The spreading of parasites by human migratory activities

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Abstract

The global spread of parasites is unquestionably linked with human activities. Migration in all its different forms played a major role in the introduction of parasites into new areas. In ancient times, mass migrations were the main causes for the spread of parasites while in the recent past and present, emigration, immigration, displacement, external and internal migration, and labour migration were the reasons for the dispersal of parasites. With the advent of seagoing ships, long-distance trading became another important mode of spreading parasites. This review summarises the spread of parasites using notable examples. In addition, the different hypotheses explaining the arrival of *Plasmodium vivax* and soil-transmitted helminths in pre-Columbian America are also discussed.

Introduction

Ever since *Homo sapiens* emerged in eastern Africa some 200,000 to 100,000 years ago [1], humans peopled the world until 15,000 years ago they inhabited all continents apart from Antarctica. On their journey, humans brought some of their parasites with them (heirloom parasites) while others were acquired from animals with which they had come in contact during migration (souvenir parasites). Because of the different climate conditions in the different regions of the world, humans would have carried along only a few parasite species. This would include only permanent parasites or those with free-living stages, which can become infectious within a short period of time even in cold temperature, or those with intermediate hosts or vectors, which are locally available and in which infectious live-cycle stages can develop under the regional climate conditions. Parasites that have been most likely spread worldwide during prehistoric human migration are the head lice *Pediculus humanus*, the pinworm *Enterobius vermicularis*, the whipworm *Trichuris trichiura*, the roundworm *Ascaris lumbricoides*, the threadworm *Strongyloides stercoralis*, the hookworms *Ancylostoma duodenale* and *Necator americanus*, and the tapeworms *Taenia saginata* and *Diphyllobothrium latum*. Evidence for this is the demonstration of these parasite species in archaeological specimens (e.g. coprolites and mummies) of prehistoric people in North and South America [2-6]. Likewise, there are indications that *P. humanus* (clade A), *E. vermicularis*, and *A. lumbricoides* were present in Australasia before the first Europeans arrived [7,8].

By 8,000 BCE, humans started to switch from a nomadic, hunter-gatherer lifestyle to a settled, agricultural way of life. This transition is characterised by the domestication of livestock, which brought humans in close contact with parasites harboured by their farmed animals. With the construction of seagoing ships by 4,000 BCE, humans became more mobile and established long-distance trading routes. By 3000 BCE, climate change, poor harvests and population pressure were the reasons for large mass migrations. All these events led to the spread of parasites, which, until then, had only a regional distribution. Other human activities like conquest, war, displacement, relocation, slavery, emigration, immigration, and travel contributed also to the dispersal of parasites. This second period of parasite spreading did not only happen in the past, but also continued in modern times. This review provides examples of

57 the introduction of parasite species into other parts of the world as a result of human migratory

58 activities.

59

60 **Endoparasites**

61 ***Malaria parasites***

62 The origin of *Plasmodium falciparum* (Table 1), the causative agent of severe human malaria,

63 in the Americas is controversial. Some studies suggest that the parasite was recently introduced

64 into the New World during slave trade, Spanish conquest, and European immigration [9]. Other

65 evidence suggests that *P. falciparum* was already present in South America in pre-Columbian

66 times [9]. New evidence indicates that *P. falciparum* evolved following a zoonotic transfer of

67 a parasite from gorillas about 50,000 years ago and emerged from a bottleneck of a single

68 parasite around 4,000-6,000 year ago [10,11]. Based on these new findings it seems unlikely

69 that *P. falciparum* was part of the original parasite fauna of the Americas. Thus, the only

70 remaining possibility for the presence of *P. falciparum* was the introduction of the parasite into

71 the New World in post-Columbian times. This scenario is supported by genetic studies

72 analysing microsatellite and SNP polymorphisms and mitochondrial DNA diversity in *P.*

73 *falciparum* populations indicating that enslaved Africans were likely the main carriers of this

74 malaria species into America [12,13].

75   As for *P. falciparum*, the arrival of the less deadly human malaria species *P. vivax* (Table

76 1) in the New World is also controversial. Previous studies suggest that *P. vivax* emerged in

77 Southeast Asia after crossing the species barrier from a macaque to human [14]. However, new

78 research points to an origin of *P. vivax* in Africa from a strain that was able to infect both

79 humans and apes [15-17]. The parasite was largely eliminated in Africa by the spread of the

80 Duffy-negative mutation while a single lineage spread through Asia and Europe representing

81 the current human-infecting *P. vivax* species [15,17]. Recent genetic studies investigating the

82 mitochondrial DNA diversity in *P. vivax* populations found significant genetic contribution

83 from African and South Asian lineages with some additional genetic input from Melanesian

84 lineages to the *P. vivax* strains of the Americas [13]. This finding suggests that the extant

85 African and South Asian *P. vivax* populations represent the major contributors to the New

World lineages of *P. vivax* and were introduced in post-Columbian times most likely by slaves from Africa and migrants from Asia (Figure 1). In addition, Australasian people may have brought *P. vivax* from the Western Pacific to the Americas in pre-Columbian times (Figure 1). It can be assumed that a malaria parasite causing recurrent infections might survive long-range ocean crossings [18]. The new findings also indicate that the founding population entering the American continent via the Behring land bridge did not bring *P. vivax* to the New World, and that this parasite was first introduce later by Melanesian seafarers, but some time before the Europeans arrived. This suggestion is corroborated by the detection of *P. vivax* antigens using chromogenic immunohistochemistry in 3,000 to 600 years old South American mummies [19].

The spread of malaria due to military conflicts has been a constant theme throughout the entire human history until modern times. A more recent example for this is the introduction of *P. vivax* malaria in Berlin at the end of the Second World War. In the summer of 1946, *P. vivax* was spread among the inmates of a prisoner-of-war camp near Lake Tegel by German soldiers who were also interned in the detention facility upon their return from Southeast Europe and Africa. Subsequently, the parasite was quickly spread to local residents with more than 500 cases recorded [20,21].

Malaria is also the most frequent imported parasitic infection in non-endemic countries. Over the last fifty years, imported malaria has continuously increased due to growing international travel and migration. For example, between 1972 and 2000, the number of imported malaria cases rose from 1,500 to 15,500, most of which were reported by Western European countries with France, Germany, and the United Kingdom counting for more than 70% of all cases [22]. However, since 2004 the number of malaria cases imported to the United Kingdom has remained unchanged at approximately 1,700 cases per year [23]. Most of the imported malaria cases were caused by *P. falciparum* acquired during travel to West Africa [24]. However, over time the epidemiological characteristics of imported malaria cases have changed. Whereas previously malaria was mainly imported to non-endemic countries by returning travellers, the last ten years have seen a continuous increase of imported malaria by immigrants and settled immigrants who travelled to visit relatives and friends still living in their country of origin after their return [22].

Trypanosomatids

With the exception of *Leishmania chagasi*, all other *Leishmania* species already inhabited the different continents long before modern humans had evolved [25]. *Leishmania chagasi* is the causative agent of visceral leishmaniasis in South America and its origin has been widely debated [26,27]. Meanwhile, it seems clear that *L. chagasi* is identical with *L infantum* (Table 1) and was introduced into the New World in post-Columbian times. Evidence for this comes from Bayesian phylogenetic analysis showing that *L. chagasi* clusters with the Portuguese *L. infantum* clade [28]. A bottleneck signature indicates that the parasite was introduced in South America about 500 years ago, probably by European settlers, and their dogs [28].

Trypanosoma evansi, *T. equiperdum*, and *T. vivax* (Table 1) are examples of animal pathogenic parasites that were spread by humans throughout the world. All three trypanosome species belong to the Salivarian group which evolved about 35 million years ago in Africa [29]. *Trypanosoma evansi* is the etiological agent of Surra in livestock animals, particularly in camelids and equids. The parasite is mechanically transmitted by biting flies such as tabanids and stomoxes. It was suggested that *T. evansi* was introduced beyond Africa by the ancient Egyptians during military campaigns in the Middle East [30]. From there, the parasite spread further eastwards and by the 8th century BCE had reached India [30]. The parasite was introduced into South America first in Colombia in the 16th century by Spanish conquistadors, and later in Brazil in the 19th century [31]. In Latin America, *T. evansi* is also transmitted via the common vampire bat *Desmodus rotundus*, which not only acts as biological vector but also as a host and reservoir for the parasite [32]. *Trypanosoma equiperdum* is the pathogen causing dourine in horses, and unlike other trypanosomes, is not transmitted by an insect vector, but directly from one animal to another during sexual contact. Because of the mode of transmission, *T. equiperdum* was easily spread worldwide through horse trade [31]. After the Second World War, *T. equiperdum* was eradicated from North America and Western Europe by systematic screening and control [31,33]. *Trypanosoma vivax* is one of the three African trypanosomes responsible for nagana disease in cattle. In Africa, *T. vivax* is mainly cyclically transmitted by tsetse flies, but also mechanically by biting flies. According to Curasson [34],

144 *T. vivax* was introduced into Latin America with a shipment of zebu cattle from Senegal to

145 French Guyana, Guadeloupe, and Martinique in 1830. However, the parasite may have been

146 introduced already in the 18th century, as cattle were shipped directly from Africa or indirectly

147 via Caribbean islands as early as 1733 [35]. As there are no tsetse flies in the New World, *T.*

148 *vivax* is transmitted mechanically by tabanids and became permanently established all over

149 South America.

150 It can be reasonably assumed that *T. brucei* (Table 1), the causative agent of African

151 sleeping sickness, must also have crossed the Atlantic with the slave trade. This can be inferred

152 from accounts of ship doctors and medical officers employed by slave-trade companies [29].

153 However, *T. brucei* could never become established in South America because tsetse flies, the

154 required vector for transmission of the protozoan parasite, are absent from the New World.

