The present distribution and predicted geographic expansion of the floodwater mosquito *Aedes sticticus* in Sweden

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ABSTRACT: The mass emergence of floodwater mosquitoes, in particular *Aedes sticticus* and *Aedes vexans*, causes substantial nuisance and reduces life quality for inhabitants of infested areas and can have a negative impact on the socio-economic conditions of a region. We compared the previous, present, and predicted geographic distribution of *Ae. sticticus* in Sweden. Previous records from the literature until 1990 list the species in three out of 21 Swedish counties. Beginning in 1998, studies show that the present distribution of the species covers 11 counties, with highest abundances in an east-west belt in Central Sweden. Using climate data from the present and predicted climate scenarios, the expected distribution of *Ae. sticticus* in 2020, 2050, and 2080 could be modelled using GIS. As variables, mean temperatures and cumulative precipitation between May and August and degree slope were chosen. The predicted geographic distribution of *Ae. sticticus* will continue to increase and include 20 out of 21 Swedish counties. The expected temperature rise will increase the suitable area towards the northern part of Sweden by 2050. Some non-suitable areas can be found along the south-east coast due to insufficient amount of precipitation in 2050 and 2080. Modelling the expected distribution of a species using predicted climate change scenarios provides a valuable tool for risk assessments and early-warning systems that is easily applied to different species and scenarios. ***Journal of Vector Ecology* 34 (1): 141-147. 2009.**

Keyword Index: Aedes sticticus, floodwater mosquitoes, GIS, climate change, distribution model.

INTRODUCTION

Floodwater mosquito species, in particular the species *Aedes sticticus* Meigen and *Aedes vexans* Meigen, are the predominant mosquitoes in areas influenced by large rivers with adjacent lowlands that flood regularly (Becker and Ludwig 1981, Merdic and Lovakovic 2001, Minar et al. 2001, Schäfer et al. 2008). In Central Sweden, mass emergence of *Ae. sticticus* occurs after floods in the lowlands of the River Dalälven. In this region, enormous numbers of mosquitoes have been reported with up to 62,100 individuals (86% were *Ae. sticticus*) in one trap and night (Schäfer et al. 2008). During recent years, unexpectedly large number of floodwater mosquitoes have been observed at several additional locations in Central and Southern Sweden (Lundström and Schäfer, unpublished information). We also found *Ae. sticticus* established in habitats not connected to rivers or lakes, such as abandoned farmland that gets flooded after heavy rainfall. Further establishment of *Ae. sticticus* in new suitable areas could cause increased mosquito nuisance problems, with substantial impact on the life quality for the human population.

Climate change observations of temperature increase are global but the increase is greater at northern high latitudes, as is the expected increase in the amount of precipitation (IPCC 2007). For Sweden, climate change scenarios for 2100 (www.smhi.se) predict an increase in mean annual temperature of 4 to 5.5° C, and an increase in annual precipitation of 10-15% in southern and central Sweden and up to 30% in northern Sweden. In addition, extreme precipitation events measured as maximum precipitation under seven consecutive days with more than 10 mm per day are predicted to increase by 10-20%. This implies an increased risk of floods producing floodwater mosquitoes and increases the probability for extremely high mosquito abundance in flood-affected areas (Lindgren and Jaenson 2006).

In this study, we show the present geographic distribution of *Ae. sticticus* in comparison to previous reports and model future distribution with regard to predicted climate change.

METHODS

Mosquito distribution data

Records of *Ae. sticticus* before 1990 are based on Dahl (1977) and references therein, Jaenson et al. (1986) and Francy et al (1989). Dahl (1977) summarized distribution of species with regard to Swedish provinces. However, the provinces are no longer used as administrative boundaries in Sweden. We transferred the province information to Swedish counties which represent larger areas in most cases, but are identical to provinces in others.

The evaluation of the present distribution of *Ae. sticticus* is based on published references and our own unpublished material (Table 1). From these studies, the locations of each sample site were also available as coordinates from GPS measurements.

