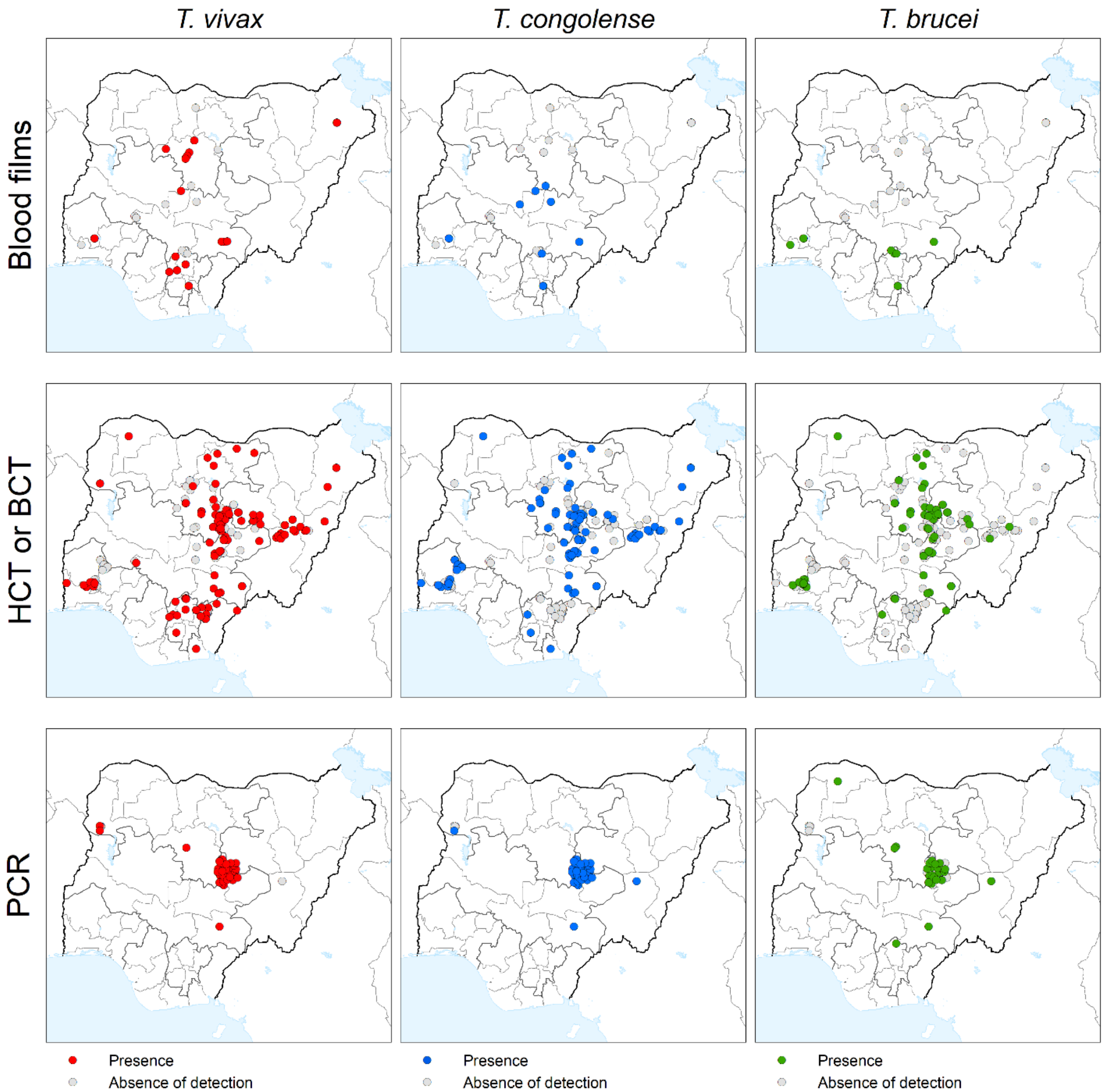

Figure 2 Confirmed presence (or absence of detection) of *T. vivax*, *T. congolense* and *T. brucei* in all susceptible livestock species as determined by blood films (wet smears/thick and thin smears), concentration techniques [haematocrit centrifugation technique (HCT) and buffy-coat technique (BCT)] and polymerase chain reaction (PCR). Reporting period: January 1990 – March 2019. Data were extracted from peer-reviewed scientific papers (Supplementary file S1).