155 *Trypanosoma cruzi* (Table 1), the pathogen responsible for Chagas disease, is an example

156 of a parasite that is spread by migrants from Latin American endemic countries to other parts

157 of the world. Recent evidence suggests that *T. cruzi* evolved from a bat trypanosomes about 7-

158 10 million years ago in South America [36]. The parasite is transmitted via the faeces of

159 triatomine bugs (kissing bugs or conenose bugs) and by other modes including blood

160 transfusion, organ transplantation, breastfeeding, congenital transmission, and ingestion of

161 contaminated food and drinks. In recent times, Chagas disease has become increasingly a

162 global health problem as the estimated number of people infected with *T. cruzi* outside Latin

163 America (mainly North American and European countries) is more than 400,000 [37,38].

164 Although any spread of *T. cruzi* in non-endemic countries is unlikely as most triatomine species

165 are restricted to tropical areas in Latin America, enzootic infection of wild animals and

166 autochthonous infections of humans have been reported from some southern States of the USA

167 [39,40]. In addition, with the tropicopolitan distribution of *Triatoma rubrofasciata* [41], a

168 kissing bug species that transmits *T. cruzi* in the Americas, the scene is set for potential

169 transmission of Chagas disease outside the New World, if South Americans would immigrate

170 to tropical Asian and African countries [42]. Regarding the global spread of *T. rubrofasciata*,

171 see section on Ectoparasites below.

172

Flatworms

Schistosomes are blood-dwelling flukes that, based on molecular data, have evolved in Asia and have dispersed into Africa by migration of their mammalian definitive and snail intermediate hosts [43]. Initially, schistosomes were probably parasites of animals and there is evidence that human schistosomiasis evolved as a zoonosis in the region of the African Great Lakes [44]. From there, it seems that the parasites spread to Egypt by the import of monkeys and slaves [44]. Whether the further spread of schistosomes (*S. mansoni* and *S. haematobium* (Table 2)) from Egypt to West Africa and subsequently to Central and South Africa was the results of the Yoruba and Bantu migration, respectively, is uncertain (Figure 2) [45]. However, it can be taken as certain that *S. mansoni*, the etiological agent of intestinal schistosomiasis in humans, was introduced in post-Columbian times into Latin America presumably by enslaved Africans. This suggestion is supported by phylogeographic analyses of mitochondrial DNA indicating that the genetic diversity of New World *S. mansoni* strains comprises only seven closely related haplotypes with West African affinities [46,47]. More recently, schistosomes have been introduced into non-endemic regions by immigrants and migrant workers. An interesting example in this context is the founding of the state of Israel in 1948. Within a few years 500,000 immigrants from schistosomiasis endemic regions from Near Eastern countries had entered Israel, of which 6-8% were infected with schistosomes [48]. Many immigrants settled along the river Yarkon near Tel Aviv where in 1951 nineteen schoolchildren contracted *S. mansoni* while swimming in the river [48]. In 1955, about 100 schoolchildren contracted *S. haematobium* after bathing in a water-storage reservoir in the Beit-She'an valley [48]. Further transmission of *S. mansoni* was stopped as its snail vector *Biomphalaria alexandria* was successfully eradicated. Also, transmission of *S. haematobium* has not been seen since, although its snail vector *Bulinus truncatus* is still widespread in Israel. An example of the introduction of a parasite by migrant workers is the spread of *S. mansoni* at the Wonji Sugar Estate in the upper Awash valley in Ethiopia [49]. Although from the beginning every effort was made to ensure that none of the migrant workers to be employed was infected with schistosomes, in 1964, ten years after the sugar estate had been established, first cases of *S. mansoni* infection among the labourers were recorded. Previously, both *S. mansoni* and the

host snail were unknown in the area. The parasite was introduced by migrant workers from the north central highlands of Ethiopia where *S. mansoni* was endemic. By 1980, the prevalence of intestinal schistosomiasis had risen to 20% in the area [50] and in 1988 the prevalence of *S. mansoni* infections in children in one of the labour camps at the Wonji estate reached 82% [51]. The main reason for the spread of *S. mansoni* in the region was the poor maintenance of sewage and hygiene facilities at the Wonji estate labour camps with latrine pipes leaking directly into canals, so that the general public living outside the sugar plantation was also affected. Another interesting case is the outbreak of urogenital schistosomiasis on the island of Corsica in the summer of 2013 when more than 120 local people and tourists contracted the parasitic disease [52]. All affected persons had never been to a schistosomiasis-endemic area and had been swimming in the Cavu River which harboured many *B. truncatus* snails. Molecular characterisation of eggs or hatched miracidia recovered from 12 patients showed infection with *S. haematobium*, *S. haematobium*/*S. bovis* hybrids and *S. bovis*. Sequence data analysis indicated that the parasites must have been introduced by individuals who contracted the schistosomes in Senegal. This case shows how easily and rapidly schistosomes can be introduced and spread into new areas provided vector host snails are present.

Liver flukes (fasciolids) are parasites of herbivores, but they can also cause disease in humans. Molecular phylogenetic analysis suggests that fasciolids originated in African proboscideans, and later radiated in Eurasian herbivores [53]. *Fasciola hepatica* (Table 2), the common liver fluke, is likely of Eurasian origin from where the parasite was spread with infected livestock to other continents and where it adapted to other lymnaeid intermediate host snail species [53,54]. This is evident from molecular clock estimations based on ITS sequences indicating that *F. hepatica* was recently introduced from Europe into South America by the import of livestock at the time of the Spanish colonisation [54]. An interesting case of reverse introduction from the New World into the Old World is the large American Liver Fluke, *Fascioloides magna* (Table 2). Probably proboscideans brought a fasciolid with them to the Nearctic in prehistoric times, where the parasite evolved into *F. magna* after adapting to cervids following the extinction of proboscideans in North America [53]. *Fascioloides magna* was at least twice introduced into Europe with imported game animals [55]. The parasite was

introduced with wapiti (*Cervus canadensis*) brought from original habitats in North America to Italy in the 19th century and to Bohemia at the beginning of the 20th century. Meanwhile, *F. magna* has become established in Slovakia, Austria, Germany, Hungary, Croatia and Serbia, spreading along the Danube River [55].

An example for the dispersal of a parasite by internal migration is the Southeast Asian liver fluke *Opisthorchis viverrini* (Table 2) in Thailand. Whereas in the 1950s the prevalence of *O. viverrini* in the Northeast region was extremely high (locally up to 80-100%), only sporadic cases of opisthorchiasis were registered in the Central region from which it was unclear whether these few cases were due to autochthonous infections [45,56]. Between 1955 and 1980, hundreds of thousands of people, many of them infected with *O. viverrini*, migrated from the Northeast region to the Central region to find a better livelihood [45]. The consequence was that within these 25 years the prevalence of *O. viverrini* in the Central region increased on average to over 14% [45]. Meanwhile, it is recognised that *O. viverrini* has become endemic in the Central region as with the presence of the first and second intermediate hosts (freshwater snails of the genus *Bithynia* and freshwater fish of the family Cyprinidae) the conditions to complete the life cycle of the parasite were met [45]. Although the nationwide prevalence of opisthorchiasis has decreased since the 1980s due to the implementation of helminthiasis control programmes, the problem of migrants moving from the still highly endemic Northeast region to other neighbouring areas still continues leading to the establishment or re-establishment of local transmission of *O. viverrini* [57].

A curious case of parasite spreading is the introduction of the pork tapeworm *Taenia solium* (Table 2) into Western New Guinea [58]. Between 1973 and 1976, an unprecedented increase in hospital admission due to high-degree burns among the native Ekari people living in the central highlands of the province Papua was reported [59]. The burns resulted from epileptic seizures while the tribal people were sleeping causing them to fall into fire places. Soon it was established that the epileptic seizures were due to neurocysticercosis caused by the larval stage of *T. solium*. As New Guinea was free of *T. solium* until then, the question was, how the parasite was brought to the island? After the Dutch left Western New Guinea in 1969, the United Nations allowed the inhabitants to join Indonesia. However, as the people were

260   undecided, the Indonesian government dispatched soldiers from Bali, where taeniasis was quite

261   common at that time, to create a *fait accompli*. Since pigs play an important role in the ritual

262   life of the Etari, the Indonesian government tried to appease them with a present of pigs which,

263   unfortunately, were infected with *T. solium* cysticerci [58]. Cysticercosis is still endemic in

264   Central Papua and has meanwhile spread to other regions of the province [58,60].

265

266   ### *Nematodes*

267   Although paleoparasitological evidence dating back to 9,000 years ago show that the soil-

268   transmitted helminths *A. duodenale*, *N. americanus*, *T. trichiura*, *A. lumbricoides*, and

269   *Strongyloides stercoralis* (Table 3) were present in ancient inhabitants of North and South

270   America, these parasites could not have been introduced into the New World with the first

271   humans crossing the Bering Land Bridge [3,5,6,19]. This is because transmission of these

272   helminths depends on the maturation of eggs or larvae released into the environment. However,

273   in order to reach infectivity, eggs and larvae need at least moderate temperature and high soil

274   moisture, conditions that could not have been met in Beringia. In addition, soil-transmitted

275   helminths have never been reported in arctic and subarctic indigenous people living traditional

276   lifestyles [5]. In contrast, the pinworm *E. vermicularis* does occur in native populations of the

277   arctic as its eggs are not dependent on climate conditions. *Enterobius vermicularis* eggs are

278   already infective as soon as they are released and are transmitted via the faecal-oral route

279   usually within family groups [5]. In the case of *S. stercoralis*, it might be possible that this

280   helminth was brought to the New World by migration through Beringia as autoinfections can

281   maintain the parasite in an individual for a lifetime. However, transmission to a new host would

282   still require that the parasite completes its lifecycle in the environment, which would not be

283   possible under the arctic climate conditions. Thus, how did soil-transmitted helminths enter the

284   New World? A possible explanation would be alternative migration routes to the New World

285   in prehistoric times. One such alternative route could have been a boat-supported coastal

286   migration pathway which could have provided environmental conditions suitable for eggs and

287   larvae of soil-transmitted helminths to mature [61]. This possibility is supported by recent

288   findings indicating that the Alaska's coast was clear of ice from about 17,000 years ago [62],

which would have made it feasible for early humans to move south along the shoreline spreading parasites into the New World. Another alternative route could have been a trans-oceanic crossing by people from the West Pacific to the Americas [5]. As such trans-pacific migration would have happened relatively quickly, intestinal parasites could have easily survived the crossing. Support for this hypothesis comes from a recent genome-wide analysis revealing that at least three South American indigenous peoples descended from a native American founding group that shares more ancestry with indigenous people from Australia, New Guinea and the Andaman Islands than with Eurasians or other Native Americans [63]. Thus, it is plausible that soil-transmitted helminths have been spread to the New World by a different route during a second migratory wave after the Clovis migration across Beringia (Figure 3).

