Response to the letter on "Climatic distribution of citrus black spot caused by *Phyllosticta citricarpa.* A historical analysis of disease spread in South Africa" by Fourie et al. (2016)

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Abstract In a previous study, Martínez-Minaya et al. (2015) performed an analysis of climate distribution of citrus black spot (CBS) in South Africa. It was found that CBS was initially confined to humid areas with summer rainfall, but later spread to arid steppe and even desert climates. A strong spatial autocorrelation of CBS distribution was found. Fourie et al. (2016) take a critical view of our study, but without presenting any analysis of results to refute our findings. Furthermore, Fourie et al. (2016) appear to have misunderstood our work, since many of their criticisms relate to the potential distribution of CBS in Europe, which is beyond the scope of our original study. Fourie et al. (2016) highlight the limitations of climate classifications in species distribution modelling. However, this was made explicit in our study, indicating that it was a preparatory work and further advanced modelling studies, including spatial effects, will be needed. Fourie et al. (2016) incorrectly assume that we used all of South Africa as the background in the spatial autocorrelation analysis. However, only citrus areas were used and a strong spatial autocorrelation was detected at all distances evaluated. Contrary to what Fourie et al. (2016) suggest, similar climate distributions of CBS were obtained at 5′ and 30′ resolution, and also with the national land-cover map of South Africa. The figure comparison presented by Fourie et al. (2016) appearsto ignore the fact that the maps we used were grid cells of 10 ×10 km and not the line polygons they suggest. Therefore, we consider the conclusions from the Martínez-Minaya et al. (2015) remain entirely valid.

Keywords *Guignardia citricarpa*, spatial autocorrelation, mapping

Fourie et al. (2016) devote the greater proportion of their letter discussing the potential global distribution of citrus black spot (CBS), caused by *Phyllosticta citricarpa* (McAlpine) van der Aa, with a particular emphasis in European citrus-producing regions.

However, it was clearly stated in the title and the objectives of our study (Martínez-Minaya et al., 2015) that it was limited to South Africa. Martínez-Minaya et al. (2015) stated that “maps of the Mediterranean Basin were also obtained to discuss the boundaries and geographic extent of Mediterranean-type climates”. However, climatic suitability of the Mediterranean Basin for CBS was not analysed nor discussed in our study. Therefore, our response will not address those comments of Fourie et al. (2016) relating to the potential distribution of CBS in Europe. For a detailed discussion on this interesting topic, we recommend a recent report by EFSA (2016), where our study and others were thoroughly assessed by an independent panel of scientists.

We focus our response primarily on the methodological issues raised by Fourie et al. (2016), as they might affect the conclusions of Martínez-Minaya et al. (2015). To complement the results obtained by Martínez-Minaya et al. (2015), an additional raster layer was assembled with the map published by Paul (2005) and its subsequent updates (Yonow et al. 2013; Anonymous 2014), but including only those grid cells of the class “cultivated commercial permanent orchards” in the 2013-2014 South African national land-cover (NLC) dataset (DEA 2015). As in Martínez-Minaya et al. (2015), a resolution of 5′ and the coordinate system WGS84 were used with the raster package for R (Hijmans, 2014).

Fourie et al. (2016) indicate that CBS distribution patterns in South Africa depended on the point of introduction and the movement of infected plant material, which we agree is self-evident. Furthermore, Fourie et al. (2016) point out that “*P. citricarpa* has had abundant opportunity over many years for range expansion, including the recorded movement of citrus trees from CBS-endemic areas (Powell 1930; Kiely 1948; Ramón-Laca 2003)”. Only the reference by Powell (1930) relates to South Africa, and CBS was not mentioned in the publication, as the disease was only reported in South Africa in 1929

(Doidge 1929). Powell (1930) indicated that citrus was first introduced in the Western Cape in 1654, from where the crop progressively expanded east. Recent phytosanitary regulations in South Africa still consider the Western Cape to be a CBS-free area, whereas most citrus regions in the east are CBS-affected (Anonymous 2014). Therefore, Powell (1930) cannot be considered by any means as a valid reference for the movement of citrus trees from CBS-endemic areas in South Africa. As indicated by Martínez-Minaya et al. (2015), “the movement of citrus material in South Africa was not regulated until 1984, but quantitative trade data among provinces was not found”. Fourie et al. (2016) do not provide any additional data or reference on this subject.