Climate data

Gridded data on temperature (degree Celsius; minimum per month, maximum per month), precipitation (mm per month), and altitude (meters above sea level) (Hijmans et al. 2005) was downloaded from http://www.worldclim.org/ with a spatial resolution of 5 arc-minutes (roughly 10 km), except of altitude that was acquired with a spatial resolution of 2.5 arc-minutes (roughly 5 km). The vertical accuracy of the altitude dataset is less than approximately 18 m (for more information see http://www2.jpl.nasa.gov/srtm/). The dataset for present climatic variables was based on data from ca. 1950 to 2000. Modeled datasets for predicted climate included year 2020, 2050, and 2080, respectively. These models used the Hadley Centre Coupled Model, version 3 (HadCM3).

From each dataset, mean temperature for the months May to August was calculated. Precipitation was computed as cumulative precipitation in mm for the months May to August. From the altitude dataset, slope in degree was derived using the Spatial Analyst tools in ArcGIS, calculating the maximum rate of change between each cell and its neighbors. All data were analyzed in ESRI ArcGIS 9.2.

Distribution modeling

For modeling the distribution of *Ae. sticticus,* the values for present mean temperature, cumulative precipitation, and slope were extracted for the positive sample sites of the present distribution. Based on this information, we defined the requirements of *Ae. sticticus* with regards to these variables. The defined thresholds were then used to model the present distribution of *Ae. sticticus* and to predict the distribution in 2020, 2050, and 2080, respectively. Modeled presence of *Ae. sticticus* required values equal or higher than the respective thresholds for temperature and precipitation and values equal or lower than the threshold for slope. For modeling the predicted distribution in 2020, 2050, and 2080, the respective datasets for mean temperature and cumulative precipitation were used, while the same data for slope was used in all calculations.

RESULTS

Geographic distribution before 1990

The geographic distribution of *Ae. sticticus* presented in Dahl (1977) covers only the counties of Uppsala (province Upland) and Dalarna (province Dalarna). Records from 1983, 1984, and 1985 (Jaenson 1986, Francy et al. 1989) add the county Gävleborg (province Gästrikland) (Figure 1a). Jaenson (1986) collected mosquitoes by human bait in six locations close to the River Dalälven at Tärnsjö and Gysinge and found 1,895 individuals of *Ae. sticticus* in total, with percentages ranging between 6.4 and 95.6 per location and date. Francy et al. (1989) reported ten individuals of *Ae. sticticus* from the Sässman area during two years of sampling using CDC light traps baited with dry ice.

Geographic distribution from 1990 to the present

Our inventories of Swedish mosquitoes from 1998 and onwards provide records of *Ae. sticticus* for 11 counties (Figure 1b). These records are all based on collections with CDC miniature light traps baited with dry ice. The maximum number of mosquitoes per trap night shown per county shows that *Ae. sticticus* is most abundant in the counties Gävleborg and Västmanland (partly the county of Uppsala now) (Table 1, Figure 2). The species can occur in large numbers in a belt in central Sweden, where it regularly accounts for more than 90% of the total catch, and is less abundant in southern Sweden. At all sample sites, *Ae. vexans* was found as well, but in smaller numbers than *Ae. sticticus*.

At the 32 sample sites with *Ae. sticticus* records, the mean temperature from May to August varied between 13.7 and 15.2° C, precipitation from May to August ranged between 211 and 285 mm, and slope varied between 0.02 and 0.33 degrees, with one outlier of 0.70 degrees (Sunne) that was not considered as a valuable threshold. These three variables together provided a good model for the present distribution of *Ae. sticticus* (Figure 3a). Restrictions for distribution in Northern Sweden are due to mean temperatures below 13.7° C from May to August. In south-central Sweden, an area occurs in the high plains with no modeled suitability for *Ae. sticticus* due to less than 211 mm cumulative precipitation from May to August.

Predicted geographic distribution

With regard to predicted climate changes, the potential areas with suitable conditions for *Ae. sticticus* will likely increase (Figures 3b, c, d). In 2020, the species still finds its most suitable conditions in the south-central part of Sweden, including the area in the southern high plains with no suitability in the modeled present distribution. However, in 2050 the expected mean temperature rise increases the suitable area towards the northern part of the country. This trend continues in 2080 along the south-east coast of Sweden, areas with no suitability for *Ae. sticticus* due to insufficient amounts of precipitation. In comparison to the present modeled distribution, the suitable area for *Ae. sticticus* has almost doubled by 2050 and almost tripled by 2080.

Looking at the number of counties with *Ae. sticticus* records, the modeled present distribution already covers 16 out of 21 counties, and this will increase to cover almost all counties including the northern part of Sweden from 2020 onwards. The only county without predicted suitability for *Ae. sticticus* over this time period is the county of Gotland.