Ancylostoma duodenale is also an example of a parasite that had been spread by mass migration. The hookworm is thought to have originated in the Mediterranean region and was probably brought to northern India by the Aryans in the 12th century BCE. The Aryans were a Central Asian pastoral tribe who from the 16th century BCE onwards were migrating to northern India. The possibility that the Aryans have introduced *A. duodenale* into northern India is supported by observation made in the 1920s (Figure 2). According to Darling [64], the incidence of *A. duodenale* infection among the people living in the north of the subcontinent was up to 80% while among the native Tamils living in the south, where the other hookworm species *N. americanus* was dominant, it was only about 2%.

The intestinal bloodsucking hookworm *A. duodenale* is probably the only parasite that became an industrial occupational hazard. The discovery of *A. duodenale* as a workplace risk began with the construction of the Saint Gotthard Tunnel between Switzerland and Italy in 1871. By 1879/80, large number of workers became so anaemic that they were unable to continue to work [65]. At first, it was thought that the workers were suffering from "miner's disease", a condition known for decades affecting mineworkers in different types of pits all over Europe. However, by 1881 it was clear that miner's disease was actually caused by *A. duodenale* [66]. Subsequently, the hookworm was reported in miners worldwide with infection rates close to 100% in some places [65,67]. In contrast, surface mine employees were usually

318 not affected by the infection indicating that the hookworm problem was intrinsically linked

319 with the underground workings [67,68]. This poses the question of how it was possible that a

320 tropical/sub-tropical parasite could manifest itself so dramatically in mines throughout the

321 world? The answer to this lies in the working conditions of miners at that time. First, the poor

322 sanitation conditions (lack of proper latrines and sewage disposal) meant that miners relieved

323 themselves almost anywhere in the mines. Second, the warm and damp conditions of mines

324 were favourable conditions for the development of hookworm larvae. The hot environment of

325 deep mines is due to the geothermal gradient, i.e., Earth's temperature increases with depth

326 (about 2-3 °C per 100 m). But also in deep buried long tunnels like the Saint Gotthard Tunnel

327 (15 km long with a maximum depth of 1700 m), it is likely to encounter temperatures more

328 than 35 °C. The elevated temperature in turn leads to the evaporation of more groundwater and

329 mine water causing an increase in humidity. In addition, the practice of sprinkling to prevent

330 coal dust explosion resulted in an increase in hookworm prevalence in many coal mines. In

331 practice, this meant that mud was building up everywhere that was carried about throughout

332 mines including the rungs of ladders. Thus, if the mud was contaminated with hookworm

333 larvae, it was almost inevitable for miners not to get infected. Important for the spreading of *A.*

334 *duodenale* throughout mines all over the world was the high mobility of mineworkers. For

335 example, in 1913, the German Ruhr region recorded that within the previous 12 months 69%

336 of coal miners left their pits while 78% were newly hired [69]. In contrast, in parts of England

337 miners were constantly recruited from various regions of the world where hookworm infections

338 were endemic [68]. However, it seems also very likely that ancylostomiasis had been within

339 the mining community for centuries, from ancient Egyptian slave pits to medieval European

340 iron mines, and early modern mining operations, constantly passing hookworm infections from

341 one generation of mineworkers to the next [67]. In the end, *A. duodenale* were successfully

342 eliminated from mines worldwide by applying hygienic, preventative, and therapeutic

343 measures developed and recommended as a consequence of the hookworm epidemic at the

344 Saint Gotthard Tunnel [65].

345   The filarial worms *Onchocerca volvulus*, *Wuchereria bancrofti*, *Mansonella perstans* and

346 *Loa loa* (Table 3) are further examples of parasites that were brought to the New World by

13

347   infected slaves in post-Columbian times. In the case of *O. volvulus*, the parasite causing river

348   blindness in humans, analysis of a tandemly repeated DNA sequence family revealed that the

349   American strains are indistinguishable from the African savannah strains indicating that the

350   parasite was recently introduced into Latin America [70]. Although *Simulium damnosum*, the

351   main vector of *O. volvulus* in West Africa, is not found in the New World, other suitable

352   *Simulium* species were present helping to spread the parasite throughout Latin America.

353   However, as the different *Simulium* species do not cover wide geographical areas, *O volvulus*

354   occurs only in relative small and isolated foci in the New World [71]. *Wuchereria bancrofti*,

355   the major cause for lymphatic filariasis, is an example of a parasite that was spread throughout

356   tropical and subtropical regions of the world by human migration. Probably originated in the

357   Malay Archipelago, *W. bancrofti* was first dispersed throughout Southeast and East Asia about

358   50,000 years ago. Austronesians most likely introduced *W. bancrofti* into Madagascar at about

359   1,500 to 1,800 years ago from where later migrations spread the parasites to continental Africa.

360   Finally, *W. bancrofti* was spread from West Africa to the New World during transatlantic slave

361   trade in post-Columbian times. Subsequently, the parasite was further distributed in Latin

362   America by the migration of people within the colonies. For example, *W. bancrofti* was

363   introduced into Costa Rica in 1871 by infected Jamaicans who came as labourers to help

364   building the railways between Puerto Limón and San José [72]. However, wuchereriasis did

365   not expand to rural areas, and ever since its introduction remained a problem in Costa Rica of

366   urban areas of Puerto Limón [72]. The geographic origin and the timing of the global wide

367   dispersal of *W. bancrofti* was recently corroborated by whole genome amplification analyses

368   [73]. In contrast to other filarial worms, *M. perstans* causes only minimal pathology with few

369   disease symptoms. Recent phylogenetic analysis of ribosomal and mitochondrial DNA

370   sequences revealed that a close relationship between *M. perstans* strains from South America

371   and Africa suggesting that this filarial worm was also introduced into the New World in post-

372   Columbian times as a consequence of slave trade [74]. *Loa lao*, the African eyeworm, has

373   repeatedly been introduced into Latin America in the recent past but could never have

374   established itself in the New World [75]. The introduction of *L. loa* into the New World is

375   evident from its first description by the French Surgeon Mongin who saw the parasite in the

376 eye of a slave from the Caribbean in 1770 and from the observation by the French ship surgeon

377 Francois Guyot who noticed recurrent ophthalmia in slaves on their way from Africa to

378 America and successfully removed the worm from one victim in 1778 [76].

379   *Wuchereria bancrofti* also provides an example of how the expansion of agriculturally

380 cultivated land can increase the prevalence of a parasitosis. Between 1903 and 1937, the Davao

381 region on the island of Mindanao, Philippines, saw an increase of abaca (*Musa textilis*)

382 plantations from 2,499 ha to 108,820 ha [77]. Abaca was commercially used for the production

383 of fibres, also known as Manila hemp, a commodity in worldwide demand at that time.

384 However, the expansion of abaca cultivation had serious consequences for the endemicity of

385 wuchereriasis in the region, because the plant provides perfect breeding conditions for the

386 vector of *W. bancrofti* on the Philippines, the mosquito *Aedes poecilus*. As a result, the

387 prevalence of wuchereriasis increased substantially, which was shown to be positively

388 correlated with the increase in the abaca cultivation area [77].

389   The guinea worm *Dracunculus medinensis* (Table 3) is another parasite that was brought

390 to the New World by enslaved Africans [78]. This has been clearly documented in several

391 accounts from the 17th and 18th century. However, as *D. medinensis* requires very specific

392 environmental conditions and human behaviour for local transmission, the parasite could

393 establish itself only in a few place in tropical America for a limited period of time. With the

394 abolition of the slave trade by the Spanish in the 1860s, no more local transmission of the

395 guinea worm was recorded in Latin America. The occasional cases of dracunculiasis brought

396 by immigrants and travellers were not enough to establish a chain of local transmission.

397   The rat lungworm *Angiostrongylus* (*Parastrongylus*) *cantonensis* (Table 3) is an example

398 of a parasite that has been introduced into new areas by the spread of its definitive host. The

399 worm is the etiological agent of eosinophilic meningitis in humans. The home range of *A.*

400 *cantonensis* is thought to be in southern Asia where several genera of rodents, with *Rattus*

401 *norvegicus* and *R. rattus* being the most important species, serve as definitive hosts [79,80].

402 Humans get accidentally infected with *A. cantonensis* when eating undercooked intermediate

403 hosts (snails and slugs) or paratenic hosts (fish, frogs, and freshwater prawns) harbouring

404 infectious L3 larvae, or when consuming vegetables contaminated with snail and slug mucus

405 containing the larvae. After ingestion, L3 larvae enter the brain where they grow into young

406 adult worms. In rodents, the adult worms leave the brain and end up in the lung while in humans

407 they remain in the brain causing eosinophilic meningitis. Since the end of the Second World

408 War, *A. cantonensis* has been dispersed throughout Southeast Asia and Western Pacific Islands,

409 including Australia [79]. The spread of the parasite was most likely via infected rats transported

410 on ships and airplanes, and via the introduction of some species of snail, in particular the

411 African land snail *Achatina fulica* [79]. Meanwhile, *A. cantonensis* is endemic in some

412 Caribbean islands, south-eastern USA, Egypt, Nigeria, Côte d'Ivoire, Brazil and Ecuador [80].

413 In addition, increasing numbers of travellers infected with *A. cantonensis* returning from

414 endemic regions have been reported in Europe [81].

415

416 **Ectoparasites**

417 ***Mosquitoes***

418 The Asian tiger mosquito *Aedes albopictus* (Table 4) is a well-documented example of the

419 global spread of an ectoparasite through international trade in the 20th century. Besides being

420 a significant biting nuisance, *A. albopictus* is also a serious health risk as vector for

421 chikungunya virus, dengue virus and dirofilariasis (*Dirofilaria immitis* and *D. repens*).

