

Chapter 2

Case Study 1: Modelling Potential Transmission Gates of Malaria Tertiana in Lower Saxony

Abstract It is widely assumed that climate change is likely to affect the geographic distribution and intensity of the transmission of vector-borne diseases such as malaria. These diseases are expected to occur, compared with the past and presence, at higher latitudes and altitudes. A slight rise in ambient temperature and precipitation is expected to extend the duration of the season in which mosquito vectors are transmitting the malaria pathogens. The parasites as well usually benefit from increased temperatures, as both their reproduction and development would accelerate. These inter-relationships and respective public discussions gave reason to examine potential effects on the seasonal transmission gate due to the predicted climate changes in Lower Saxony (North-Western Germany). The federal state Lower Saxony was a former endemic malaria region with highest incidences of *Anopheles atroparvus* and tertian malaria along the coastal zones until malaria had finally been eradicated in the early 1950s. However up to now, the malaria vector *Anopheles* is still present. Accordingly, a pilot study should settle whether a new autochthonous transmission could take place if the malaria pathogen is introduced again in Lower Saxony. Thus, the spatial and temporal structure of temperature-driven malaria transmissions was investigated using the basic reproduction rate (R_0) to model the risk for an outbreak of tertian malaria due to measured (1947–1960, 1961–1990, 1985–2004) and predicted (2020, 2060, 2100, each best case and worst case scenario) air temperatures and to geostatistically map the respective risk areas. The risk maps revealed that the gate of potential tertian malaria transmissions in terms of R_0 could be expected to increase from two months in the past to six months in the future in Lower Saxony. Past and recent findings of *A. atroparvus* coincide with those regions where the potential malaria transmission gate accounts for four months in 2060 (best case scenario) and for six months in 2100 (worst case scenario) and, in addition, where tertian malaria occurred up to the 1950s. The estimated maps on malaria risk were intersected with a map on ecological land units, enabling an ecological regionalisation.

Keywords *Anopheles atroparvus* • Basic reproduction rate • Epidemiologic climate change impact • Malaria tertiana • *Plasmodium vivax*

2.1 Background and Goals

Malaria is one of the major causes of global mortality and morbidity even though the aetiology of the disease has been known for many years (Ross 1911). Public health related management of malaria is assumed to be supported by enhanced application of existing knowledge. Modelling approaches could help combining various sources of data regarding different aspects of the disease dynamics and link these aspects with external causes or covariates serving as driving forces or as surrogates for them.

The latest incidences of autochthonous malaria in Germany were reported in the early 1950s (Weyer 1956). However, in the face of current climate change, research on vector-borne diseases and investigations on the population density and distribution of *Anopheles* were conducted in some European countries (Eritja et al. 2000; Kubica-Biernat 1999; Romi et al. 1997; Schaffner 1998). For Germany only poor data sets were available (Maier et al. 2003). This gap together with the rise of air temperatures and the correlated ecological changes as indicated by, e.g., plant phenology throughout Germany (Schröder et al. 2005) gave reason to investigate whether the former malaria region Lower Saxony could be at risk of a new outbreak and to what extent higher temperatures could prolong the potential transmission gate of the tertian malaria pathogen.

2.2 Methods

2.2.1 Literature Research on Malaria Transmission

The estimation of the geographical patterns for the incidence of malaria vectors presumes that their correlation with habitat characteristics and their life stages can be quantitatively described. To this end literature research was conducted. The following information was initially researched and used for the GIS-based risk modelling of a climate warming induced malaria tertiana outbreak in Lower Saxony. Later on, the same methodology was applied to the German-wide investigation, too (Sect. 2.3).

Approximately 3,500 species of mosquitoes grouped into 41 genera are known and about 30–40 of about 430 *Anopheles* species transmit malaria. From these, six species could be identified in Germany. Females of the genus *Anopheles* (Diptera, Culicidae) transmit tertian malaria (Ramsdale and Snow 2000). In Lower Saxony, *A. atroparvus* was dominantly associated with malaria cases (Hackett and Missiroli 1935; Martini 1920a, b; Weyer 1940). In this study, all historical *Anopheles* findings and malaria cases documented in literature were localised and mapped in a GIS. They were supplemented by *Anopheles* findings since 1985 documented in the digital so-called BOG-archive (Biologische Oberflächengewässer) held by the Lower Saxony Authority for Environmental Affairs (Schröder et al. 2007) or published by Wilke et al. (2006) (Sect. 2.2.2).

Apart from several factors that affect the aquatic juvenile stages of *A. atroparvus*, one of the main driving forces for development is air temperature. Jetten and Takken (1994) compiled data on the required time for development and related temperature values: the lower development threshold, the optimum temperature, and the upper limit above which no further progress is possible. This information was essential for the identification of areas at risk. As mainly climate conditions influence the development of the Anophelinae, the number of generations growing in one season varies spatially. Martini (1946) estimated 5–7 generations as an average value for Central Italy, 2–4 generations for Southern Germany and 2–3 for Northern Germany (Heinz 1950). In the summer of 1947 showing unusually high temperatures in north-western Germany, the growing of up to 5 generations could have been possible (Heinz 1950).

Malaria is caused by infection with an intracellular protozoan parasite of the genus *Plasmodium*. Human beings are commonly infected by *P. falciparum*, *P. vivax*, *P. ovale*, or *P. malariae*. Their development in the vector mosquito is predominantly influenced by temperature. *P. vivax* causes tertian malaria, which was dominant in north-western Germany (Mühlens 1930). A recently infected mosquito needs a period of at least 105 days at 14.5 °C, the lower thermal threshold for the development of *Plasmodium* in mosquitoes, to get infectious. This period may be interrupted by some colder days (Jetten and Takken 1994). Concerning both case studies, the identification of the high-risk areas was performed by data referring to *P. vivax* given by Jetten and Takken (1994).

2.2.2 Data Compilation in a Geographic Information System

Data processing and risk assessment were based on data compiled from several sources and integrated into a Geographic Information System (GIS): From literature, information on historical *Anopheles* findings were collected (Sect. 2.2.1). These included information on the taxonomy of the respective species, the name of the locality, the Gauß-Krüger (transverse Mercator projection) coordinates and the literature source, respectively. Referring to the recent (since 1985) findings of the Lower Saxony Authority for Environmental Affairs documented in the “BOG-Archiv”, the same metadata were collected and supplemented with additional details about the name of the water body and the date the *Anopheles* larvae were found.