Figure 2 shows that all three main species of trypanosomes are widespread in Nigeria, with a relatively broader distribution for *T. vivax*. They can be found in all six geopolitical zones, including tsetse-free areas.

Regarding the use of the different diagnostic methods, blood films were the most frequently used (49.2% of the samples), followed by concentration techniques (45.7%), PCR (2.2%), and other methods (2.9%). Predictably, different techniques provided different average prevalence, i.e. approximately 3.5% for blood films, 23.3% for HCT/BCT, and 31.0% for PCR (Table 3). In particular, in cattle the overall average prevalence was 14.3% (i.e. 3.7%, 8.6%, and 35.4% for blood films, concentration techniques and PCR respectively) and in small ruminants it was 33.3% (i.e. 2.3%, 37.9% and 71.7% for blood films, concentration techniques and PCR respectively). In pigs, the overall average prevalence was 11.8%.

Table 3 Average prevalence of African animal trypanosomosis in Nigeria based on different diagnostic techniques.

Livestock species	Blood films		HCT/BCT		PCR	
	Animals tested [n]	Average prevalence [%]	Animals tested [n]	Average prevalence [%]	Animals tested [n]	Average prevalence [%]
All species	12,356	3.5	81,339	23.3	14,576	31.0
Cattle	4,892	3.7	31,475	8.6	11,858	35.4
Sheep and goats	6,373	2.3	41,176	37.9	205	71.7
Pigs	227	11.4	4,981	11.2	1,312	13.0

T. vivax and *T. congolense* were the predominant trypanosome species in cattle (46.0% and 43.6% of the infections, respectively), with *T. brucei* accounting for 10.4% of the infections. Of the *T. congolense* infections analysed with molecular techniques (i.e. 2,402), almost all belong to the savannah type (97.8%), the remaining belonging to the forest (2.2%) or kilifi types (<0.01%). Furthermore, one study using multi-species PCR found one case of infection with *T. godfreyi* and nine cases of infection with *T. simiae* in a cattle herd in Kebbi State (North-West) (Yusuf et al., 2015).

In small ruminants, the predominant trypanosomal infections were attributed to *T. vivax* (64.1% of the infections), followed by *T. congolense* (22.6%) and *T. brucei* (13.3%). In pigs, the majority of trypanosomal infections were attributed to *T. brucei* (58.2% of the infections), followed by *T. congolense* (41.8%). One study reported *T. simiae* infections in pigs in Oyo State (Ademola and Onyiche, 2013).

Information on the tested breeds was available for approximately 79% of the studies on cattle and 80% of the studies on small ruminants. Most sampled cattle were Zebus, which can be found throughout Nigeria but predominantly in the northern states. Trypanotolerant breeds, predominantly N'Dama and Muturu, are mostly confined to the southern states. Studies on small ruminants were conducted on the trypanotolerant WAD sheep and goats (83%) (Geerts et al., 2009), Sokoto Red and Sahel goats (11%) and Yankasa sheep (6%). WAD sheep and goats are predominantly present in the south, whereas trypanosusceptible breeds are distributed across the country.

Our review also identified a few studies suggesting the circulation of *T. brucei gambiense* in domestic animals in Nigeria, thus refining a recent review that looked at the animal reservoir of this parasite at the continental level (Büscher et al., 2018). One such study reporting the possible detection of *T. brucei gambiense* in domestic animals in Nigeria was carried out on pigs in Enugu State (Onah and Ebenebe, 2003) by using the blood incubation infectivity test (Hawking, 1976; Rickman and Robson, 1970a, b). Another study carried out in cattle and pigs in Benue and Taraba states (Karshima et al., 2016b) used PCR (Radwanska et al., 2002), even though no positive control was used and no figure of the PCR gels was provided. The latter study targeted an historic focus of sleeping sickness (Gboko) (Aiyedun and Amodu, 1976; Who, 1998), even though no case of HAT has been reported from this area for over twenty years (Franco et al., 2018; WHO, 2013). Other studies that only used the Card Agglutination Trypanosomiasis Test (CATT) (Magnus et al., 1978) for the detection of *T. brucei gambiense* in animals cannot be considered reliable because of the possibility of cross-reaction with *T. brucei brucei*, *T. vivax, T. congolense* and *T. evansi*.

