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Abrupt and gradual temperature changes influence on the climatic suitability of Northwestern Alpine grapevine-growing regions for the invasive grape leafhopper *Scaphoideus titanus* Ball (Hemiptera, Cicadellidae)

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ABSTRACT

The paper aims to elucidate the influence of abrupt and gradual climate changes on the suitability for colonization of *Scaphoideus titanus* populations in grapevine-growing areas of the Northwestern Alpine region. This study spans several decades of temperature recordings and is carried out in ten grapevine-growing areas. A time-varying distributed delay with attrition model, linked to a grapevine phenology model, is used to simulate the development of *S. titanus* populations and produce an annual Climatic Suitability Index (CSI). Area-specific CSI time series were obtained. The Breusch-Godfrey test revealed few significant partial autocorrelations in nine areas and the occurrence of six consecutive - first decreasing and then increasing - partial correlations in one case only. The occurrence of abrupt and gradual changes of the index were studied via multiple least square regression analyses. In general, the climatic suitability of all areas tended to improve through time. However, gradual and abrupt temperature changes were not consistently reflected in gradual and abrupt CSI patterns: abrupt and gradual CSI changes were observed in two areas, abrupt changes were detected in three areas, and exclusively gradual changes in the remaining five. Pest control institutions of the region under study may deal with different scenarios of pest status such as long-time presence and increasing risks, high colonization risks or limited colonization risks for the foreseeable future. Institutions charged with pest control elsewhere are advised to use a mechanistic demographic model to study area-specific infestation patterns and colonization risks because the results obtained here cannot be transferred to other areas without site-specific evaluations.

1. Introduction

Many studies have been undertaken to document changing climates at different spatial and temporal scale extents and resolutions (Anisimov et al., 2013; Anwer, 2015; Portmann et al., 2009; Reiter et al., 2012). According to the global dataset HadCRUT4 (Morice et al., 2012), global temperatures increased by +0.85 °C since 1850, while the main part of this increase (about +0.5 °C) occurred in the period 1977–1998. During the same period, European temperatures increased by about +1.3 °C (Mariani et al., 2012).

Voluminous literature deal with the effects of changing climates on populations, communities and ecosystems (Graham and Grimm, 1990; Gutierrez et al., 2008; Parmesan, 2006; Yates et al., 2010). The temperature component of climate change is particularly important for poikilothermic organisms whose development depend on body temperatures that vary broadly with environmental temperatures (May 2005). The methods used to investigate the impact of changing temperatures on population development and geographical distributions of poikilotherms fall broadly into two categories. The first category comprises species distribution models (SDMs) that combine observations of species occurrence or abundance with environmental estimates to characterize climatically the species to gain ecological and evolutionary insights and to predict distributions across landscapes, sometimes requiring extrapolation in space and time (Elith and Leathwick, 2009).

The second category of interest here comprises of physiologically-based demographic models (PBDMs), built on mechanistic representations of poikilothermic population development. PBDMs model the biology of the target species, and, when driven by weather, predict the

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phenology, age-structured dynamics, and distribution of the species across wide geographic areas independent of the availability of distribution information (Ponti et al., 2015). Since weather is an important driver for PBDMs, they are particularly appropriate for dealing with climate change effects.

In the case of pests and their abundance, the capacity of PBDMs to predict the potential geographic distribution under past, current and future climate change scenarios is fundamental in developing sound policies for their control (Gutierrez and Ponti, 2013; Ponti et al., 2015). Their ability to represent the regional suitability and the spatial distributions of insect pests on explanatory grounds is a complement to the work of international organizations such as the European and Mediterranean Plant Protection Organization (EPPO) that monitors and delineates the spread of pests and provides directions on quarantine pests management (Smith et al., 1996).

The Nearctic leafhopper *Scaphoideus titanus* Ball (Hemiptera, Cicadellidae), vector of the Grapevine Flavescence dorée (FD) phytoplasma, is a key pest of grapevine in Europe. *S. titanus* was accidentally introduced in France in the 1950s (Bonfils and Schvester, 1960; Schvester et al., 1961, 1962a; 1962b) and gradually extended its area of distribution. Actually, it is present throughout Western and Southeastern Europe from the Atlantic Ocean to the Black Sea, and the area of distribution is still expanding (Chuche and Thiéry, 2014; Tóthová et al., 2015).

Since the spread of *S. titanus* and FD continues, pest control institutions in regions with high risks of being invaded and colonized should prepare in time for intensive monitoring and expensive control operations. The risk of invasion and colonization depends on the dispersal ability of *S. titanus* and the suitability of the newly-invaded area. After its accidental introduction into Europe, the spread was so fast that most grapevine-growing areas should have been colonized by now. This is not the case, however, and the ongoing expansion suggests that the influence of the high dispersal ability on distribution patterns is constrained by other factors. Empirical and theoretical evidence suggest that climate, undergoing the aforementioned changes since the time of *S. titanus* introduction, plays an important role. In fact, Rigamonti et al. (2014b) found that the climate in two Swiss grapevine-growing areas changed in favor of *S. titanus* and hypothesized that the climatic suitability determines the colonization success and largely explains the changing geographical distribution in Europe.