DISCUSSION

We report a recent increase in the geographic distribution of the floodwater mosquito *Ae. sticticus* in Sweden and predict a further expansion northwards based on climate change scenarios. With regard to the known

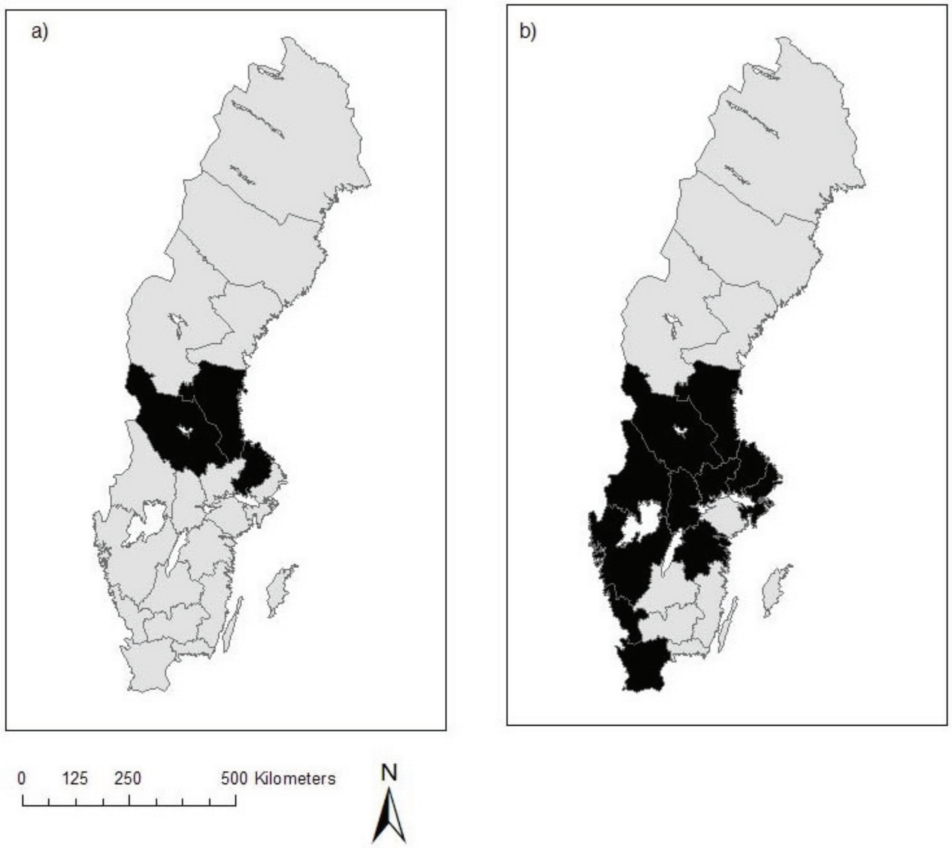

Figure 1. The geographic distribution of *Ae. sticticus* in Swedish counties, a) records before 1990 and b) records after 1990. Counties with records of *Ae. sticticus* are marked in black. Projected Coordinate System: Swedish National Grid RT90 2.5 gonV.