Air temperature data from 54 observation sites in Lower Saxony were provided by the German Weather Survey in terms of diurnal extreme values that were aggregated to monthly means of air temperature. Taking into account that in temperate climatic zones such as Northern Germany a successful transmission of the malaria pathogen is only possible in the warmest months of the year, this study focusses on the period from June to August for past and present analyses. September and May were not included for processing the past periods because the low average temperatures did not allow pathogen transmission. According to the predicted global warming, the calculations for future trends were also performed

for these two months and, additionally, October. For data processing, several data sets were generated which list the monthly means of temperature of June, July or August, respectively, of the following periods: 1947–1960, 1961–1990 and 1985–2004. The beginning of the latter period was set to 1985 instead of 1991 because the BOG-Archiv starts with respective findings of Anophelinae larvae in 1985. By this, a complete temporal link between the data on both, the air temperatures and the findings of potential vectors, was assured.

The site-specific meteorological data were geostatistically transformed to surface data (Sect. 2.2.3) and spatially differentiated in terms of ecologically defined land units (Sect. 2.2.4). The geostatistical surface estimations enabled the spatial link of the air temperature data with the Anopheles findings and associated malaria incidences until the early 1950s and with the Anopheles findings documented in the literature and the BOG-archive since 1985 (Sect. 2.2.1).

2.2.3 Geostatistical Estimation of Temperature Maps

Since the measurement data from the 54 meteorological observation sites (1947–1960, 1961–1990, 1985–2004) did not match spatially with both the Anopheles findings and the malaria cases, we used the geostatistical tool FUZZ-EKS (Bartels 1997; Piotrowski et al. 1996) to derive maps on air temperature conditions in Lower Saxony for the different periods of investigation. Geostatistics enable to analyse and model the spatial autocorrelation of biological, chemical and physical measurements, and, based on this variographic modelling, to calculate surface estimations by spatially weighted kriging interpolation (Webster and Oliver 2001). The quality of the estimation was proved by cross-validation: Each measurement was sequentially extracted from the sample and was then estimated by kriging according to the variographic model. The differences between measured and geostatistically estimated values were then statistically investigated yielding good results. This approach enables to correlate spatially incongruent data, such as air temperature measurements, Anopheles findings, malaria cases, and data on landscape characteristics from a map on ecological landclasses (Sect. 2.2.4).

In addition, projected monthly air temperature means (IPCC 2001) for the years 2020, 2060 and 2100 were calculated in the GIS environment. For each of these years, two different climate predictions were used: the “best case (b.c.)” represents the lowest predicted temperature values, the “worst case (w.c.)”, by contrast, reflects the highest possible temperature values calculated in the 35 climate scenarios published by IPCC (2001): 2020 b.c. +0.3 °C, w.c. +0.9 °C; 2060 b.c. +0.9 °C, w.c. +3.3 °C; 2100 b.c. +1.4 °C, w.c. +5.8 °C). For each period and scenario, the predicted values were added to the temperature grid of the period 1985–2004 to get according maps for 2020, 2060, and 2100, one indicating the best and one another indicating the worst case scenario. These projected air temperature data as well as the measured values covering the years 1947–2004 were used as input for the calculation of the basic reproduction rate R_0 (Sect. 2.2.5).

2.2.4 Ecological Land Classification

Ecological land classifications were computed based on data which represent several interacting factors which may be of importance for natural processes such as the transmission of malaria. Hence, consideration of maps depicting the spatial structure of complex interacting ecological factors for the modelling of potential malaria transmission covers at least partly the requirements postulated by Reiter (2008). The ecological land classification used in both case studies was calculated from the data in Table 2.1 applying Classification and Regression Trees (CART; Breiman et al. 1984). The respective computations yielded maps (Fig. 2.1) illustrating the spatial patterns of georeferenced ecologically defined land classes which synonymously are called natural land classes, ecoregions or landscapes (Schmidt 2002; Schröder 2006; Schröder et al. 2006). All ecoregions are itemised with regard to the values or the statistical distribution of values of 48 ecological characteristics which were used to generate the land classes by use of CART (Schröder and Schmidt 2001).

Table 2.1 Data used for ecological land classification (according to Schröder and Schmidt 2008)

Map title	Observation period/State	GIS layer	Source
Potential natural vegetation	1998	1	BfN
Soil texture	2000	1	BGR
Altitude above sea level	1996	1	UNEP
Mean of monthly global radiation March–November	1981–1999	9	DWD
Mean of monthly evaporation January–December	1961–1990	12	DWD
Mean of monthly precipitation January–December	1961–1990	12	DWD
Mean of monthly air temperature January–December	1961–1990	12	DWD

BfN Federal Agency for Nature Conservation, *BGR* Federal Institute for Geosciences and Natural Resources, *GIS* Geographical Information System, *UNEP* United Nations Environmental Programme, *DWD* German National Meteorological Service

2.2.5 Calculation of the Basic Reproduction Rate (R_0)

The geostatistically calculated surface air temperature maps were used for GIS-based risk modelling of a climate warming induced outbreak of malaria tertiana in Lower Saxony. Traditional approaches measuring whether malaria transmission has the potential for epidemics have focused on the bio-mathematical relationships between the parasite and its primary host, the mosquito (Smith and McKenzie 2004). These relationships have been quantified, e.g., as the stability index, basic reproduction rate and vectorial capacity (Snow et al. 1999). In the investigation at hand, the basic reproduction rate (R_0) was used to analyse whether areas at risk for