Fourie et al. (2016) indicate that the use of climate classifications is the most simplistic of all the species distribution models available, and so the biological relevance of climate zones should be carefully considered. We were fully aware of this point, as EFSA (2014) already indicated that global climate zones are based on factors and thresholds that are broad and not necessarily representative of those that are critical for the pathogen and its host. This point was stated explicitly by Martínez-Minaya et al. (2015) in the objectives: “This preparatory work was part of a larger modelling project where the potential geographical range of CBS will be estimated based on relevant environmental variables and spatial effects”, and in the conclusions: “Further modelling studies should integrate the relative contribution of environmental variables together with the spatial structure of the data to better estimate the potential geographical range of CBS”. Fourie et al. (2016) do not acknowledge these statements in their letter.

Martínez-Minaya et al. (2015) indicated that “A map of the CBS distribution in Australia was also available (Paul 2005), but without details and resolution of the original data, so it was not considered in the present study”. However, Fourie et al. (2016) criticize our study for not considering CBS data from Australia and claim that both CBS distribution maps, Australia and South Africa, had a similar level of detail. For South Africa, Paul (2005) indicated that “areas of CBS presence and absence in commercial orchards and backyard trees were mapped by six field specialists with extensive knowledge of the disease onto a map of South Africa at a scale 1:10^6 (2 × 2 m). Disease presence records (…) were transcribed to a 29.7 × 45 cm map and scanned. Data on CBS distribution were confirmed by 200 citrus growers and researchers from South Africa at a citrus meeting in 2002”. However, for Australia, Paul (2005) only indicated that “Information on the presence of CBS in Australia was obtained from the Australian Plant Pest Database” and “A map of the known occurrence of CBS in Australia was drawn up from these data". Hence, the paucity of details in Paul (2005) on the original data from Australia when compared with those from South Africa is self-evident.

With regard to our analysis of spatial autocorrelation of CBS distribution in South Africa, Fourie et al. (2016) point out that “Martínez-Minaya et al. (2015) used all of South Africa as the background for the analysis (…) Had Martínez-Minaya et al. (2015) used citrus production regions as the background for the autocorrelation analysis, the apparent levels of spatial autocorrelation can be expected to decrease significantly”. Fourie et al. (2016) make these serious assertions without presenting any analysis of spatial autocorrelation of the data. Furthermore, it is an incorrect assumption of Fourie et al. (2016) that we used all of South Africa as the background. Moran’s I and Geary’s C analyses were performed with the 2014 dataset considering only grid cells in citrus areas, assigning a value of 0 for CBS absence and 1 for CBS presence or low prevalence. Indeed, Moran’s I and Geary’s C were not calculated for the 1950 dataset because only CBS presence, and not CBS absence, was available for that year.

In addition to the Moran’s I and Geary’s C calculated with contiguity-based neighbours by Martínez-Minaya et al. (2015), we present all the values for these indices at increasing distances (Fig. 1). The presence of strong spatial autocorrelation in the current CBS distribution data in citrus areas in South Africa was evident in both, the dataset used by Martínez-Minaya et al. (2015) and the one assembled based on the NLC map. As pointed out by Martínez-Minaya et al. (2015), further modelling efforts should consider not only environmental variables, but also the spatial dependence of CBS distribution data in South Africa. Ignoring this dependence may lead to inaccurate model parameterization and inadequate quantification of uncertainty (Banerjee et al. 2015).