Tsetse fly distribution

Regarding the tsetse distribution component, the database includes a total of 124 surveys, corresponding to 122 different geographic locations and covering 21 states in Nigeria (Table 2).

A total of 21,231 tsetse flies were caught, of which approximately 78.6% of the palpalis group [*G. palpalis palpalis* (51.2%), *G. tachinoides* (47.4%), *G. pallicera pallicera* (0.7%) and *G. caliginea* (0.6%)], 3.3% of the morsitans group [*G. morsitans submorsitans* (99.6%) and *G. longipalpis* (0.4%)], 0.3% of the fusca group [*G. fusca congolensis* (89.2%) and *G. nigrofusca nigrofusca* (10.8%)]. For 17.8% of the reported tsetse flies the species was not specified. Other biting flies (mainly *Tabanus*, *Stomoxys* and *Chrysops*) were reported, although they were not included in the database. Trapping of flies was performed mainly by using Biconical or Nitse traps (with or without odour attractant) (Challier and Laveissière, 1973; Omoogun, 1994), and to a lesser extent using other devices [e.g. hand nets, Pyramidal (Gouteux and Lancien, 1986) and Nzi traps (Mihok, 2002)].

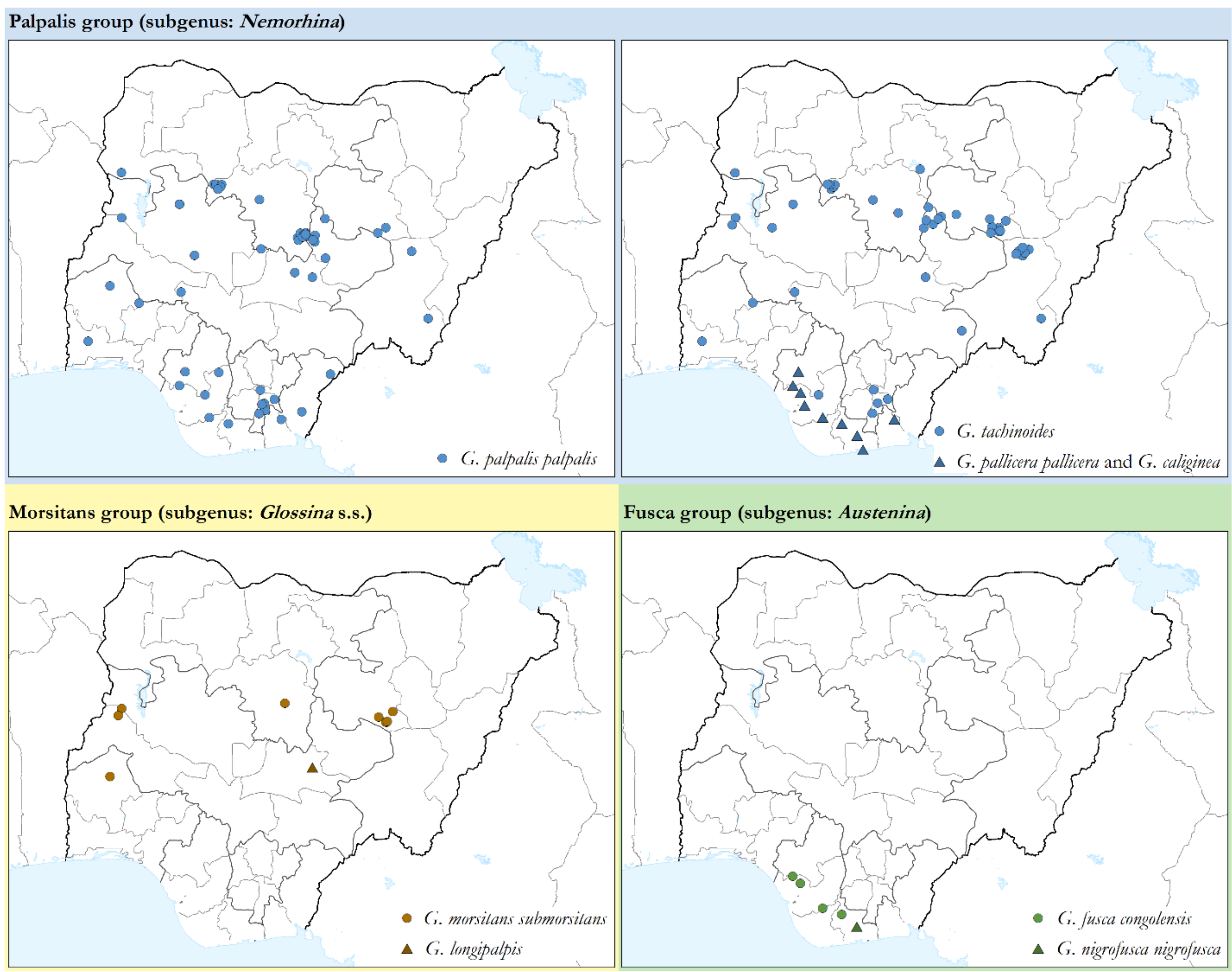

Figure 3 The occurrence of *Glossina* species/subspecies in Nigeria. Data collection period: January 1990 – March 2019. Data were extracted from peer-reviewed scientific papers (Supplementary file S2).

Figure 3 summarizes of the reported geographic distribution of the different tsetse species in Nigeria. Overall, eight out of the eleven historically known tsetse species in Nigeria were reported. *G. palpalis palpalis* and *G. tachinoides* are the species with the broadest geographic distribution. Their occurrence