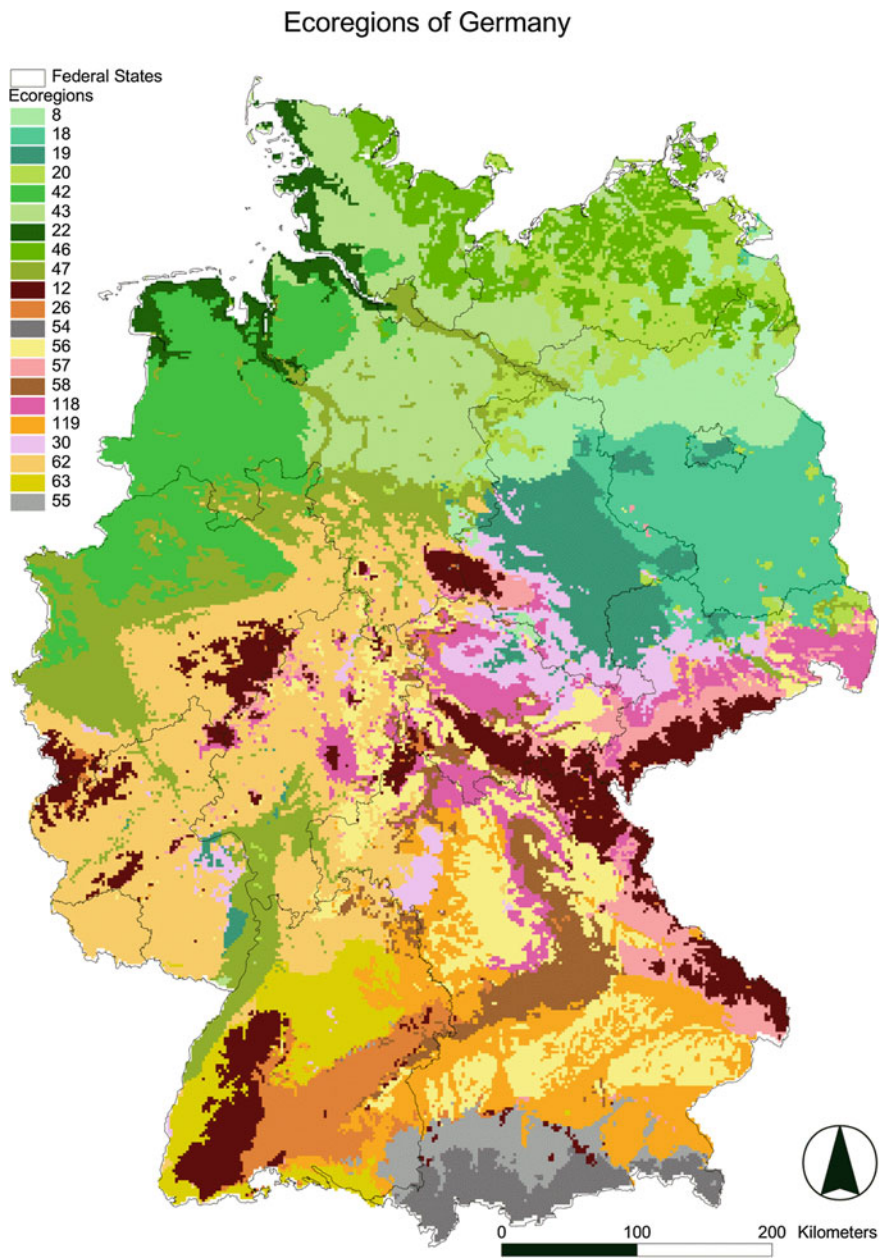


Fig. 2.1 Eco-regions of Germany calculated by CART (Classification and regression trees) from the data in Table 2.1 (according to Schröder and Schmidt 2001)

an outbreak of malaria tertiana can be found in Lower Saxony due to its temperature conditions. Considering the malaria protozoon, R_0 could be more precisely defined as the average number of secondary infections occurring when a single infected individual is introduced into a potential host population in which each member is susceptible. If $R_0 \geq 1$, the disease will proliferate indefinitely, if $R_0 < 1$, the disease will die out (Martens et al. 1999: 92). The original formula was altered and specified over the years by several authors, but its function remains the same. The R_0 -formula used for this analysis is shown and explained below:

$$\frac{m \cdot a^2 \cdot b \cdot p^n}{-\ln(p) \cdot r}$$

m	relative density of female Anophelines
a	frequency of feeding on a person, expressed as a daily rate
$m \cdot a$	number of bites per person per day (product was set to 1, Lindsay and Thomas 2001: 81)
a	h/u
h	proportion of mosquito blood meals taken from people instead of other animals, also expressed as HBI (the model assumes a mean value for h of 0.42 for indoor-resting mosquitoes, Jetten and Takken 1994: 50)
u	length in days of the gonotrophic cycle (interval between each mosquito's blood meal and oviposition)
u	$f_1/(T - g_1)$
f_1	thermal sum, measured in degree days (36.5 at threshold of 9.9 °C, Jetten and Takken 1994: 36)
T	average ambient temperature
g_1	threshold below which development ceases (9.9 °C, Jetten and Takken 1994: 36)
b	proportion of female mosquitoes developing parasites after taking an infected blood meal (as no value could be found in literature for German <i>Anopheles</i> mosquitoes, a mean value was calculated out of records from England and the Netherlands. Thus, the assumed value for Germany is 0.14)
p	daily survival probability of an adult female mosquito (the model considers a median value of mortality rate for <i>Anopheles atroparvus</i> = 0.029/day, $p = 0.97$ /day, Jetten and Takken 1994: 42)
n	period of parasite development within the adult female mosquitoes in days: sporogonic cycle
n	$f_2/(T - g_2)$
f_2	thermal sum, measured in degree days (105 at threshold of 14.5 °C, Jetten and Takken 1994: 46)
T	average air temperature
g_2	minimum temperature required for parasite development (14.5 °C, Jetten and Takken 1994: 46)

r rate of recovery of humans from infection from malaria (the usual assumption is that the duration of each infection is therefore $1/r$ days. According to Lindsay and Thomas (2001: 81), it is assumed that an infection would be present for 60 days, resulting in a value for $1/r$ of 0.0167/day)

The application of the basic reproduction rate formula to the monthly mean temperature maps (Sect. 2.2.3) enabled detecting potential areas at risk for a tertian malaria outbreak in Lower Saxony. The resulting maps depict areas with different transmission periods where tertian malaria could be spread under past, present and future climate conditions. These operations were performed with the help of the tool Map Query included in the GIS software ArcView 3.3 distributed by ESRI.

Concerning the prediction maps about areas at risk in future (2020, 2060, 2100), the same approach was used. To the air temperature grid averaged for the period 1985–2004 the according projected air temperature rise (Sect. 2.2.3) was added for each map pixel. For each of the future years, two different climate change models were used: the “best case” represents the lowest predicted temperature values, the “worst case”, by contrast, reflects the highest possible temperature values calculated in the 35 IPCC climate scenarios mentioned above.