422 Originally, *A. albopictus* was native to the forests of Southeast Asia [82]. From there, the

423 mosquito spread eastwards to Japan and South Korea and westwards to Madagascar, but did

424 not immediately reach mainland Africa [83]. The first documented introduction of *A.*

425 *albopictus* into the USA was in Los Angeles in 1946 and a second in Oakland in 1971 [82]. In

426 both cases, the introduction of the mosquito could be traced back to the import of car tyres

427 from the Philippines and Vietnam, respectively (Figure 4). It should be pointed out that the

428 natural breeding habitats of *A. albopictus* are small, restricted, shaded bodies of waters like

429 water-filled tree holes, leaf axils, and rock pools, and thus man-made objects like jars, car tyres,

430 and tin cans provide acceptable alternatives. The mosquito was introduced a third time in

431 Memphis in 1983, but the introduction route remained unclear [82]. However, all three

432 introductions failed to establish *A. albopictus* in the USA. The first autochthonous occurrence

433 of *A. albopictus* was recorded in Harris County, Texas, in 1985 [82]. As breeding places, car

tyres and other vessels were identified, which were also suspected as the vehicles for the introduction of the mosquito. It should be mentioned that between 1978 and 1985, the USA imported 11.6 million used car tyres, two-thirds of which were from *A. albopictus* endemic regions [84]. Whether Harris County was the starting point for the expansion of the mosquito northwards and eastwards to other regions in the USA remains unclear. However, the spreading was not a natural expansion process as the maximum flying distance of *A. albopictus* is about 300 m/day [85], and thus it would have not been possible for the mosquito to reach the east coast within 2 years. More likely is that the mosquito was spread across the country through the trade with used car tyres [82]. In addition, it cannot be ruled out that the occurrence of *A. albopictus* in different regions of the USA was due to repeated introductions of the mosquito [82]. The first evidence of *A. albopictus* in Latin America was recorded in the State of Rio de Janeiro in 1986 [86]. Subsequent detection of the mosquito along the Brazilian east coast initially suggested that *A. albopictus* may have been brought into Brazil from the USA. But this seems unlikely as the characteristics of the *A. albopictus* populations in Brazil indicated a different origin [82]. In the following decades, the mosquito spread throughout Latin America and is currently endemic in 19 countries [87]. In Europe, *A. albopictus* was discovered for the first time in Albania in 1979 [88]. The mosquito was probably introduced with a shipment of goods from China in the mid-1970s [88]. The next European country that became infested with *A. albopictus* was Italy. The mosquito was first detected in Genoa in 1990 [89]. In 1991, the first breeding population of *A. albopictus* was discovered in Padua in the Veneto Region (Figure 4) [90]. It seems very likely that the mosquito was brought into Italy with imported used car tyres from Atlanta, Georgia, USA [91]. In the following years, the mosquito has become established in most regions in Italy below 600 m and the country is now the most heavily infested territory in Europe [92]. Since the millennium, *A. albopictus* has been introduced into many European countries, in most of which the mosquito has become established [92]. Besides the introduction via imported used car tyres, the mosquito has been trapped along motorways indicating that it is spread in Europe via road traffic [92,93]. An alternative pathway of the introduction of *A. albopictus* into the Netherlands and Belgium has been by the import of Lucky bamboo shipments from China [94,95]. In Africa, *A. albopictus*

has been reported for the first time in South Africa in 1990 (Figure 4) [96]. Once again, it was found that the mosquito was introduced with imported used car tyres, but this time from Japan [96]. Although *A. albopictus* did not become established in South Africa, the mosquito has meanwhile colonised several other African countries [92]. Initial breeding sites were found in harbours and coastal areas indicating that the insect was probably spread by international shipping trade. The introduction of *A. albopictus* into Cameroon was most likely due to imported used car tyres [97].

   Aedes aegypti (Table 4) is another mosquito species that had been spread by human activities in the past. The mosquito poses a serious health risk as vector for yellow fever virus, dengue virus, chikungunya virus and Zika virus. Nowadays, it is one of the most widespread mosquito species in tropical and subtropical regions [98]. Historically, *A. aegypti* has been dispersed throughout the world on sailing ships from Africa [98], the original distribution range of the mosquito. Seventeenth century reports on dengue-like epidemics (note that *A. aegypti* is the main vector for Dengue) in the Caribbean suggest that the mosquito was probably already introduced into the Americas with the onset of the slave trade [99]. From the late 18th to the mid-20th century, *A. aegypti* became established in Southern Europe [98]. Unlike *A. albopictus*, *A. aegypti* has not extended its distribution range in Europe beyond the Mediterranean because the eggs of the mosquito are unable to undergo winter diapause [98]. During the second half of the 20th century, *A. aegypti* has disappeared from many foci in Europe and America. The reasons for its disappearance are not fully understood but eradication programmes have contributed to the reduction of *A. aegypti* in South America between 1947 and 1970 [99] and the global spread of *A. albopictus* since the 1970s may have resulted in the competitive displacement of *A. aegypti* [100,101]. More recently, however, *A. aegypti* is recolonising Europe via modern transport systems (air and road travel) [98]. In the summer of 2010, the mosquito was discovered in the Netherlands at tyres yards [102]. Genetic analysis revealed that *A. aegypti* was introduced via a shipment of tyres from Miami, Florida, USA (Figure 4) [103]. This finding was quite unusual as the spread of *A. aegypti* is not directly associated with the international trade in used tyres [104].

491   Two more *Aedes* species have been spread around the world by commercial transport of
492   used tyres. *Aedes atropalpus* (Table 4) is a native North American mosquito species that has
493   been introduced into Europe several times between 1990 and 2009 [105]. Although *A.*
494   *atropalpus* is reproducing in Europe, the established populations have remained localised so
495   far [105]. *Aedes japonicus* (Table 4) is endemic in East Asia and has been spread since the
496   1990s [106]. The mosquito was first reported outside its native range in New Zealand in 1994
497   [107]. In 1998, *A. japonicus* was discovered in the north-eastern USA [108] and the spread of
498   the mosquito within the country may have been facilitated by the Standardbred horse trade
499   [109]. Since 2000, *A. japonicus* has been present in Europe and established in western regions
500   of Germany [106]. However, both mosquito species are not considered important vectors for
501   diseases.

502

503   ***Kissing bugs***

504   The tropicopolitan distribution range of the triatomine species *T. rubrofasciata* (Table 4),
505   a vector for *T. cruzi* in Latin America, can be only explained by recent spreading events. DNA
506   sequence analyses using nuclear and mitochondrial marker genes showed high similarity
507   between New World and Old World specimens indicating a common and recent origin of Asian
508   and American populations of *T. rubrofasciata* [110,111]. The close association of *T.*
509   *rubrofasciata* with domestic rats (especially *R. rattus*) suggests that the triatomine bug was
510   spread around the globe by international shipping during the 16th to 18th centuries [112].
511   However, the place of origin of *T. rubrofasciata* is still debated. One hypothesis suggests that
512   *T. rubrofasciata* originated in the New World and could be the common ancestor of other Asian
513   triatomines [42]. An alternative hypothesis proposes that the triatomine bug is of Asian origin
514   and was recently introduced into the Americas [42]. Meanwhile, *T. rubrofasciata* has become
515   a serious biting nuisance and a public health problem in Vietnam as bites by the insect can
516   produce severe anaphylactic reactions in humans [42,111,]. Reports of people bitten by the
517   triatomine bug have significantly increased in different Vietnamese cities over the last decade
518   [111]. The reason for the current widespread infestation of *T. rubrofasciata* in urban areas in
519   Vietnam is unclear. One explanation could be the massive culling of peridomestic chickens in

520 urban and periurban areas in the previous decade in order to control avian influenza.

521 Triatomines readily feed on chickens, which in rural Latin America have been shown to be

522 important for the bug's transition from sylvatic to domestic lifestyles. Thus, it seems that

523 human interference led to the loss of a primary host of *T. rubrofasciata* driving the triatomine

524 bug to prey on people [42].

525

526 ### *Sand fleas*

527 The sand flea *Tunga penetrans* (Table 4) is one of the few examples of a parasite that has

528 been spread from the New World to the Old Word. Only fertilised female fleas become skin

529 parasites and burrow into the stratum granulosum of the epidermis. In contrast, *T. penetrans*

530 larvae live in sand and soil while adult sand fleas feed intermittently on their host. Originally,

531 *T. penetrans* was a parasite of Xenarthra (armadillos, anteaters, and sloths) and/or Carviidae

532 (guinea pigs and capybaras) in the neotropics [113]. With the arrival of *H. sapiens* in Central

533 and South America, the flea adopted humans as an additional host in pre-Columbian times

534 [114]. The parasite expanded its host range further to include domestic animals and rodents

535 introduced by Europeans during the colonisation of America. The introduction of *T. penetrans*

536 into Africa can be traced back to a single event. In September 1872, the flea was brought from

537 America to Africa with the English ship "Thomas Mitchell" that sailed from Rio de Janeiro to

538 Ambriz in Angola [113-115]. With ballast sand, old coffee bags, infected sailors, and people

539 visiting the ship, the parasite got ashore. First, the flea was dispersed along the coast by

540 shipping active in those days. Within a few years, the parasite was spread eastwards and

541 southward along trading routes with traders, explorers, and soldiers, and by 1888 and 1890 had

542 already reached Mozambique and Natal, respectively [113]. By the end of the 19th century, sea

543 trade had brought the flea onto the islands off the African east coast (Madagascar, Zanzibar,

544 Seychelles, Comoros, Mauritius and Reunion). In 1899, British soldiers introduced *T.*

545 *penetrans* into the Indian subcontinent but the flea never became established there [115].

546 Meanwhile, *T. penetrans* has established itself in most sub-Saharan countries.

547

548 **Concluding remarks**

549 The human tendency to explore and colonise new areas has largely contributed to the spread

550 of parasites. The different forms of voluntary migration (emigration, immigration, external and

551 internal migration, labour migration) were and still are one of the main causes for the dispersal

552 of parasites throughout the world. The transatlantic slave trade, which can be regarded as a

553 special form of forced migration, played an important role for the introduction of many new

554 parasite species into the Americas. Displacement and relocation of people caused by war and

555 civil unrest are also types of forced migration that have led to the spread of parasites up to the

556 present day. Trade, in particular shipping, has been and still remains a very effective mode of

557 spreading parasites around the world. More recently, air and road transport have also

558 contributed to the spread of parasites. In addition, through modern mass tourism, parasites have

559 been repeatedly introduced into non-endemic areas, in most cases without consequences for

560 the range expansion of the species involved.