is also reported in areas that were either historically free [e.g. Jos Plateau (Ford, 1970; Onyiah et al., 1983b)] or that had been freed and later reinvaded. The presence of *G. morsitans submorsitans* was reported in seven studies (Abubakar et al., 2016; Ajibade and Agbede, 2008; Enwezor et al., 2009; Idehen et al., 2018; Isaac et al., 2016; Omoogun et al., 1994; Shaida et al., 2018) and mainly found in protected areas (e.g. game reserves or national parks). Four additional species (i.e. *G. caliginea* and *G. pallicera pallicera* of the palpalis group and *G. fusca congolensis* and *G. nigrofusca nigrofusca* of the forest group) were only reported in one study in the South South zone (Edo, Delta, Bayelsa, Rivers and Akwa Ibom states). No catches of *G. tabaniformis*, *G. medicorum* or *G. haningtoni* were reported.

Tsetse infection

Regarding the tsetse infection component, the database includes 75 records. A total of 6,482 tsetse fly examinations were carried out, of which approximately 81.8% of the palpalis group [*G. palpalis palpalis* (77.3%) and *G. tachinoides* (22.7%)], 1.6% of the morsitans group [*G. morsitans submorsitans* (97.1%) and *G. longipalpis* (2.9%)] and 16.6% for which the species was not specified. Tsetse infection data were obtained from 54 distinct geographic locations corresponding to 15 states in Nigeria (Figure 4).

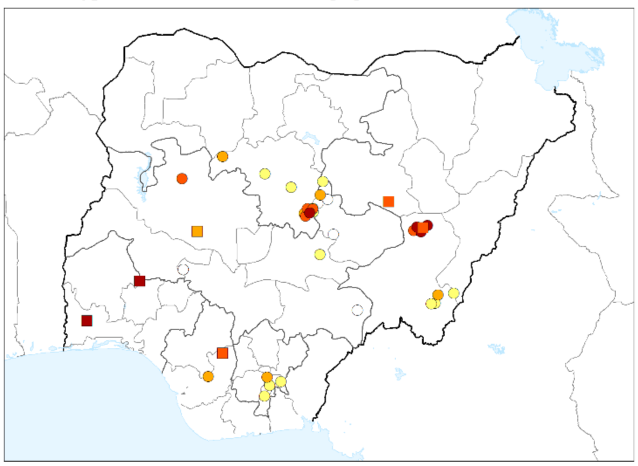

Figure 4 Geographic distribution of tsetse trypanosomal infection rates in Nigeria (Minimum sample size: 10 flies). Data collection period: January 1990 – March 2019. Data were extracted from peer-reviewed scientific papers (Supplementary file S3).