2.3 Results

2.3.1 *Potential Transmission Gates Calculated with Temperature Measurements*

The calculations yielded maps on areas at risk of malaria outbreak and maps on the duration of the potential transmission periods of the tertian malaria pathogen due to past, recent and future monthly mean air temperatures. The following sections focus on the potential transmission gates calculated for the periods from 1947 to 1960, 1961 to 1990 and 1985 to 2004 as well as for the projected temperatures in 2020, 2060 and 2100 (Table 2.2).

1947–1960

From 1947 to 1960 in most of the area of Lower Saxony *Anopheles* mosquitoes can successfully transmit malaria for two month (coverage 81.6 %). The regions for a three months’ spread are by far smaller (16.2 %), but still larger than those of one month or of no transmission. The longest period of transmission can be found in the loess belt in the far south of Lower Saxony (Fig. 2.2, left). Smaller spots can be found along the river Elbe and the far southwest (city of Lingen). Due to comparable colder weather conditions, the least possible transmission duration (0–1 month) can be found in the low mountain ranges in the South. The map also shows those locations where Malaria infections and *Anopheles* findings were

Table 2.2 Number of months of potential malaria transmission expressed in coverage percentage of the investigation area (Lower Saxony) for different climatic periods in past and future (according to Schröder et al. 2007)

No. of months	0	1	2	3	4	5	6	Sum (%)
Period (projected temperature rise)								
1947–1960	0.9	1.3	81.6	16.2	0.0	0.0	0.0	100.0
1961–1990	2.3	0.9	74.8	21.9	0.0	0.0	0.0	100.0
1985–2004	0.5	0.1	74.4	25.1	0.0	0.0	0.0	100.0
2020 (+0.3 °C)	0.1	0.1	49.9	49.9	0.0	0.0	0.0	100.0
2020 (+0.9 °C)	0.0	0.0	6.0	93.9	0.1	0.0	0.0	100.0
2060 (+0.9 °C)	0.0	0.0	6.0	93.9	0.1	0.0	0.0	100.0
2060 (+3.3 °C)	0.0	0.0	0.0	1.3	4.0	94.7	0.0	100.0
2100 (+1.4 °C)	0.0	0.0	1.9	76.5	21.6	0.0	0.0	100.0
2100 (+5.8 °C)	0.0	0.0	0.0	0.0	0.0	43.9	56.1	100.0

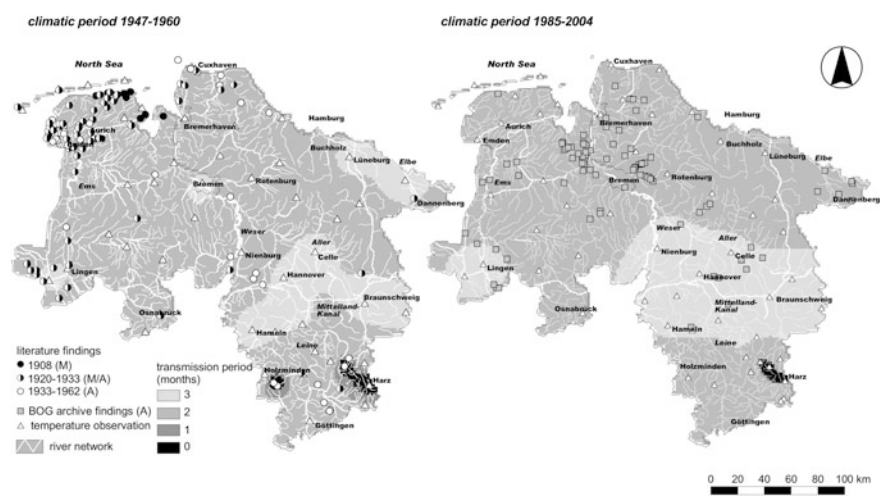


Fig. 2.2 Potential transmission gates of the tertian malaria pathogen for 1947–1960 and 1985–2004 in Lower Saxony (*M* Malaria incidences, *A* *Anopheles* findings) (according to Schröder et al. 2007)

documented in literature (black/white circles). The main localities can be found at the coastal lowlands south of the North Sea.

1961–1990

From 1961 to 1990, the transmission map reveals a maximum duration of three months for infection, too (coverage 21.9 %). Nevertheless, the predominant transmission duration is two months (74.8 %). Areas where no transmission is possible can be found in the mountain range in the far southeast of Lower Saxony. The districts with a potential *Plasmodium vivax* spread of three months are distributed nearly identically as in the previous period but the spots now become larger.

1985–2004

From 1985 to 2004, the monthly transmission map (Fig. 2.2, right) shows just one very small area where no transmission is possible (Harz Mountains). Most of Lower Saxony is again dominated by a transmission period of two months (74.4 %). Three months areas are located in the centre and again in the south-westmost part of Lower Saxony (25.1 %). The bigger one is a broad belt along the waterway Mittellandkanal that runs from east to west touching the city of Hanover. The second and also smaller spot can be found again in the southwest with the city of Lingen in its centre. The map also shows those locations where *Anopheles* findings were documented in the BOG-Archiv (Sect. 2.2.1) from the early 1980s (grey squares). The main localities can be found at the rivers in the northern third of Lower Saxony.

2.3.2 *Potential Transmission Gates Calculated with Estimations of Future Temperatures*

The future transmission periods are calculated by the combination of the geostatistically computed temperature maps and selected IPCC climate scenarios. Accordingly, the best case would be the lowest expected temperature rise for the respective year, the worst case the highest prospected temperature rise.

Year 2020

The best case scenario 2020 was based on a predicted climate warming of 0.3 °C. The areas where no transmission of tertian malaria is possible together with the areas of one month duration represent less than one percentage of Lower Saxony (Fig. 2.3, left). The rest of the federal state refers equally to transmission areas of two and three months. While the first is located in the northern and southern parts, the second is a central broad belt from the west to the east of Lower Saxony.

In the worst case expecting an air temperature rise of 0.9 °C, for the first time the disease might be transmitted for four months (0.1 %). Also for the first time, whole Lower Saxony is a potential transmission country without any exception, regions with a potential transmission gate of three months are most frequent (coverage 93.9 %). Only four regions (6.0 %) remain, representing zones with a transmission period of two months (low mountain range in the far south and spots near the cities of Hamburg and Aurich in the north).