In Martínez-Minaya et al. (2015), a raster layer of CBS distribution in South Africa was generated from the map published by Paul (2005) and its subsequent updates (Yonow et al. 2013; Anonymous 2014). As indicated in the Material and Methods of Martínez-Minaya et al. (2015), and also noted in the acknowledgments, all data were georeferenced to the coordinate system WGS84 by a mapping specialist. In their letter, Fourie et al. (2016) point out that CBS distribution maps in Paul et al. (2005) are adequate for modelling at 30′ scale, but not at a 5′ scale used in our study. Martínez-Minaya et al. (2015) stated that “similar results (not shown for the sake of simplicity) were obtained with the 30′ resolution”. To demonstrate this, we now present the proportion of grid cells according to CBS status by Köppen-Geiger climate types (Köppen 1936) at both the 30′ and 5′ resolution obtained by Martínez-Minaya et al. (2015) (Fig. 2). As previously indicated and as can now be seen, similar results were obtained at both scales. Furthermore, comparable results were derived from the dataset assembled using the NLC map at 5′ resolution, where only grid cells with “cultivated commercial permanent orchards” were considered (Fig. 2c). In this dataset, no commercial citrus areas were located under the arid cold desert (BWk) climate, which were indeed considered as CBS-free by Martínez-Minaya et al. (2015).

Fourie et al. (2016) plot side by side Fig. 1d of Martínez-Minaya et al. (2015) and Fig. 1a of Yonow et al. (2013), stating that “polygons depicting CBS distribution were clearly coarser that those of Yonow et al. (2013)”. Although Martínez-Minaya et al. (2015) made it explicit in Material and Methods, Fourie et al. (2016) apparently misunderstood that our maps were in fact grid cells and not line polygons as in Yonow et al. (2013). Each grid cell represented a 5′ square of about 10 ×10 km, which was evident from the scale bars in both Fig. 1 and Fig. 2 of Martínez-Minaya et al. (2015). Values of CBS status and environmental variables were for the grid centroids, always contained within the polygons of the map published by Paul (2005) and its subsequent updates (Yonow et al. 2013; Anonymous 2014). Fourie et al. (2016) persist in this misapprehension stating that “CBS-present polygons also extended into neighbouring countries and even into the ocean”. Again, it should be noted that grid cells and not polygons were represented by Martínez-Minaya et al. (2015). Moreover, the WorldClim database includes only land areas and not oceans (Hijmans et al. 2005). Also, as clearly indicated in Martínez-Minaya et al. (2015), our study was limited to South Africa. For more in-depth information on this point, the functions 'getData' and 'crop' in the raster package for R as used in our study should be examined (Hijmans, 2014).

Fourie et al. (2016) state that “it is clear that CBS occurs in the BSh climate zone in South Africa, and is essentially absent from BSk climates”. Again, Fourie et al. (2016) make this strong assertion without presenting any analysis of the data. Presence of CBS under the cold arid steppe climate (BSk) was obtained by Martínez-Minaya et al. (2015) at 5′ and 30′resolutions, as well as here with the dataset assembled using the NLC map (Fig. 2). Fourie et al. (2016) focus more directly on the BSk climate, but they appear to overlook that the hot arid steppe climate (BSh), which is the predominant climate under which CBS is becoming established in South Africa (Fig. 2), is also a climate type occurring in important citrus-producing areas in the Mediterranean Basin (Fig. 3a of Martínez-Minaya et al. (2015)).

From a biogeographical perspective, it is more remarkable that *P. citricarpa* thrives under the hot arid desert climate (BWh) found in parts of South Africa (2.3% of grid cells), although Fourie et al. (2016) made no comments on this fact. The arid desert areas where CBS is present in South Africa are located in northern Limpopo province (Fig. 2a of Martínez-Minaya et al. (2015)), as clearly specified by phytosanitary regulations “The Limpopo province, towns of Musina and Soutpansberg - north of the 22° 50′S or west of 29° 20′ E” (Anonymous 2014). These areas have low pest (disease) prevalence for CBS (Anonymous 2014), so they are subject to effective surveillance, control or eradication measures (IPPC 2005; 2007). The presence of CBS in desert areas demonstrates that *P. citricarpa* is able to complete its disease cycle under arid conditions typical of the BWh climate classification. Indeed, with the dataset assembled using the NLC map, annual rainfall as low as 340 mm was recorded in areas were CBS is endemic, similar to the values reported by Martínez-Minaya et al. (2015).