Dissection and microscopical examination of different tsetse organs is still the method most frequently used for investigating tsetse infection rates (Lloyd and Johnson, 1924), having been used in 46 different surveys (i.e. 79%) and 4,735 flies (i.e. 73%). PCR was used in 12 different surveys and 1,747 flies. PCR was conducted either on the whole tsetse body, or on selected organs or body parts.

With dissection and microscopical examination, the average trypanosomal infection rate was 6.0% (287/4,735). Trypanosomal infection was not always reported at the sub-genus/type level; when it was (i.e. 3,219 flies), the respective rates were found to be 79.3% (157 flies), 20.2% (40) and 0.5% (1) for infections respectively reported as *Duttonella*-type (or *T. vivax*-type), *Nannomonas*-type (or *T. congolense*-type) and *Trypanozoon*-type (or *T. brucei*-type).

With PCR, the average trypanosomal infection rate was 24.4% (427/1,747). This includes both species-specific and multi-species PCR. Species specific PCR was applied only in one study and one location (Karshima et al., 2016a), and it revealed the presence of *T. brucei* s.l. (Moser et al., 1989), *T. brucei brucei*, *T. congolense* forest (Masiga et al., 1992), *T. congolense* savannah (Masiga et al., 1992). In addition to the species detected by species-specific PCR, the five studies using multi-species PCR (Njiru et al., 2005) also revealed the presence of *T. vivax*, *T. simiae* and *T. godfreyi* (Isaac et al., 2016; Karshima et al., 2016c; Odeniran et al., 2019; Onyekwelu et al., 2017; Yusuf et al., 2015).

Discussion

The database on tsetse and AAT assembled for Nigeria contains information from 133 peer-reviewed scientific publications, with a fairly good geographical coverage.

For the AAT component, a substantial amount of information was available for a variety of diagnostic methods and a range of livestock species, while no data on wildlife was identified. The AAT map presented here is the first of its kind in Nigeria. Recent meta-analyses on AAT at the national level did not look at the geographical distribution of the disease, nor did they tackle tsetse distribution and infection (Isaac et al., 2017; Odeniran and Ademola, 2018; Odeniran et al., 2018). Indeed, the most recent map of tsetse distribution in Nigeria was assembled in 1995 (Onyiah, 1995).

All three major livestock-infective trypanosome species (*T. vivax*, *T. congolense* and *T. brucei*) are reported to be widespread in the country. With regard to the northern limit of occurrence, AAT was reported in the northern states of Sokoto (Fajinmi et al., 2011), Katsina (Danbirni et al., 2010), Kano (Kalu and Lawani, 1996), Jigawa (Kalu and Lawani, 1996) and Borno (Ahmed et al., 1994; Amina et al., 2017; Mbaya et al., 2010; Nawathe et al., 1995; Paul et al., 2016). Since tsetse flies are not documented to be present in most of these areas, the occurrence of AAT is likely to be associated with movements of infected animals or mechanical transmission. As an example, animal sampling in Borno and Sokoto was performed in abattoirs, whose catchment basin can extend over distances exceeding two hundred kilometres. Animals tested in these abattoirs may have originated from neighbouring states or even from neighbouring countries.

Relatively little information is available on human-infective *T. brucei gambiense* in animals in Nigeria. Reports from the very limited number of studies suggest that it may circulate in a few areas besides the Delta State, the state where occasional HAT cases have been reported in the past ten years (Franco et al., 2018; Luintel et al., 2017).

As compared to AAT, relatively less information is available on tsetse distribution and infection rates. In particular, little published information is available to confirm the tsetse-free status of the northernmost parts of Nigeria, and therefore accurately to delineate the northern limit of the tsetse distribution. To address this gap, surveys have recently been made in Jigawa State for a period of three years, which did not result in any tsetse catch. Similar investigations have not been carried out in other northern states.