Year 2060

The best case-prediction 2060 is exactly the same as the 2020 worst case, i.e. the temperature rise is expected to be 0.9 °C. The IPCC presumes a worst case temperature rise of 3.3 °C. Thus, the transmission map of that year reveals that Lower Saxony is almost totally situated with five months of transmission

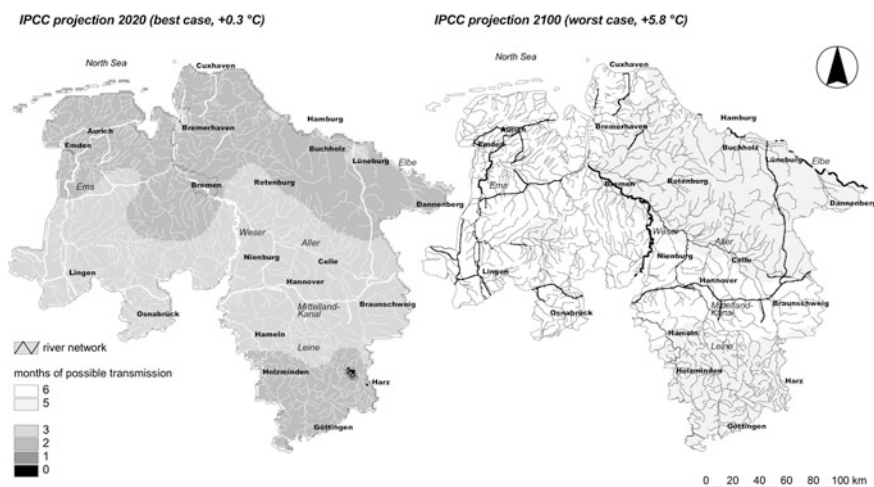


Fig. 2.3 Potential transmission gates of the tertian malaria pathogen projected for 2020, best case ($T + 0.3\text{ }^{\circ}\text{C}$), and 2100, worst case ($T + 5.8\text{ }^{\circ}\text{C}$) in Lower Saxony (according to Schmidt et al. 2008)

(coverage 94.7 %). Again, only the highlands in the far south and the coastal zone in the north make an exception in duration (3–4 months).

Year 2100

The best case scenario estimates a minimum climate warming of $1.4\text{ }^{\circ}\text{C}$ and includes September as the fourth month of a successful transmission of malaria. The main transmission period is three months (coverage 76.5 %). Regions with four months of transmission (21.6 %) are located in a broad belt along the waterway Mittellandkanal in the south and around the city of Lingen in the southwest most part of Lower Saxony. Now, also coastal areas at the North Sea are included and tidal mud flat islands, too. The worst case calculation is based on a temperature rise of $+5.8\text{ }^{\circ}\text{C}$ (Fig. 2.3, right). Given this, Lower Saxony is divided into two parts of transmission length: The western part reveals a predicted transmission period of six months (coverage 56.1 %). These areas represent those regions which are usually warmer in comparison to the rest of the country. A disease spread of five months (43.9 %) can be found within the rectangle of the river Weser in the northwest and the waterway Mittellandkanal in the south. Another area covers the low mountain range in the south most part of Lower Saxony.

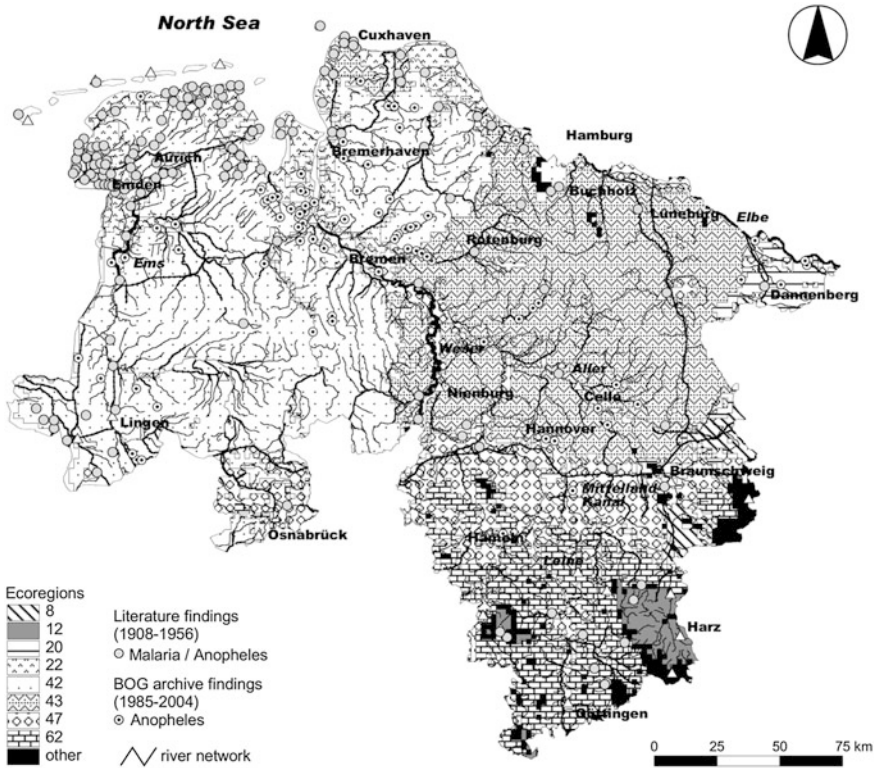


Fig. 2.4 Ecoregions of Lower Saxony calculated by CART (Classification and regression trees) from the data in Table 2.1 and briefly described in Table 2.3 (according to Schröder and Schmidt 2008)

2.3.3 Ecoregionalised Transmission Gates

The ecological land classification calculated on the data described in Table 2.1 by use of Classification and regression trees (CART; Breiman et al. 1984) yielded a hierarchy of maps differentiating Germany by an according number of ecoregions. Using the map with 21 ecologically defined regions in Germany (Fig. 2.1), 8 of them are located in Lower Saxony, each of the them covering more than 1 % of Lower Saxony's territory each (Fig. 2.4) (Schröder 2006; Schröder et al. 2006). Each of these ecoregions is detailed by descriptive statistics of selected characteristics such as climate, soil texture, altitude above sea level, and Potential natural vegetation (PNV), giving a portrayal of the natural floristic biodiversity and indicating areas with similar site properties and natural growth properties (Bohn et al. 2000/2003) (Table 2.3).