The incorrect assumptions made by Fourie et al. (2016) in respect to our methods, their apparent misinterpretations of our results, and taking into account the additional evidence we present here we consider that the conclusions of Martínez-Minaya et al. (2015) are indeed correct, valid, and stand, further demonstrating the facts that: i) CBS in South Africa has expanded from its original geographic range in summer rainfall areas to adjacent, more arid regions; ii) the results contradict statements indicating that CBS occurs exclusively in climates with summer rainfall (Fourie et al. 2016; Graham et al. 2014; Kotzé 2000); and iii) further modelling studies are required to integrate the relative contribution of environmental variables and the spatial structure of the data.

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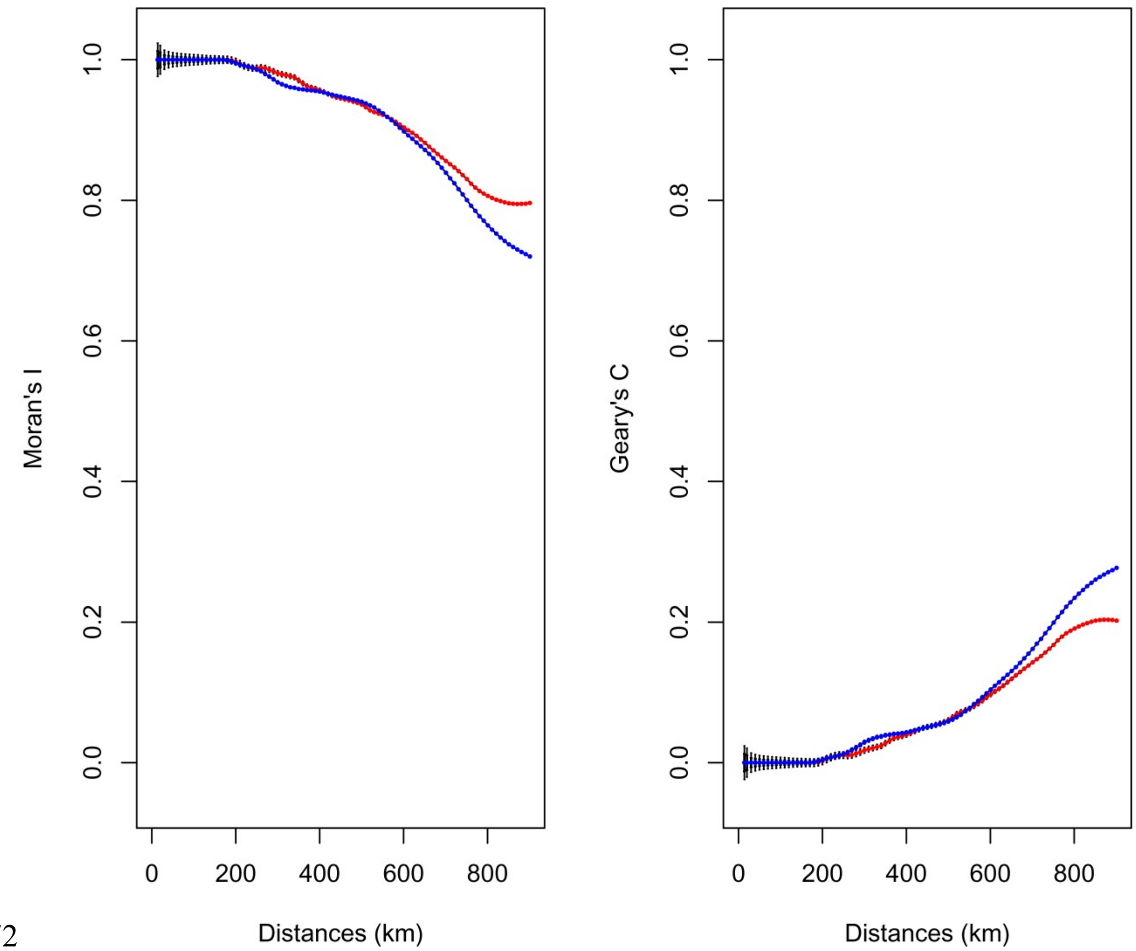
Fig. 1 Moran's I and Geary's C values at increasing distances. The blue lines represent the dataset used by Martínez-Minaya et al. (2015) from Paul (2005) and its subsequent updates (Yonow et al. 2013; Anonymous 2014). The red lines represent the same dataset but including only grid cells of the class "cultivated commercial permanent orchards" from the 2013-2014 South African national land-cover map (DEA 2015).