561 It has been predicted that climate and environmental changes will affect the geographical

562 distribution of parasites and their human hosts [116-118]. Global warming should facilitate the

563 establishment of parasites and diseases vectors into more temperate parts of the world as their

564 optimal temperature for development will shift northwards [116]. Increased precipitation and

565 humidity should favour parasites that rely on aquatic and free-living life cycle stages (e.g.

566 mosquitoes and soil-transmitted helminths, respectively) [116]. Environmental changes (e.g.

567 deforestation) can create novel habitats for parasites that can help to establish them in new

568 areas [116,119]. Importantly, climate change may cause massive migrations as some areas may

569 become uninhabitable through droughts, an increasing problem particularly in sub-Saharan

570 Africa [117]. It can be expected that migrants will carry parasites and introduce them into new

571 regions [117]. However, it is quite difficult to predict what overall impact anthropogenic

572 climate change will have on the spread of parasites in the future.

573

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576

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References

[1] Mounier A, Mirazón Lahr M. Deciphering African late middle Pleistocene hominin diversity and the origin of our species. Nat Commun. 2019;10:3406.

[2] Horne PD, Kawasaki SQ. The Prince of El Plomo: a paleopathological study. Bull N Y Acad Med. 1984;60:925-931.

[3] Reinhard KJ. Archaeoparasitology in North America. Am J Phys Anthropol. 1990;82:145-163.

[4] Hugot J-P, Reinhard KJ, Gardner SL, et al. Human enterobiasis in evolution: origin, specificity and transmission. Parasite. 1999;6:201-208.

[5] Araújo A, Reinhard KJ, Ferreira LF, et al. Parasites as probes for prehistoric human migrations? Trends Parasitol. 2008;24:112-115.

[6] Araújo A, Reinhard K, Ferreira LF, et al. Paleoparasitology: the origin of human parasites. Arq Neuropsiquiatr. 2013;7:722-726.

[7] Andrews JR. The parasitology of the Maori in pre-European times. N Z Med J. 1976;84:62-65.

[8] Light JE, Allen JM, Long LM, et al. Geographic distributions and origins of human head lice (*Pediculus humanus capitis*) based on mitochondrial data. J Parasitol. 2008;94:1275-1281.

[9] de Castro MC, Singer BH. Was malaria present in the Amazon before the European conquest? Available evidence and future research agenda. J Archaeol Sci. 2005;32:337-340.

[10] Otto TD, Gilabert A, Crellen T, et al. Genomes of all known members of a *Plasmodium* subgenus reveal paths to virulent human malaria. Nat Microbiol. 2018;3:687-697.

607   [11]   Galaway F, Yu R, Constantinou A, et al. Resurrection of the ancestral RH5 invasion

608   ligand provides a molecular explanation for the origin of *P. falciparum* malaria in

609   humans. PLoS Biol. 2019;17:e3000490.

610   [12]   Yalcindag E, Elguero E, Arnathau C, et al. Multiple independent introductions of

611   *Plasmodium falciparum* in South America. Proc Natl Acad Sci U S A. 2012;109,:511-

612   516.

613   [13]   Rodrigues PT, Valdivia HO, de Oliveira TC, et al. Human migration and the spread

614   of malaria parasites to the New World. Sci Rep. 2018;8:1993.

615   [14]   Cornejo OE, Escalante AA. The origin and age of *Plasmodium vivax*. Trends

616   Parasitol. 2006;22:558-563.

617   [15]   Liu W, Li Y, Shaw KS, Learn GH, et al. African origin of the malaria parasite

618   *Plasmodium vivax*. Nat Commun. 2014;5:3346.

619   [16]   Loy DE, Liu W, Li Y, et al. Out of Africa: origins and evolution of the human malaria

620   parasites *Plasmodium falciparum* and *Plasmodium vivax*. Int J Parasitol. 2017;47:87-

621   97.

622   [17]   Loy DE, Plenderleith LJ, Sundararaman SA, et al. Evolutionary history of human

623   *Plasmodium vivax* revealed by genome-wide analyses of related ape parasites. Proc

624   Natl Acad Sci U S A. 2018;115:E8450-E8459.

625   [18]   Carter R. Speculations on the origins of *Plasmodium vivax* malaria. Trends Parasitol.

626   2003;19:214-219.

627   [19]   Gerszten E, Allison MJ, Maguire B. Paleopathology in South American mummies: a

628   review and new findings. Pathobiology 2012;79:247-256.

629   [20]   Kirchberg E, Mamlock E. Malariabekämpfung in Berlin im Jahre 1946. Ärztl

630   Wochenschr. 1946;1:119-122.

631   [21]   Kirchberg E, Mamlock E. Schlußwort zur Frage der Malariabekämpfung. Ärztl

632   Wochenschr. 1946;2:764-765.

633   [22]   Mischlinger J, Rönnberg C, Álvarez-Martínez MJ, et al. Imported malaria in countries

634   where malaria is not endemic: a comparison of semi-immune and nonimmune

635   travellers. Clin Mircobiol Rev. 2020;33:e00104-19.

[23] Moyo QM, Besser M, Lynn R, et al. Persistence of imported malaria into the United Kingdom: an epidemiological review of risk factors and at-risk groups. Clin Infect Dis. 2019;69:1156-1162.

[24] Tatem AJ, Jia P, Ordanovich D, et al. The geography of imported malaria to non-endemic countries: a meta-analysis of nationally reported statistics. Lancet Infect Dis. 2017;17:98-107.

[25] Steverding D. The history of leishmaniasis. Parasit Vectors. 2017;10:82.

[26] Maurício IL, Stothard JR, Miles MA. The strange case of *Leishmania chagasi*. Parasitol Today. 2000;16:188-189.

[27] Dantas-Torres F. Leishmania infantum versus *Leishmania chagasi*: do not forget the law of priority. Mem Inst Oswaldo Cruz. 2006;101:117-118.

[28] Leblois R, Kuhls K, François O, et al. (2011) Guns, germs and dogs: on the origin of *Leishmania chagasi*. Infect Genet Evol. 2011;11:1091-1095.

[29] Steverding D. The history of African trypanosomiasis. Parasit Vectors. 2008;1:3.

[30] Desquesnes M, Holzmuller P, Lai D-H, et al. *Trypanosoma evansi* and surra: a review and perspectives on origin, history, distribution, taxonomy, morphology, hosts, and pathogenic effects. Biomed Res Int. 2013;2013:194176.

[31] Desquesnes M. Livestock Trypanosomoses and their Vectors in Latin America. Paris: OIE; 2004.

[32] Desquesnes M, Dargantes A, Lai D-H, et al. *Trypanosoma evansi* and surra: a review and perspectives on transmission, epidemiology and control, impact, and zoonotic aspects. Biomed Res Int. 2013;2013:321237.

[33] Claes F, Büscher P, Touratier L, et al. *Trypanosoma equiperdum*: master of disguise or historical mistake? Trends Parasitol. 2005;21:316-321.

[34] Curasson G. Traité de Protozoologie Vétérinaire et Comparée, Vol. I. Paris: Vigot Frères; 1943.

[35] Maillard N, Maillard JC. Historique du peuplement bovine et de l'introduction de la tique *Amblyomma variegatum* dans la îles françaises des Antilles: synthèse bibliographique. Ethnozootechnie. 1998;61:19-36.

665   [36]   Steverding D. The history of Chagas disease. Parasit Vectors. 2014;7:317.

666   [37]   Schmunis GA, Yadon ZE. Chagas disease: a Latin American health problem

667   becoming a world health problem. Acta Trop. 2010;115:14-21.

668   [38]   Strasen J, Williams T, Ertl G, et al. Epidemiology of Chagas disease in Europe: many

669   calculations, little knowledge. Clin Res Cardiol. 2014;103:1-10.

670   [39]   Bern C, Kjos S, Yabsley MJ, et al. *Trypanosoma cruzi* and Chagas' disease in the

671   United States. Clin Microbiol Rev. 2011;24:655-681.

672   [40]   Cantey PT, Stramer SL, Townsend RL, et al. The United States *Trypanosoma cruzi*

673   infection study: evidence for vector-borne transmission of the parasite that causes

674   Chagas disease among United States blood donors. Transfusion. 2012;52:1922-1930.

675   [41]   Ryckman RE, Archbold EF. The Triatominae and Triatominae-borne trypanosomes

676   of Asia, Africa, Australia and the East Indies. Bull Soc Vector Ecol. 1981;6:143-166.

677   [42]   Dujardin J-P, Lam TX, Khoa PT, et al. The rising importance of *Triatoma*

678   *rubrofasciata*. Mem Inst Oswaldo Cruz. 2015;110:319-323.

679   [43]   Lawton SP, Hirai H, Ironside JE, et al. Genomes and Geography: genomic insights

680   into the evolution and phylogeography of the genus *Schistosoma*. Parasit Vectors.

681   2011;4:131.

682   [44]   Di Bella S, Riccardi N, Giacobbe DR, et al. History of schistosomiasis (bilharziasis)

683   in humans: from Egyptian medical papyri to molecular biology on mummies. Pathog

684   Glob Health. 2018;112:268-273.

685   [45]   Hinz E. *Homo sapiens migrans*: Sein Beitrag zur Ausbreitung von Parasitosen. Mitt

686   Österr Ges Tropenmed Parasitol. 1998;20:1-16.

687   [46]   Desprès L, Imbert-Establet D, Monnerot M. Molecular characterization of

688   mitochondrial DNA provides evidence for the recent introduction of *Schistosoma*

689   *mansoni* into America. Mol Biochem Parasitol. 1993;60:221-229.

690   [47]   Morgan JAT, Dejong RJ, Adeoye GO, et al. Origin and diversification of the human

691   parasite *Schistosoma mansoni*. Mol Ecol. 2005;14:3889-3902.