Since the temperature regime in European grapevine-growing regions has and will undergo changes (Intergovernmental Panel on Climate Change (IPCC), 1996), a previously-unsuitable region may become suitable through time. Mariani et al. (2012) viewed climate variability as the superimposition of gradual and abrupt changes. Gradual changes can be interpreted as the effect of progressive changes in forcings (Intergovernmental Panel on Climate Change (IPCC), 2013), while abrupt changes are the result of sharp changes in the frequency and persistence of different circulation patterns (Sneyers et al., 1993). During the period 1977–1998, European temperatures increased by about 1.3 °C, while the main part of this increase was observed at the end of the 1980s, where an abrupt change is evident on thermal time series (Mariani et al., 2012).

The paper aims to elucidate the effects of abrupt and gradual climate change on *S. titanus* population development through an analysis of long-term suitability patterns in a geographically-restricted region with high temperature variability among grapevine-growing areas. For each area, a PBDM provides a long-term time series of annual suitability indices whose similarity, depending on time lags, prepares the ground for testing the appearance of abrupt and gradual changes in area-specific patterns of the suitability index.

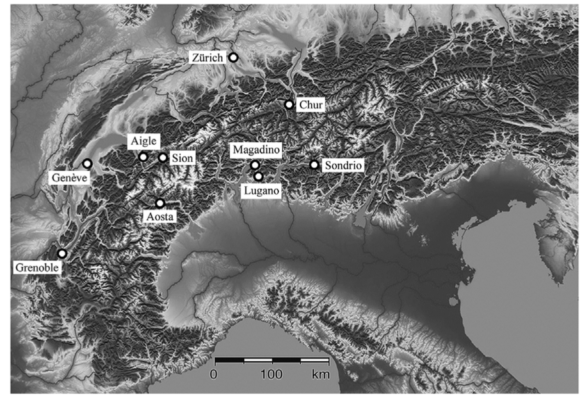

Fig. 1. The Northwestern Alpine region with the different areas in that the development of grape leafhopper *Scaphoideus titanus* populations was simulated.

2. Materials and methods

2.1. Study sites and temperature recordings

The suitability of grapevine-growing regions for *S. titanus* colonization is assessed in a region referred to as Northwestern Alps (Fig. 1, Table 1). This region has been selected because of its location near the northern limits of *S. titanus* distribution and the high climatic variability among grapevine growing areas therein. Both aspects are considered as useful prerequisites for elucidating the effects of climate change on the suitability of the region for colonization by *S. titanus*. Though outside the Alpine zone, we included the Zürich area in the analysis. At meteorological stations located in the different areas, daily temperature maxima and minima were readily available over 53 or 39 years periods (Table 1). To simplify the geographical notations, the location name is used as a name for the area. The locations of all the weather stations except Grenoble, are within or close to the grapevine growing areas.

The temperatures measured at the Swiss locations (Zürich, Lugano, Genève, Aigle, Sion, Chur and Magadino) are referred to as revised data retrieved from the data bank of the Swiss National Weather Service (MeteoSwiss). Namely, during the measuring periods, the position of the temperature sensors was often changed and new equipment were adopted. MeteoSwiss corrected for these changes (Begert et al., 1999, 2003, 2005) and kindly made available a data set referred to as homogenized data. Most of the data for Sondrio were kindly made available by Dr. M. Salvetti (Fondazione Fojanini, Sondrio) and reportedly did not require any correction. In the absence of respective information, the raw data measured at the Aosta and Grenoble stations obtained from Yang et al. (2010) at [https://beaumont.tamu.edu/ClimaticData/] and from the US weather service at [http://www.geodata.us/weather/], respectively, were used in the analyses. The gaps in the Sondrio and Aosta data sets were respectively filled by linear regression of Sondrio data on data measured at the nearby Poschiavo station operated by MeteoSwiss, and linear regression of Aosta data were regressed from data measured at the Torino-Caselle station.

2.2. Model characteristics and computation of the climatic suitability index

Basic model development. Rigamonti et al. (2011, 2014a) took into account the high variability in development times of nymphs relative to the mean (*cf*. Di Cola et al., 1999) and linked the appropriate "time-varying distributed delay with attrition" variant of the widely used time distributed delay models (Gutierrez, 1996; Gutierrez et al., 2015; Manetsch, 1976; Vansickle, 1977; Welch, 1984; Welch et al., 1978) to the grapevine plant phenology model of Mariani et al. (2013). They noticed that the *S. titanus* population model was appropriate for long-term studies since it allows the representation of multi-cohort and