Table 2.3 Relevant characteristics of the ecoregions of Lower Saxony (according to Schröder and Schmidt 2008)

Landscape characteristics		Ecoregions ¹							
		12	20	22	42	43	47	62	8
PNV ²	Frequency (Germany) (%)	6.3	3.8	1.6	7.3	7.2	8.1	14.0	4.1
		F60	F71	U21	F5	F52	F68	F55	F54
		F59	F68		F52	F5	U7	F70	U19
		F61	F52		F53		F52		F68
		F56					F23		F52
Soil texture ³		Loamy sand, gritty	Loamy sand, loam	Sandy clay silt	Sand, loamy sand	Sand, silty sand	Clay silt to silty loam	Sandy clay loam	Loamy sand, loam
		Sandy clay, loam	Sand, silty sand		Peat	Loamy sand, loam	Clayey silt to loamy clay	Sand to silty loam	Sand, loamy sand
		Sand to silty loam	Sand, loamy sand		Loamy sand, loam	Sand, loamy sand	Loamy sand, silty loam	Clay silt to silty loam	Peat
			Peat		Sand, silty sand	Peat			Sand, silty sand
Altitude above sea level (m)	Min	158.0	0.0	0.0	0.0	0.0	0.0	156.0	0.0
	Med	598.0	50.0	2.0	35.0	38.0	90.0	282.0	45.0
	Max	1414.0	155.0	20.0	154.0	155.0	155.0	673.0	152.0
Global radiation (Wh/month)	Min	65.0	62.9	59.0	61.6	58.0	61.6	61.4	61.8
	Med	334.4	335.3	326.7	327.3	328.7	330.4	333.2	334.9
	Max	554.8	566.7	533.3	516.7	553.3	554.8	558.1	556.7
Precipitation (mm/month)	Min	37.8	22.0	32.3	37.8	28.3	27.3	30.8	24.75
	Med	87.9	48.3	65.8	63.4	59.0	60.9	68.4	45.6
	Max	214.5	83.0	104.0	98.5	107.8	140.2	172.0	78.3
Evaporation rate (mm/month)	Min	6.0	5.0	5.0	6.0	5.0	6.0	8.0	5.0
	Med	40.5	48.0	44.9	46.5	46.7	48.0	47.1	49.0
	Max	91.0	104.0	92.0	91.8	106.0	107.0	108.5	99.0

(continued)

Table 2.3 (continued)

Landscape characteristics		Ecoregions ¹							
		12	20	22	42	43	47	62	8
Air temperature (°C/ month)	Min	-5.0	-1.6	0.2	-0.2	-1.2	-1.4	-0.7	-1.5
	Med	6.5	8.2	8.6	8.9	8.4	9.3	8.3	8.5
	Max	17.7	17.7	17.3	18.4	19.3	19.7	19.5	18.7

¹ Covering at least 1 % of the territory
² Contributing at least 10 % to the respective ecoregion, after Bohn et al. (2000/2003), see Annex Table 2.3
³ Contributing at least 10 % to the respective ecoregion
Min Minimum, *Med* Median, *Max* Maximum

Annex Table 2.3

Code	Potential natural vegetation according to Bohn et al. (2000/2003)
F 5	East Armorican thermophilous oak forests (<i>Quercus petraea</i> , <i>Q. robur</i> , locally <i>Quercus pyrenaica</i>) of the Loire-basin with <i>Peucedanum gallicum</i> , <i>Festuca heterophylla</i> , <i>Luzula forsteri</i> , <i>Erica scoparia</i>
F 23	Galician-north Lusitanian oak forests (<i>Quercus robur</i> , <i>Q. pyrenaica</i>) with <i>Betula pubescens</i> subsp. <i>celtibérica</i> , <i>Cytisus striatus</i> , <i>Dryopteris aemula</i> , <i>Anemone trifolia</i> subsp. <i>albida</i> , <i>Omphalodes nitida</i>
F 52	South subatlantic sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i>), rich in thermophilous species, alternating with thermophilous mixed beech and oak forests (<i>Fagus sylvatica</i> , <i>Quercus petraea</i> , <i>Ulmus minor</i> , <i>Carpinus betulus</i> , <i>Tilia cordata</i> , partly <i>Quercus pubescens</i>)
F 53	South subatlantic thermophilous sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i>) with <i>Quercus pubescens</i> , partly with <i>Buxus sempervirens</i>
F 54	Sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i>) on siliceous soils with <i>Castanea sativa</i> in the west Alps
F 55	Central European sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i>), mostly with <i>Fagus sylvatica</i> , with <i>Sorbus torminalis</i> , <i>Carex montana</i> , <i>Hepatica nobilis</i>
F 56	Pre-Sudeten sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i> , <i>Q. robur</i>), mostly with <i>Fagus sylvatica</i> , submontane type with <i>Senecio ovatus</i> , <i>Prenanthes purpurea</i> , partly <i>Carex brizoides</i>
F 59	Northwest Pannonian thermophilous oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i> , <i>Q. robur</i>) with <i>Primula veris</i> , <i>Carex michelii</i> , <i>Pulmonaria mollis</i>
F 60	Transsylvanian sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i>) with <i>Lathyrus hallersteinii</i>
F 61	Northeast pre-Carpathian sessile oak-hornbeam forests (<i>Carpinus betulus</i> , <i>Quercus petraea</i> , <i>Q. robur</i>) with <i>Fagus sylvatica</i> , with <i>Aposeris foetida</i>
F 68	East Moesian-west Pontic mixed sessile oak-hornbeam-silver lime forests (<i>Tilia tomentosa</i> , <i>Carpinus betulus</i> , <i>Quercus petraea</i> , <i>Q. dalechampii</i> , <i>Q. polycarpa</i>), partly with <i>Carpinus orientalis</i> , with <i>Nectaroscordum siculum</i> subsp. <i>bulgaricum</i>
F 70	Baltic-south Sarmatian lime-pedunculate oak forests (<i>Quercus robur</i> , <i>Tilia cordata</i>), partly with <i>Picea abies</i>
F 71	North Ukrainian-south Sarmatian lime-pedunculate oak forests (<i>Quercus robur</i> , <i>Tilia cordata</i>) with <i>Fraxinus excelsior</i> , <i>Acer campestre</i> , <i>A. tataricum</i>
U 7	Irish-British hardwood alluvial forests (<i>Quercus robur</i> , <i>Fraxinus excelsior</i> , <i>Salix atrocinerea</i>) in combination with willow alluvial forests (<i>Salix fragilis</i> , <i>S. alba</i> , <i>S. viminalis</i>)
U 19	Danubian hardwood alluvial forests (<i>Fraxinus angustifolia</i> subsp. <i>danubialis</i> , <i>F. pallisae</i> , <i>Quercus robur</i> , <i>Q. pedunculiflora</i> , <i>Ulmus minor</i>) in combination with poplar and willow alluvial forests (<i>Populus alba</i> , <i>P. nigra</i> , <i>Salix alba</i>)
U 21	Caucasian hardwood alluvial forests (<i>Quercus robur</i> , <i>Ulmus minor</i>) in combination with poplar and willow alluvial forests (<i>Populus x canescens</i> , <i>P. alba</i> , <i>Salix alba</i>) and willow scrub (<i>Salix triandra</i>)