692   [48]   Saliternik Z, Witenberg G. Investigations on the control of bilharziasis vectors in

693   Israel. Bull World Health Organ. 1959;21:161-177.

694   [49]   Grosse S. Schistosomiasis and water resources development: a re-evaluation of an

695   important environment-health linkage. Working Paper of the Environment and

696   Natural Resources Policy and Training Project, EPAT/MUCIA, Technical Series No

697   2. Ann Arbor: University of Michigan Press; 1993.

698   [50]   Kloos H, Lo CT, Birrie H, et al. Schistosomiasis in Ethiopia. Soc Sci Med.

699   1988;26:803-827.

700   [51]   Simonsen PE, Nega A, Furu P. Intestinal schistosomiasis among children in a labour

701   village of Wonji Sugar Estate, Ethiopia. East Afr Med J. 1990;67:532-538.

702   [52]   Boissier J, Grech-Angelini S, Webster BL, et al. Outbreak of urogenital

703   schistosomiasis in Corsica (France): an epidemiological case study. Lancet Infect Dis.

704   2016;16:971-979.

705   [53]   Lotfy WM, Brant SV, DeJong RJ, et al. Evolutionary origins, diversification, and

706   biogeography of liver flukes (Digenea, Fasciolidae). Am J Trop Med Hyg.

707   2008;79:248-255.

708   [54]   Mas-Coma S, Funatsu IR, Bargues MD. *Fasciola hepatica* and lymnaeid snails

709   occurring   at   very   high   altitude   in   South   America.   Parasitology.

710   2001;123(Suppl):S115-S127.

711   [55]   Malcicka M. Life history and biology of *Fascioloides magna* (Trematoda) and its

712   native and exotic hosts. Ecol Evol. 2015;5:1381-1397.

713   [56]   Sadun EH. Studies on *Opisthorchis viverrini* in Thailand. Am J Hyg. 1955;62:81-115.

714   [57]   Pumidonming W, Katahira H, Igarashi M, et al. Potential risk of a liver fluke

715   *Opisthorchis viverrini* infection brought by immigrants from prevalent areas: a case

716   study in the lower Northern Thailand. Acta Trop. 2018;178:213-218.

717   [58]   Del Brutto OH, García HH. *Taenia solium* cysticercosis – The lessons of history. J

718   Neurol Sci. 2015;359:392-395.

719   [59]   Subianto DB, Tumada LR, Margono SS. Burns and epileptic fits associated with

720   cysticercosis in mountain people of Irian Jaya. Trop Geogr Med. 1978;30:275-278.

721 [60] Singh G, Prabhakar S, Ito A, et al. *Taenia solium* taeniasis and cysticercosis in Asia.

722 In: Singh G, Prabhakar S, editors. *Taenia solium* Cysticercosis. From Basic to Clinical

723 Science. Wallingford, Oxon: CABI Publishing; 2002. p. 111-128.

724 [61] Montenegro A, Araujo A. Eby M, et al. Parasites, paleoclimate, and the peopling of

725 the Americas. Using the hookworm to time the Clovis migration. Curr Anthropol.

726 2006;47:193-200.

727 [62] Lesnek AJ, Briner JP, Lindqvist C, et al. Deglaciation of the Pacific coastal corridor

728 directly preceded the human colonization of the Americas. Sci Adv. 2018;4:eaar5040.

729 [63] Skoglund P, Mallick S, Bortolini MC, et al. Genetic evidence for two founding

730 populations of the Americas. Nature. 2015;525:104-108.

731 [64] Darling ST. Comparative helminthology as an aid in the solution of ethnological

732 problems. Am J Trop Med Hyg. 1925;s1-5:323-337.

733 [65] Peduzzi R, Piffaretti JC. *Ancylostoma duodenale* and the Saint Gothard anaemia. Br

734 Med J (Clin Res Ed). 1983;287:1942-1945.

735 [66] Bugnion E. On the epidemic caused by *Ankylostomum* among the workmen in the St.

736 Gothard Tunnel. Br Med J. 1881;1(1054):382.

737 [67] Nauss RW. Hookworm in California gold mines. Am J Public Health (N Y).

738 1921;11:439-451.

739 [68] Boycott AE, Haldane JS. An outbreak of ankylostomiasis in England: No I. J Hyg

740 (Lond). 1903;3:95-136.

741 [69] Geary D. The myth of the radical miner. In: Berger S, Croll A, LaPorte N, editors.

742 Towards a Comparative History of Coalfield Societies. Aldershot: Ashgate

743 Publishing; 2005. p. 43-64.

744 [70] Zimmerman PA, Katholi CR, Wooten MC, et al. Recent evolutionary history of

745 American *Onchocerca volvulus*, based on analysis of a tandemly repeated DNA

746 sequence family. Mol Biol Evol. 1994;11:384-392.

747 [71] Gustavsen K, Hopkins A, Sauerbrey M. Onchocerciasis in the Americas: from arrival

748 to (near) elimination. Parasit Vectors. 2001;4:205.

749 [72] Paniagua F. Prevalence study of bancroftian filariasis in Puerto Limón, Costa Rica.
750   Epidemiol Bull. 1983;4:13-14.

751 [73] Small ST, Labbé F, Coulibaly YI, et al. Human Migration and the spread of the
752   nematode parasite *Wuchereria bancrofti*. Mol Biol Evol. 2019;36:1931-1941.

753 [74] Tavares da Silva LB, Crainey JL, Ribeiro da Silva TR, et al. Molecular verification of
754   New World *Mansonella perstans* parasitemias. Emer Infect Dis. 2017;23:545-547.

755 [75] Crewe W. Loiasis. In: Service MW, editor. The Encyclopedia of Arthropod-
756   transmitted Infections of Man and Domesticated Animals. Wallingford, Oxon: CABI
757   Publishing; 2001. p. 286-290.

758 [76] Cox FEG. History of human Parasitology. Clin Microbiol Rev. 2002;15:595-612.

759 [77] Hinz E. Human Helminthiases in the Philippines. The Epidemiological and
760   Geomedical Situation. Berlin, Heidelberg: Springer-Verlag; 1985.

761 [78] Watts S. Dracunculiasis in the Caribbean and South America: a contribution to the
762   history of dracunculiasis eradication. Med Hist. 2000;45:227-250.

763 [79] Kliks MM, Palumbo NE. Eosinophilic meningitis beyond the Pacific Basin: the global
764   dispersal of a peridomestic zoonosis caused by *Angiostrongylus cantonensis*, the
765   nematode lungworm of rats. Soc Sci Med. 1992;34:199-212.

766 [80] Martins YC, Tanowitz HB, Kazacos KR. Central nervous system manifestations of
767   *Angiostrongylus cantonensis* infection. Acta Trop. 2015;141(Pt A):46-53.

768 [81] Wang Q-P, Wu Z-D, Wei J, et al. Human *Angiostrongylus cantonensis*: an update.
769   Eur J Clin Microbiol Infect Dis. 2012;31:389-395.

770 [82] Hinz E. Einschleppung und Ausbreitung von *Aedes albopictus* (Diptera: Culicidae) in
771   Amerika. Mitt Österr Ges Tropenmed Parasitol. 1991;13:101-110.

772 [83] Reiter P. Erratum: *Aedes albopictus* does not occur in Africa. J Am Mosq Control
773   Assoc. 1986;2:378.

774 [84] Reiter P, Sprenger D. The used tire trade: a mechanism for the worldwide dispersal of
775   container breeding mosquitoes. J Am Mosq Control Assoc. 1987;3:494-501.

776   [85]   Marini F, Caputo B, Pombi M, et al. Study of *Aedes albopictus* dispersal in Rome,
777   Italy, using sticky traps in mark-release-recapture experiments. Med Vet Entomol.
778   2010;24:361-368.

779   [86]   Forattini OP. *Aedes* (*Stegomyia*) *albopictus* (Skuse) identification in Brazil. Rev
780   Saude Publica. 1986;20:244-245.

781   [87]   Carvalho RG, Lourenço-de-Oliveira R, Braga IA. Updating the geographical
782   distribution and frequency of *Aedes albopictus* in Brazil with remarks regarding its
783   range in the Americas. Mem Inst Oswaldo Cruz. 2014;109:787-796.

784   [88]   Adhami J, Reiter P. Introduction and establishment of *Aedes* (*Stegomyia*) *albopictus*
785   Skuse (Diptera: Culicidae) in Albania. J Am Mosq Control Assoc. 1998;14:340-343.

786   [89]   Raineri V, Trovato G, Sabatini A, et al. Ulteriori dati sulla diffusione a Genova di
787   *Aedes albopictus*. Parassitologia. 1991;33:183-185.

788   [90]   Della Pozza G, Majori G. First record of *Aedes albopictus* establishment in Italy. J
789   Am Mosq Control Assoc. 1992;8:318-320.

790   [91]   Della Pozza GL, Romi R, Severini C. Source and spread of *Aedes albopictus* in the
791   Veneto region of Italy. J Am Mosq Control Assoc. 1994;10:589-592.

792   [92]   European Centre for Disease Prevention and Control. *Aedes albopictus* – Factsheet
793   for experts. 2016. [cited 2020 June 14]. Available from:
794   https://www.ecdc.europa.eu/en/disease-vectors/facts/mosquito-factsheets/aedes-
795   albopictus

796   [93]   Medlock JM, Vaux AGC, Cull B, et al. Detection of the invasive mosquito species
797   *Aedes albopictus* in southern England. Lancet Inf Dis. 2017;17:140.

798   [94]   Scholte E-J, Dijkstra E, Blok H, et al. Accidental importation of the mosquito *Aedes*
799   *albopictus* into the Netherlands: a survey of mosquito distribution and the presence of
800   dengue virus. Med Vet Entomol. 2008;22:352-358.

801   [95]   Demeulemeester J, Deblauwe I, De Witte J, et al. First interception of *Aedes*
802   (*Stegomyia*) *albopictus* in Lucky bamboo shipments in Belgium. J Eur Mosq Control
803   Assoc. 2014;32:14-16.

804 [96] Cornel AJ, Hunt RH. *Aedes albopictus* in Africa? First records of live specimens in
805 imported tires in Cape Town. J Am Mosq Control Assoc. 1991;7:107-108.