Despite the limitations, an Atlas based on peer-reviewed literature manages to draw a meaningful general picture for the economically important tsetse species. Overall, 8 species were reported (out of the 11 that are known to occur in Nigeria). Riverine species are, by far, those with the broadest geographical range of occurrence, also thanks to their ability to adapt to anthropization and the progressive erosion of natural vegetation. As regards savannah species, their distribution appears to be highly fragmented and confined to a few, relatively small protected areas. This is a pattern that has been observed in other western Africa countries (Courtin et al., 2010; Diarra et al., 2019) and elsewhere in Africa (Lord et al., 2018). Finally, very little information is available on the forest species, as a result of their limited geographical distribution, marginal veterinary importance, and difficult-to-access habitat.

The Atlas also enables to track the relatively-recent process of invasion of tsetse flies into historically-free (i.e. highlands) or previously-reclaimed areas (i.e. in parts of the North East and North West zones).

Conclusions

Risk-based targeting of control and monitoring activities is a pillar of the PCP for AAT. However, most affected countries lack information systems to assemble and analyse epidemiological datasets collected by different actors at the national-level. To address this challenge, FAO is promoting the Atlas of tsetse and AAT. The Atlas is a two-pronged initiative, with a top-down continental component (based on published data), and bottom-up, national level components (based on both published and unpublished data). The continental component is directly implemented by FAO, and the results are shared with affected countries, while the national Atlases are implemented by affected countries, with FAO providing guidance and technical assistance. As we write, national Atlases have been developed for five countries (i.e. Burkina Faso, Ghana, Mali, Kenya, Sudan and Zimbabwe), although only the experience of Sudan and Mali has been published so far (Ahmed et al., 2016; Diarra et al., 2019). Concerning the continental Atlas, more than half of the 38 AAT endemic countries have been covered, although results have been published only for four of them, i.e. Ethiopia, Kenya and Uganda (Cecchi et al., 2015; Cecchi et al., 2014) and, with the present paper, Nigeria.

In the context of the PCP, national Atlases are recommended to be developed at Stage 1, as they are considered crucial tools for planning the subsequent stages of intervention. These interventions can either aim at a sustainable, economically-profitable reduction of AAT burden (i.e. Stage 2), or disease elimination (Stages from 3 to 5). In the absence of a national Atlas, the FAO continental Atlas can temporarily fill the gap but, in the longer run, it cannot replace the development of an information system at the country level. Following the present exercise, it is therefore recommended that Nigeria embark on the development of a national Atlas, and that the necessary human and financial resources be made available.

In addition to assisting in the evidence-based planning of interventions, the Atlases are also crucial to assess the effectiveness and impact of control actions. This is true regardless of the goal of interventions (i.e. either reduction or elimination of AAT). As regards AAT elimination, the World Organisation for Animal Health (OIE) is in the process of developing a new chapter of the OIE Terrestrial Animal Health Code on AAT. This will define, among other things, under what conditions a country or a zone can be considered free from AAT. National Atlases of tsetse and AAT are expected to provide endemic countries with crucial data to assess their disease status, and possibly support claims of AAT freedom, either at national or subnational level. On the related topic of tsetse freedom, mathematical methods based on the intensity and strategy of trapping enable to estimate the probability of tsetse being absent from an area (Barclay and Hargrove, 2005; Hargrove, 2005; Kajunguri et al., 2019). These methods do not constitute internationally-agreed guidelines, which are lacking, but they do provide useful scientific references. For example, available data on the absence of tsetse captures in certain states or areas in Nigeria could be analysed through these mathematical methods to provide a quantitative, statistical basis to the assumption of tsetse-freedom.

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Disclaimers

The boundaries and names shown and the designations used on the maps presented in this paper do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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Appendix A. Supplementary data

Supplementary file S1

Papers analysed to generate maps of the distribution of African animal trypanosomosis in Nigeria. Period: January 1990 – March 2019.

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Supplementary file S2

Papers analysed to generate maps of the distribution tsetse fly species (Genus: *Glossina*) in Nigeria. Period: January 1990 – March 2019.

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Supplementary file S3

Papers analysed to generate maps of the distribution of tsetse trypanosomal infection in Nigeria. Period: January 1990 – March 2019.

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