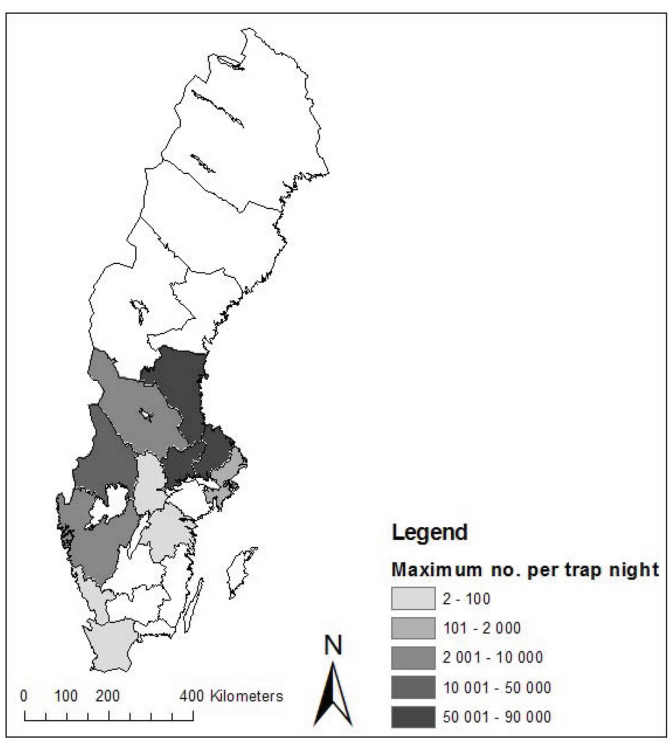

Figure 2. Abundance of *Ae. sticticus* in Swedish counties, based on maximum numbers of individuals per trap night from studies between 1999 and 2005. Projected Coordinate System: Swedish National Grid RT90 2.5 gonV.

Table 1: Sample locations and year for records of *Ae. sticticus* in Sweden from 1998 onwards. Coordinates for longitude and latitude are in WGS84.

County	Site	Longitude	Latitude	Collection years	Max. no. per trap night	Reference
Skåne	Hässleholm-Magle	13.763084	56.135718	1999	1	Schäfer et al. 2004
Skåne	Kristianstad-Egeside	14.168486	56.012937	1998	4	Schäfer and Lundström 2001
Skåne	Nöbbelöv	14.075073	56.223772	1999	9	Schäfer et al. 2004
Halland	Halmstad-Vallås	12.900024	56.683293	1999	2	Schäfer et al. 2004
Östergötland	Linköping-Stavsätter new	15.671645	58.304055	1999	1	Schäfer et al. 2004
Östergötland	Linköping-Stavsätter old	15.658364	58.296207	1999	16	Schäfer et al. 2004
Västra Götaland	Gullspång	14.196966	58.935549	2005	5000	unpublished
Västra Götaland	Sjön Östen	13.965613	58.609932	2007	2996	Lundström and Schäfer 2007
Örebro	Örebro-Karlslund	15.139675	59.262147	2004	2	unpublished
Örebro	Örebro-Kårsta	15.185557	59.348509	2004	18	unpublished
Örebro	Örebro-Ormesta	15.282133	59.268466	2004	13	unpublished
Örebro	Örebro-Vattenparken	15.256991	59.281451	2004	7	unpublished
Västmanland	Bännbäck	16.583382	60.169033	2001-2006	1419	unpublished
Västmanland*	Färnebofjärden NP	16.780549	60.125133	2001-2006	37964	unpublished
Västmanland*	Huddunge-Hallsjön	17.016532	60.067850	2005-2006	2945	unpublished
Västmanland*	Sälja	16.983642	60.268650	2000-2002	53141	Schäfer et al. 2008
Stockholm	Danderyd	18.009632	59.405217	2006-2007	1036	Lundström and Hagelin 2008
Uppsala	Marma	17.423916	60.507900	2001-2006	120	unpublished
Uppsala	Mehedeby	17.376449	60.434633	2001-2006	1877	unpublished
Uppsala	Söderfors	17.244649	60.379950	2001-2006	485	unpublished
Uppsala	Enköping-Domta	17.149770	59.797292	2005	86864	unpublished
Gävleborg	Fågle	16.726616	60.245000	2000-2002	20485	Schäfer et al. 2008
Gävleborg	Hadeholm	17.038189	60.292211	2000-2002	19788	Schäfer et al. 2008
Gävleborg	Hedesunda-Ålbo	16.986766	60.344017	2001-2006	1589	unpublished
Gävleborg	Kågbo	17.215032	60.442933	2001-2006	499	unpublished
Gävleborg	Österfärnebo-Karinmossen	16.829618	60.327797	2000-2002	27432	Schäfer et al. 2008
Gävleborg	Österfärnebo-Valmbäcken	16.841516	60.297467	2000-2002	51256	Schäfer et al. 2008
Gävleborg	Sevallbo	17.105866	60.315567	2001-2006	2664	unpublished
Gävleborg	Tavelmuren	16.730314	60.409028	2000-2002	6600	Schäfer et al. 2008
Dalarna	Avesta-Sonnbo	16.285616	60.130733	2001-2006	3024	unpublished
Dalarna	Näckenbäck	16.517049	60.156308	2001-2006	2178	unpublished
Värmland	Sunne-Sjön Björken	13.209185	59.891412	2005-2007	12858	unpublished

*now within county of Uppsala.