Fig. 2 Köppen-Geiger climate types and citrus-growing areas in relation to the distribution of citrus black spot (CBS) caused by *Phyllosticta citricarpa* in South Africa. The dataset used by Martínez-Minaya et al. (2015) from Paul (2005) and its subsequent updates (Yonow et al. 2013; Anonymous 2014) shown at 30′ **(a)** and 5′ **(b)** resolution, and (**c)** the same dataset at 5′ resolution but including only grid cells of the class "cultivated commercial permanent orchards" in the 2013-2014 South African national land-cover map (DEA 2015).

Fig 1.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Distances (km)
Geary's C
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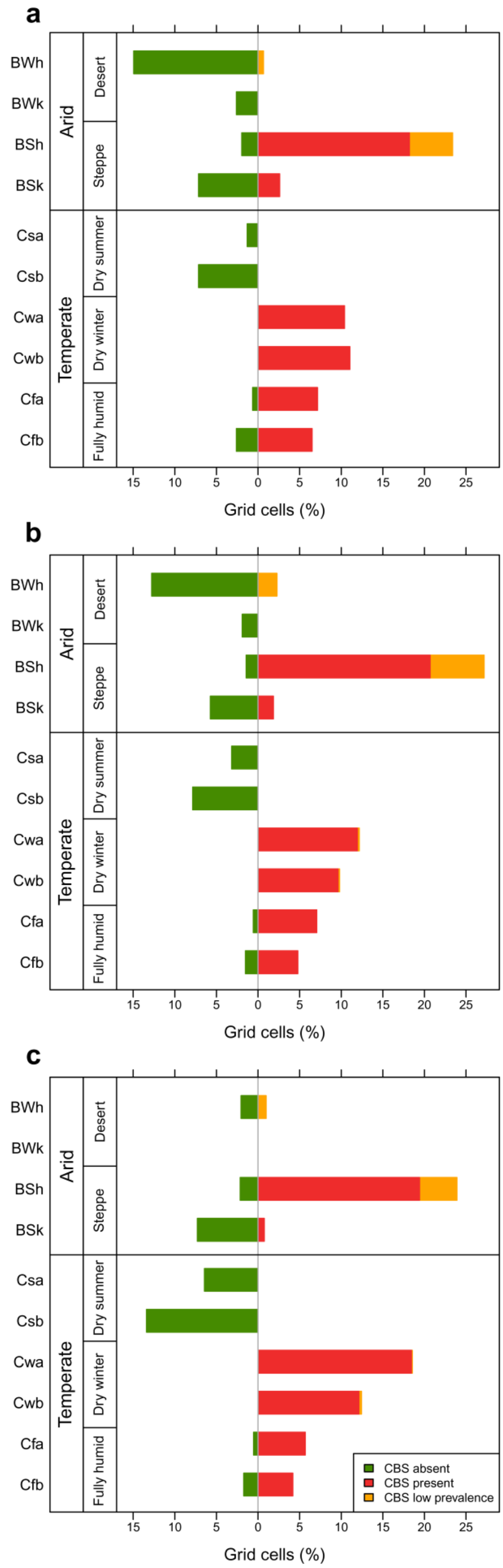
Distances (km)

Fig 2.


a
b
c
BWh
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BSk
Csa
Csb
Cwa
Cwb
Cfa
Cfb
Arid
Temperate
Desert
Steppe
Dry summer
Dry winter
Fully humid
15 10 5 0 5 10 15 20 25
Grid cells (%)
CBS absent
CBS present
CBS low prevalence