The geostatistical estimation resulted in air temperature maps (Sect. 2.2.3) which were used for the application of the R_0 formula. In result, maps on areas at risk of malaria outbreak as well as maps on the length of the transmission gates of

the tertian malaria pathogen were derived considering recent (Sect. 2.3.1) and future monthly mean air temperatures (Sect. 2.3.2). In a next step, each of the risk maps was spatially differentiated in terms of natural landscapes by intersection with the map on ecoregions in a GIS (Sect. 2.2.4). Those ecoregions covering more than 1 % of Lower Saxony’s territory are described in Table 2.3 with regard to those landscape characteristics which were used for ecoregionalisation (Table 2.1). The following paragraphs focus on the seasonal transmission gates within these ecoregions considering the periods 1947–1960, 1961–1990, and 1985–2004 as well as the projected future development in 2020, 2060 and 2100 (Tables 2.4–2.11).

From 1947 to 1960, areas with potential malaria transmission over two months per year cover 81.7 % of the territory of Lower Saxony. A three-month transmission gate would have been possible on 16.1 % of the land area. These two transmission regions are mainly distributed in ecoregions (ER) 42, 43 (North German coastal heath land), and 47 (Table 2.4). The remaining area is situated by a seasonal transmission gate of only one month or no transmission is possible. The longest seasonal transmission gate can be found in the loess belt in the far south of Lower Saxony (ER 47) with mean annual air temperatures of 9.3 °C. Smaller spots can be found along the river Elbe and the far south-west (ER 43). Due to cold weather conditions (mean annual temperatures 6.5–8.3 °C), the least possible annual transmission gate (0–1 month) can be found in the low mountain ranges in the south (ER 12 and ER 62) with average altitudes between 282 m and 598 m above sea level (see Table 2.3).

From 1961 to 1990, malaria transmission would have been possible over three months (21.8 %), whereas the predominant annual transmission period accounts for two months (74.9 %) (Table 2.5). Again, areas where no transmission was possible could be found in the mountain range in the far south-east of Lower Saxony (ER 12 and ER 62). The regions with a possible *P. vivax* spread of three months were almost identical to those in the previous period but the spots became larger.

From 1985 to 2004, just one very small area could be identified where no transmission was possible (ER 12, Harz Mountains) (Table 2.6). The rest of

Table 2.4 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 1947–1960 (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
0	81.1	0.0	0.0	0.0	0.0	0.0	3.6	0.0	0.9
1	46.2	0.0	0.0	0.0	0.0	0.6	26.3	0.0	1.3
2	0.2	1.3	8.4	41.9	24.6	11.8	8.4	0.9	81.7
3	0.0	6.2	0.9	5.8	39.4	32.6	7.1	3.2	16.1
Total 1947–1960	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Table 2.5 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 1961–1990 (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
0	50.5	0.0	0.0	0.0	0.0	7.3	21.8	0.0	2.3
1	14.0	0.0	0.0	7.9	3.5	7.9	38.6	0.0	1.0
2	0.2	0.9	9.3	43.9	22.4	12.2	8.0	0.4	74.9
3	0.0	6.4	0.0	10.1	44.3	25.3	6.9	4.4	21.8
Total 1961–1990	1.5	2.1	7.0	35.2	26.5	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Table 2.6 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 1985–2004 (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
0	98.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
1	92.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
2	1.3	1.8	9.4	42.8	24.5	8.2	8.6	0.2	74.5
3	0.0	2.8	0.0	13.0	32.9	35.3	7.7	4.7	25.0
Total 1985–2004	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Lower Saxony was characterised by a potential transmission gate of two months (74.5 %). Areas with a three month transmission potential are located in the middle and in the south-western part of Lower Saxony (25 %) (ER 43 and ER 47).

The *best case scenario* 2020 is based on a predicted temperature increase of about 0.3 °C when compared to the reference period 1961–1990. The areas where no transmission of tertian malaria would be possible together with the areas of one month transmission represent less than 1 % of the territory of Lower Saxony (Table 2.7). The remainder of the country was divided equally in transmission gates of two and three months. While the former was located in the northern and southern parts, the latter formed a central broad belt from western to eastern Lower Saxony.

In the 2020 *worst case scenario*, expecting an average air temperature rise of 0.9 °C referred to the reference period 1961–1990, malaria might be transmittable for four months (0.1 % of the land area) for the first time (Table 2.8). Additionally, in the whole territory of Lower Saxony, transmission was expected to be possible and a transmission gate of three months prevails (93.9 %). Only four ecoregions (6.0 %) may remain, representing zones with a transmission gate of two months (the low mountain range in the south, ER 12 and ER 62, and spots in the north, ER 42 and ER 43).