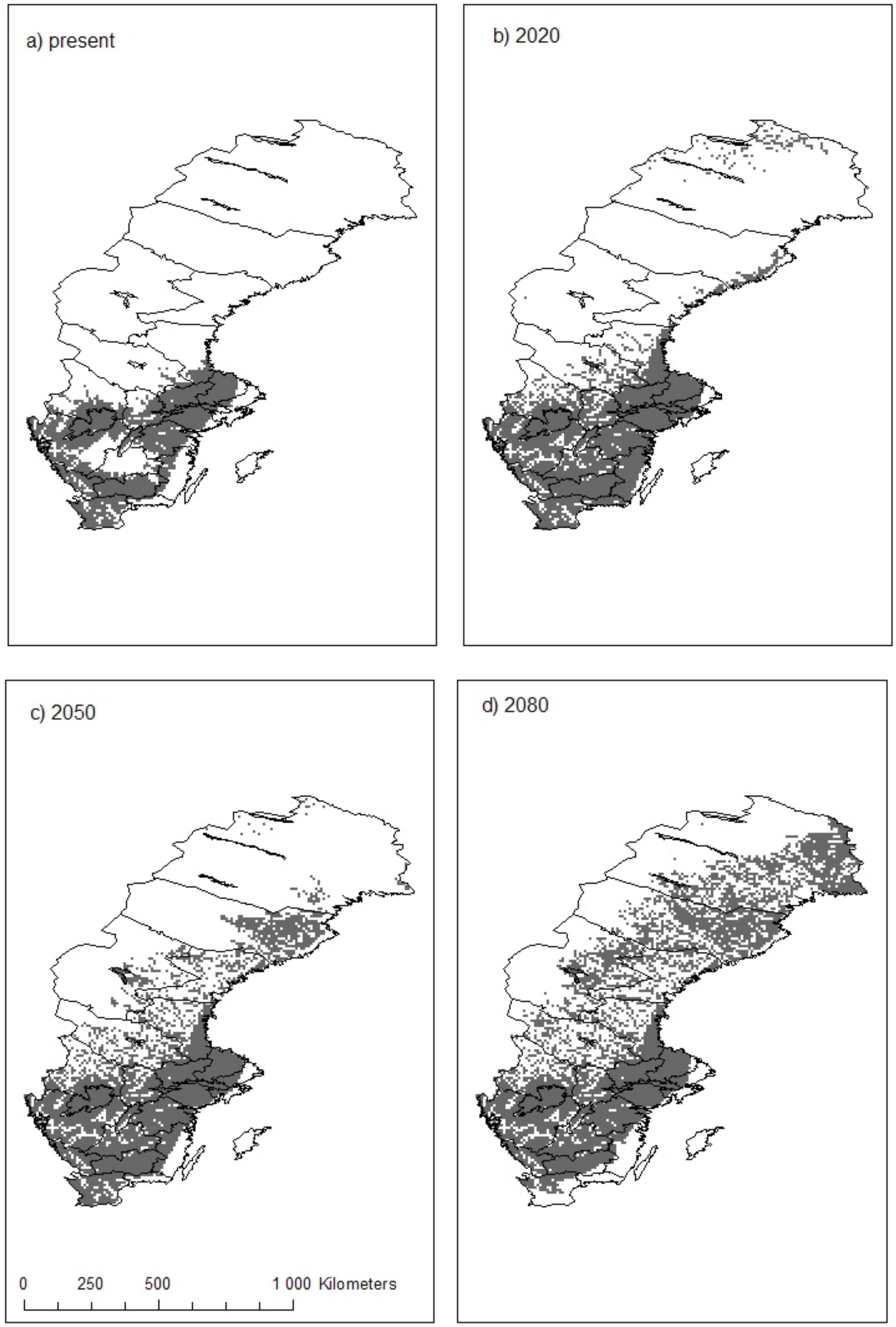

Figure 3. Modeled geographic distribution of *Ae. sticticus* (shown in dark grey) in Sweden a) at present, and with regard to climate change in b) 2020, c) 2050, and d) 2080. Climate change scenarios are based on HadCM3. Geographic Coordinate System: WGS84.

impact of mass emergence of floodwater mosquitoes on living conditions and the potential impact on the economic progress of an area, an increasing distribution and abundance of *Ae. sticticus* could cause considerable negative effects over a large part of Sweden.