806 [97] Fontenille D, Toto JC. *Aedes* (*Stegomyia*) *albopictus* (Skuse), a potential new Dengue
807 vector in southern Cameroon. Emerg Infect Dis. 2001;7:1066-1067.

808 [98] European Centre for Disease Prevention and Control. *Aedes aegypti* – Factsheet for
809 experts. 2016. [cited 2020 June 14]. Available from:
810 https://www.ecdc.europa.eu/en/disease-vectors/facts/mosquito-factsheets/aedes-
811 aegypti

812 [99] Brathwaite Dick O, San Martín JL, Montoya RH, et al. The history of dengue
813 outbreaks in the Americas. Am J Trop Med Hyg. 2012;87:584-593.

814 [100] Hobbs JH, Hughes EA, Eichold BH 2nd. Replacement of *Aedes aegypti* by *Aedes*
815 *albopictus* in Mobile, Alabama. J Am Mosq Control Assoc. 1991;7:488-498.

816 [101] Muzari M, Davis J, Bellwood R, et al. Dominance of the tiger: the displacement of
817 *Aedes aegypti* by *Aedes albopictus* in parts of the Torres Strait, Australia. Commun
818 Dis Intell. 2019;43:17.

819 [102] Scholte EJ, Den Hartog W, Dik M, et al. (2010) Introduction and control of three
820 invasive mosquito species in the Netherlands, July-October 2010. Euro Surveill.
821 2010;15:19710.

822 [103] Brown JE, Scholte E-J, Dik M, et al. *Aedes aegypti* mosquitoes imported into the
823 Netherlands, 2010. Emerg Infect Dis. 2011;17:2335-2337.

824 [104] Schaffner F. Mosquitoes in used tyres in Europe: species list and larval key. Eur Mosq
825 Bull. 2003;16:7-12.

826 [105] European Centre for Disease Prevention and Control. *Aedes atropalpus* – Factsheet
827 for experts. 2014. [cited 2020 June 14]. Available from:
828 https://www.ecdc.europa.eu/en/disease-vectors/facts/mosquito-factsheets/aedes-
829 atropalpus

830 [106] European Centre for Disease Prevention and Control. *Aedes japonicus* – Factsheet for
831 experts. 2014. [cited 2020 June 14]. Available from:

832   https://www.ecdc.europa.eu/en/disease-vectors/facts/mosquito-factsheets/aedes-

833   japonicus

834   [107]   Laird M, Calder L, Thornton RC, et al. Japanese *Aedes albopictus* among four

835   mosquito species reaching New Zealand in used tires. J Am Mosq Control Assoc.

836   1994;10:14-23.

837   [108]   Peyton EL, Campbell SR, Candeletti TM, et al. *Aedes* (*Finlaya*) *japonicus japonicus*

838   (Theobald), a new introduction into the United States. J Am Mosq Control Assoc.

839   1999;15:238-241.

840   [109]   Fonseca DM, Campbell S, Crans WJ, et al. *Aedes* (*Finlaya*) *japonicus* (Diptera:

841   Culicidae), a newly recognized mosquito in the United States: analyses of genetic

842   variation in the United States and putative source populations. J Med Entomol.

843   2001;38:135-146.

844   [110]   Hu Y, Gao M-Z, Huang P, et al. Taxonomic integrative and phylogenetic

845   identification of the first recorded *Triatoma rubrofasciata* in Zhangzhou, Fujian

846   Province and Maoming, Guangdong Province, China. Infect Dis Poverty. 2019;8:70.

847   [111]   Hieu HV, Do LT, Pita S, et al. Biological attributes of the kissing bug *Triatoma*

848   *rubrofasciata* from Vietnam. Parasit Vectors. 2019;12:585.

849   [112]   Patterson JS, Schofield CJ, Dujardin JP, et al. Population morphometric analysis of

850   the tropicopolitan bug *Triatoma rubrofasciata* and relationships with Old World

851   species of *Triatoma*: evidence of New World ancestry. Med Vet Entomol.

852   2001;15:443-451.

853   [113]   Hinz E. Zur Verbreitung und Ausbreitung der Gattung *Tunga* (Siphonaptera:

854   Pulicidae) unter besonderer Berücksichtigung von *T. penetrans*. Mitt Österr Ges

855   Tropenmed Parasitol. 1996;18:173-182.

856   [114]   Hoeppli R. Parasitic diseases in Africa and the western hemisphere: early

857   documentation and transmission by the slave trade. Acta Trop Suppl. 1969;10:1-240.

858   [115]   Heukelbach J. Tungiasis. Rev Inst Med Trop Sao Paulo. 2005;47:307-313.

859   [116]   Lebarbenchon C, Brown SP, Poulin R et. al. Evolution of pathogens in a man-made

860   world. Mol Ecol. 2008;17:475-484.

861   [117]   Rosenthal J. Climate change and the geographic distribution of infectious diseases.
862   Ecohealth. 2009;6:489-495.

863   [118]   Swaminathan A, Viennet E, McMichael AJ, et al. Climate change and the
864   geographical distribution of infectious diseases. In: Peterson E, Chen LH,
865   Schlagenhauf-Lawlor P, editors. Infectious Diseases: A Geographic Guide, Second
866   edition. John Wiley & Son Ltd.; 2017. p. 470-480.

867   [119]   Walsh JF, Molyneux DH, Birley MH. Deforestation: effects on vector-borne disease.
868   Parasitology. 1993;106(Suppl):S55-S75.

869

870 **Table 1.** Information about protozoan parasites spread by human migratory activity.

Name	Life cycle type	Vector	Origin	Current distribution
Plasmodiidae				
Plasmodium falciparum	indirect	*Anopheles* sp.	Western Africa	worldwide but mainly tropical and subtropical
Plasmodium vivax	indirect	*Anopheles* sp.	Central Africa	worldwide between latitudes 16° N and 20° S
Trypanosomatidae				
Leishmania infantum	indirect	*Lutzomyia* sp. *Phlebotomus* sp.	East Africa	Mediterranean region, Middle East, East Africa, China, Latin America
Trypanosoma evansi	indirect	*Tabanus* sp. *Stomoxys* sp.	Western Africa	North Africa, Near and Middle East, Central and South Asia, Latin America
Trypanosoma equiperdum	direct	-	Eastern Africa	Mediterranean region, North and South Africa, Asia, Latin America
Trypanosoma vivax	indirect	*Glossina* sp. *Tabanus* sp.	sub-Saharan Africa	tropical Africa, South America, Caribbean
Trypanosoma brucei	indirect	*Glossina* sp.	sub-Saharan Africa	sub-Saharan Africa
Trypanosoma cruzi	indirect	*Triatoma* sp. *Rhodnius* sp. *Panstrongylus* sp.	South America	South and Central America

871

33

872   **Table 2.** Information about flatworms spread by human migratory activity.

Name	Life cycle type	Intermediate host(s)	Origin	Current distribution
Schistosomatidae				
Schistosoma mansoni	indirect	*Biomphalaria* sp.	East Africa	Africa, Middle East, parts of South America and the Caribbean
Schistosoma haematobium	indirect	*Bulinus* sp. *Physopsis* sp.	East Africa	Africa, Middle East
Fasciolidae				
Fasciola hepatica	indirect	*Lymnea* sp.	Eurasia	worldwide
Fascioloides magna	indirect	*Fossaria* sp. *Stagnicola* sp. *Galba truncatula* *Radix perega*	North America	North America, Europe
Opisthorchiidae				
Opisthorchis viverrini	indirect	1st: *Bithynia* sp. 2nd: Cyprinidae	Southeast Asia	Thailand, Cambodia, Laos
Taenidae				
Taenia solium/cysticercosis*	indirect	pigs	sub-Saharan Africa	worldwide

873   *, in cysticercosis, the transmission of *T. solium* is direct from human to human via ingestion of eggs released by humans infected with the

874   tapeworm, and thus humans are final and intermediate host at the same time.

875

876 **Table 3.** Information about nematodes spread by human migratory activity.

Name	Life cycle type	Intermediate host(s)/vector	Origin	Current distribution
Ancylostomatidae				
Ancylostoma duodenale	direct	-	North African Mediterranean region	worldwide but predominately in the Middle East, North Africa and southern Europe
Necator americanus	direct	-	presumably in Africa	worldwide but predominately in the Americas and Australia
Trichuridae				
Trichuris trichiura	direct	-	presumably in Africa	worldwide but more frequent in tropical areas
Ascariidae				
Ascaris lumbricoides	direct	-	presumably in Africa	worldwide but predominately in tropical and subtropical areas
Strongyloidae				
Strongyloides stercoralis	direct	-	presumably in Africa	worldwide in tropical and subtropical areas
Onchoceridae				
Onchocerca volvulus	indirect	*Simulium* sp.	Africa	Africa, Middle East, Latin America
Filaridae				
Wuchereria bancrofti	indirect	*Aedes* sp. *Culex* sp.	Malay Archipelago	worldwide in tropical areas
Mansonella perstans	indirect	*Culicoides* sp.	most likely in Africa	West and Central Africa, South America
Loa loa	indirect	*Chrysops* sp.	most likely in Africa	West and Central Africa

|				
Dracunculoidea				
Dracunculus medinensis	indirect	*Cyclops* sp.	presumably in Africa	sub-Saharan Africa, Ethiopia, Middle East, India
Metastrongylidae				
Angiostrongylus cantonensis	indirect	snails, slugs, crabs, shrimps	southern Asia	Southeast Asia, Pacific Basin, Africa, Caribbean

877

878 **Table 4.** Information about insects spread by human migratory activity.

| Name	Origin	Current distribution
Culicidae		
Aedes albopictus	Southeast Asia	worldwide
Aedes aegypti	Africa	worldwide in tropical and subtropical regions
Aedes atropalpus	eastern North America	North America, Europe
Aedes japonicus	East Asia	East Asia, North America, Europe, New Zealand
Reduviidae		
Triatoma rubrofasciata	South America or Asia	Americas, Asia, Africa, Oceania
Pulicidae		
Tunga penetrans	South America	Central and South America, sub-Saharan Africa