Table 2.7 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 2020 best case (b.c.) (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
1	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
2	2.5	2.6	13.4	36.4	23.9	6.4	10.4	0.2	50.1
3	0.0	1.6	0.5	34.1	29.2	23.6	6.3	2.4	49.7
Total 2020 b.c.	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Table 2.8 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 2020 worst case (w.c.)/2060 best case (b.c.) (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
2	24.0	0.0	6.6	12.9	14.3	3.8	24.2	0.0	6.0
3	0.1	2.2	7.0	36.6	27.2	15.6	7.4	1.4	93.9
Total 2020 w.c./2060 b.c.	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

The 2060 *best case scenario* equals the 2020 worst case, i.e., the average temperature rise compared to the reference period 1961–1990 is expected to be 0.9 °C. The IPCC presumes an average worst case temperature rise of 3.3 °C. Thus, a transmission gate of five months dominated in Lower Saxony (coverage 94.3 %) (Table 2.9). Again, only the highlands in the south (ER 12 and ER 62) and the coastal zone in the north (ER 22) differed (3–4 months).

The 2100 *best case scenario* estimates a minimum climate warming of 1.4 °C when compared to the reference period 1961–1990 and included September as the fourth month susceptible for transmission of malaria (Table 2.10). The most frequent seasonal transmission gate lasted three months (76.6 %). Regions with four months transmission (21.4 %) were located in a broad belt in the south and in the south-western part of Lower Saxony (ER 42 and ER 47). Also coastal areas at the North Sea were included and tidal mud flat islands, too (ER 22).

The worst case calculation was based on a temperature rise of 5.8 °C compared to the reference period 1961–1990. Lower Saxony would then be divided into two parts with differing transmission gates (Table 2.11). The western part revealed a predicted transmission gate of six months (coverage 55.8 %). These areas represent those regions which are usually warmer compared with the other parts of the country (ER 42) showing annual mean temperatures of 8.9 °C (1961–1990), whereas the average for Lower Saxony was 8.6 °C in that period. A seasonal

Table 2.9 Potential malaria seasonal transmission gate (months) in the ecoregions of Lower Saxony 2060 worst case (w.c.) (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
3	82.8	0.0	0.0	0.0	0.0	0.0	3.4	0.0	1.2
4	7.3	0.0	17.7	8.2	0.0	4.7	41.9	0.0	4.5
5	0.1	2.2	6.6	36.9	28.1	15.6	6.8	1.4	94.3
Total 2060 w.c.	1.4	2.1	7.0	35.2	26.5	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Table 2.10 Potential malaria seasonal transmission gate (months) in the ecoregions (12–8) of Lower Saxony 2100 best case (b.c.) (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
2	65.5	0.0	0.0	2.2	1.7	0.0	9.9	0.0	1.9
3	0.3	2.2	6.5	36.7	31.4	10.9	9.1	0.7	76.6
4	0.0	1.8	9.4	32.7	10.9	30.5	5.6	3.5	21.4
Total 2100 b.c.	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

Table 2.11 Potential malaria seasonal transmission gate (months) in the ecoregions (12–8) of Lower Saxony 2100 worst case (w.c.) (percentage per ecoregion; total = percentage of overall coverage) (according to Schröder and Schmidt 2008)

Months	Ecoregions (ER)* after Schröder et al. (2006)								Total (%)
	12 (%)	20 (%)	22 (%)	42 (%)	43 (%)	47 (%)	62 (%)	8 (%)	
5	3.4	3.3	2.0	13.7	46.0	11.2	15.1	1.2	44.2
6	0.0	1.1	10.9	52.1	10.9	17.8	3.0	1.4	55.8
Total 2100 w.c.	1.5	2.1	7.0	35.2	26.4	14.9	8.4	1.3	100.0

* Covering at least 1 % of the territory of Lower Saxony

transmission gate of five months (coverage 44.2 %) was found within the rectangle of the river Weser in the north-west and the waterway ‘Mittellandkanal’ in the south (ER 43). Another area covered the low mountain range in the south of Lower Saxony (ER 12).

2.3.4 Discussion

The investigation revealed areas in Lower Saxony that are susceptible for a new tertian malaria outbreak transmitted by *A. atroparvus* due to their high summer mean temperatures. The calculations corroborate that although malaria is not an

endemic disease in Germany, the risk of an autochthonous transmission does exist (Krüger et al. 2001). Pathogens of the respective malaria types enter the country by infected travellers and by mosquitoes from endemic areas.

Concerning the period from 1947 to 2004, in terms of transmission length, the dominant transmission period was two months (74–82 %). In all the three periods, the regions with the highest risk of a disease spread are located around the city of Lingen in the southwest and along a broad belt in the south touching the cities of Braunschweig, Hanover and Nienburg. A similarity between former malaria zones and recent *Anopheles* findings listed in the BOG-Archiv can be noticed. Some areas mentioned there are exactly those which represent the highest risk of a *Plasmodium vivax* transmission for all investigated periods. In the southern parts of Germany, *Anopheles* findings had not been determined to the species level. However, recent studies give evidence that *Anopheles atroparvus* and *Anopheles messeae* are still present in the coastal areas (Wilke et al. 2006). It is just this area, where best case scenarios already calculated a four months risk of transmission in 2060. And it is this area, where malaria tertiana occurred up to the 1950s (Weyer 1956).

Furthermore, it was tested to what extend the predicted climate warming prolongs the transmission period of the tertian malaria pathogen. Hence, the formula of the model was applied to IPCC predicted climate warming scenarios. Outcomes were calculated for the years 2020, 2060 and 2100, illustrated by maps of best and worst case scenarios at each year. In worst case, the predicted maximum air temperature rise for the present century is expected to be more than four times higher than in the best case scenario. As the difference between the chosen years is, in average, 2.45 °C for the worst case, the mean temperature increase is 0.55 °C in best case considering the development of the 80 years' period between 2020 and 2100. By comparing all the maps, some striking trends become obvious. First of all, the climate warming between 2020 and 2060 prolongs the transmission period for nearly all areas of Lower Saxony by two months. This does not hold true for the last prospected period (2100), where an average prolongation of one another month is expected. The second point is similar to one mentioned when discussing the best case scenarios. The coastal areas show different warming characteristics than the continental regions. Up from 2020 to 2060 and 2100 at last, the potential tertian malaria transmission gate turns from two months to four and then directly to six. As explained before, this climate condition is a result of the warm west winds from the North Sea bringing mild temperature conditions in autumn. This development gets consequently obvious, when months like September or October become transmission months of tertian malaria, like they do in terms of the worst case maps.

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