The increased geographic distribution from the 1990s in comparison to records in the 1970s can partly be explained by more intense sampling efforts during the recent time period. Also, some of the sampling was more or less directed to floodwater mosquitoes as a consequence of nuisance reports from local people. Floodwater mosquitoes are hard to miss once they reach a certain population size. In particular, the species *Ae. sticticus* and *Ae. vexans* can be pest species molesting both humans and animals due to their day-active and rather aggressive biting behavior and their long-range dispersal, thereby invading settlements 15 to 20 km away from their breeding sites (Becker et al. 2003). Therefore, we believe that although there is some sampling bias, the trend of increasing abundance and geographic distribution is valid.

One explanation for the observed geographic expansion could be that *Ae. sticticus* was present at more locations even before the 1990s, only the populations were smaller and remained unnoticed in the 1950s to 1980s. An alternative explanation suggests a geographically restricted population of *Ae. sticticus* that in recent decades has dispersed and occupied new suitable areas. This original population would be located in an east-west belt in central Sweden where the species has been recorded and where it occurred in highest numbers in recent studies. DNA-based population studies will provide more insights about these suggested explanations. In both cases, however, some factors lead to an increased population size of the species in more places. This could be due to changes in climate such as increased precipitation leading to more frequent floods during summer months, increased summer temperatures speeding up larval development and/or prolonging the adult activity season, and increased areas subject to flooding, e.g., abandoned farmland.

The model we used to predict future distribution of *Ae. sticticus* is of course restricted to the input features. More variables could have been employed, e.g., precipitation during winter, or soil type, but we chose to focus on the most important variables. Precipitation during May to August is the main driving force of floods during summer. The expected decreased amount of snow in Sweden, and thus fewer floods due to snow melt, are therefore not considered here. Mean temperature during May to August is influential since eggs of the species *Ae. sticticus* and *Ae. vexans* will not hatch at water temperatures below approximately 8° C and 10° C, respectively (Becker 1989, Becker et al. 2003). The optimum temperature for development of *Ae. sticticus* is approximately 25° C, and of *Ae. vexans* 30° C, resulting in a development time of six to eight days from hatching of larvae to emergence of adults (Becker et al. 2003). Slope was selected since surface water can only remain standing as temporary flooded areas in rather flat terrain. Altogether, these variables were sufficient to model the present distribution and thus were employed for predictive models.

The HadCM3 model is one of many available climate scenarios used for modeling plausible future climates. Different models can produce different simulation outcomes for a given period and place depending on the assumed atmospheric concentration of greenhouse gases and future emission scenarios (for more information see http:\\www.ipcc.ch). The outcome of the HadCM3 model should be seen as one of many possible scenarios, but the general trend of increased temperature and rainfall in Sweden is consistent with other scenarios, e.g., the model by the Canadian Centre for Climate Modelling and Analysis (CCCMA, http://www.cccma.bc.ec.gc.ca/). The increase of mean temperature between May and August is the major cause of the predicted increasing suitability for *Ae. sticticus* in the northern part of Sweden. In addition, the mean temperature increase could also lead to a prolonged mosquito season in southern and central Sweden. Along the southeast coast of Sweden, insufficient amount of precipitation is a limiting factor for *Ae. sticticus*. This area of precipitation with less than 211 mm cumulative precipitation from May to August is even broader in the CCCMA model.

We have modeled the future distribution of one mosquito species, *Ae. sticticus*, in Sweden and found that the expected rise in mean temperature and increased precipitation from May to August could allow a massive geographic expansion of this species. This could apply to other mosquito species as well, both in Sweden and other Nordic countries, including, for example, higher abundance of the species *Ae. cinereus* that is involved in the transmission of Sindbis virus from birds to humans (Lundström 1999). Modeling the expected distribution using predicted climate scenarios provides a valuable tool for risk assessments and is easily applied for different species and scenarios if the present distribution is sufficiently known. GIS and remote sensing techniques are increasingly used for modeling approaches (Dale and Knight 2008), covering mainly diseases such as malaria, West Nile virus or Ross River virus, and their vectors (Zou et al. 2007, Jacups et al. 2008, Schröder and Schmidt 2008), but the application of such predictive models as early warning systems applies to other situations as well.

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