879
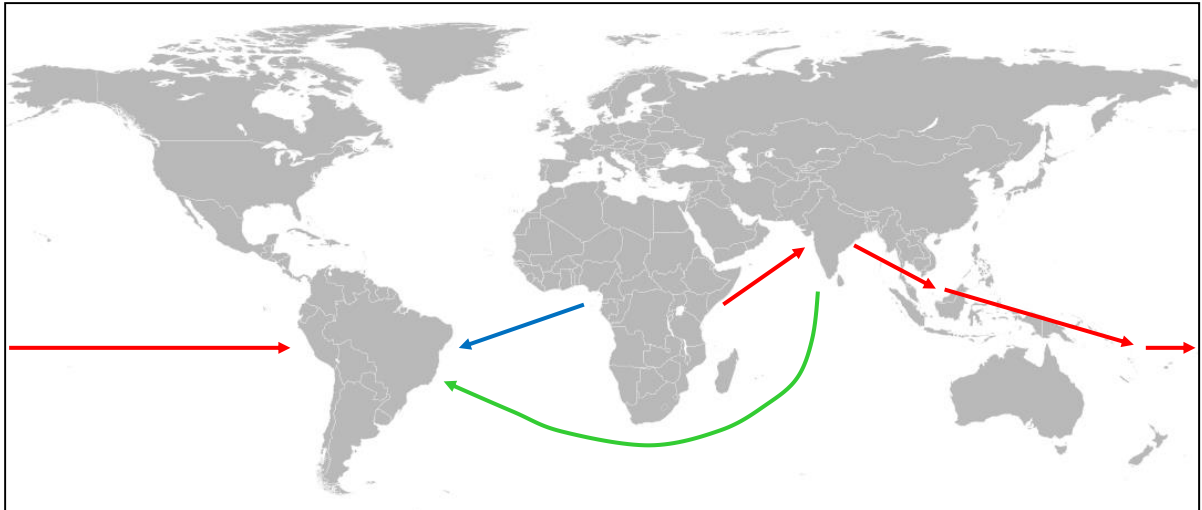
Figure 1. Spreading of *P. vivax*.

New research indicates that *P. vivax* originated in Africa and was spread to Asia and Australasia, from where the parasite was spread to South America in pre-Columbian times (red arrows) [13]. In post-Columbian times, *P. vivax* was introduce into Latin America from West Africa by slaves (blue arrow) and from Asia by migrants (green arrow) [13].
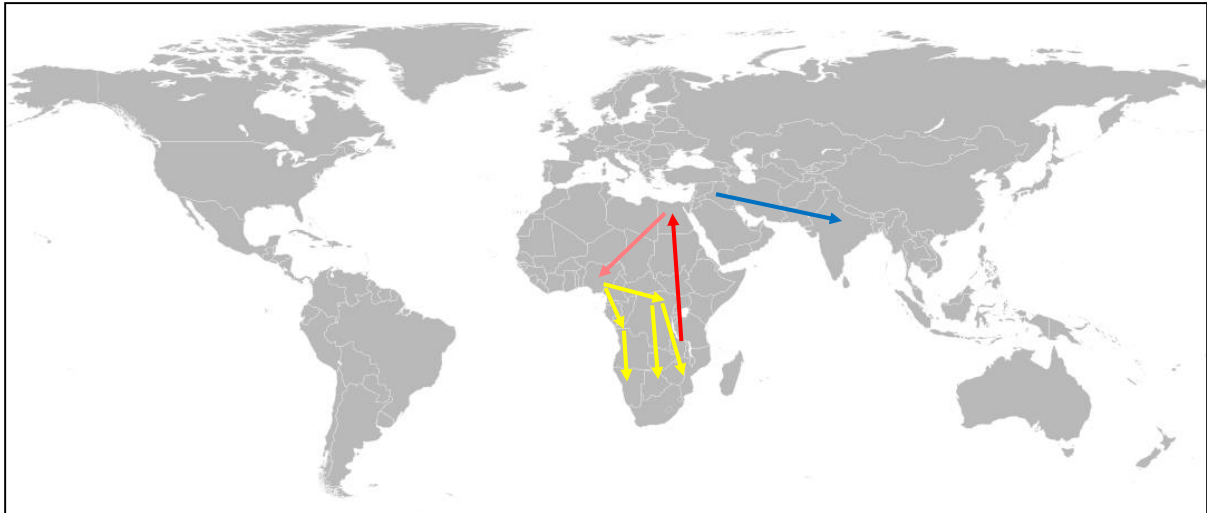
Figure 2. Spreading of schistosomes (*S. mansoni* and *S. haematobium*) and *A. duodenale* by mass migration.

African schistosomes have evolved the region of the African Great Lakes, from where they have been spread along the Nile (red arrow) [44]. It is likely that the schistosomes have been dispersed to West Africa in the course of the Yoruba mass migration (orange arrow) and further to Central and South Africa in the course of the Bantu mass migration (yellow arrows) [45]. Originated in the Mediterranean region, *A. duodenale* has been introduced into North India in the course of the Aryan mass migration (blue arrow) [45].
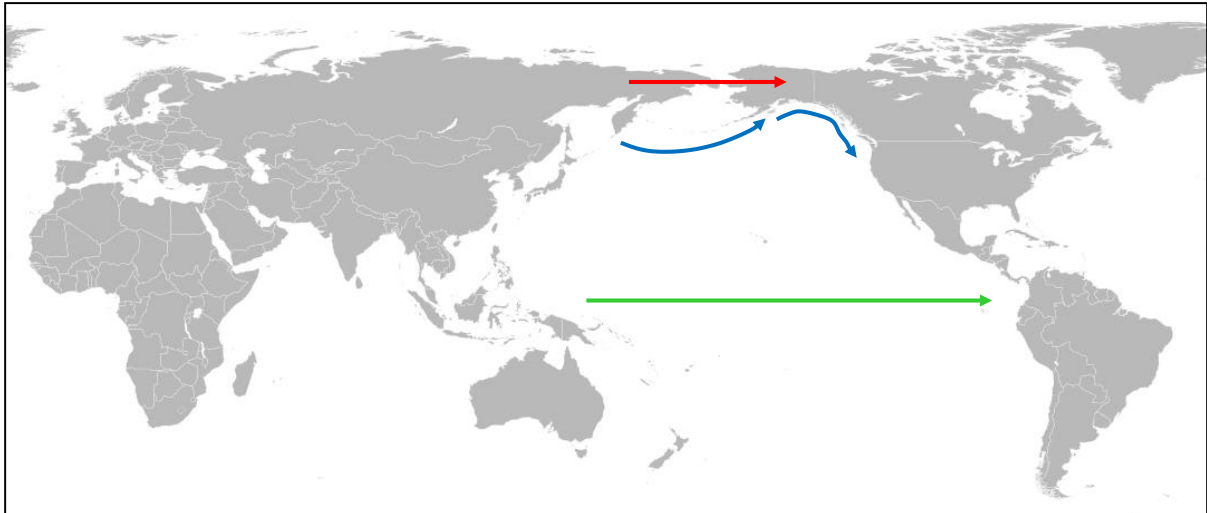
898

899 **Figure 3.** Introduction of soil-transmitted helminths into the Americas.

900 It is unlikely that soil-transmitted helminths (*A. duodenale*, *N. americanus*, *T. trichiura*, *A.*

901 *lumbricoides*, and *S. stercoralis*) have been introduced into the New World by humans

902 migrating through Beringia (red arrow) because the harsh climate conditions of this route

903 would have been detrimental for the development of their free-living life cycle stages [5].

904 Instead, soil-transmitted helminths could have been introduced into the New World via costal

905 migration (blue arrows) and/or trans-pacific migration (green arrow) in pre-historic times [5,

906 61-63].

907
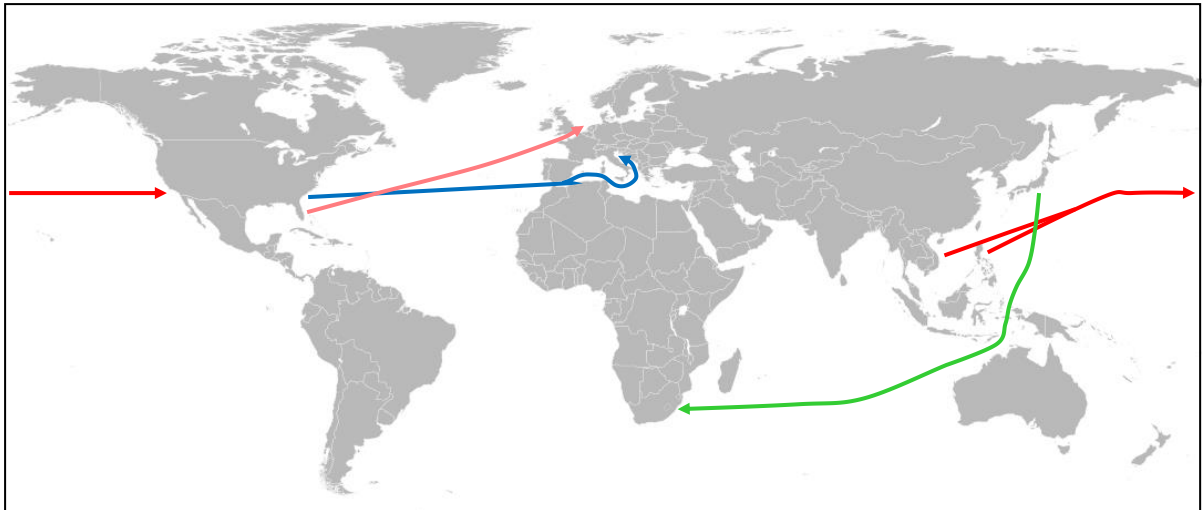
Figure 4. Spreading of *Aedes* sp. via international tyre trade.

The first introduction of *A. albopictus* into the USA (Los Angeles and Oakland in California) could be traced back to a shipment of used car tyres from the Philippines and Vietnam (red arrows) [82]. The establishment of *A. albopictus* in Padua, Italy, could be linked to used car tyres imported from Atlanta, Georgia, USA (blue arrow) [91]. The first reported case of *A. albopictus* in South Africa could be attributed to a consignment of used car tyres from Japan (green arrow) [96]. The introduction of *A. aegypti* into the Netherlands could be tracked to a shipment of tyres from Miami, Florida, USA (orange arrow) [103].