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Research article

Seasonality of the Mediterranean Fruit Fly (Diptera: Tephritidae) on Terceira and Sao Jorge Islands, Azores, Portugal

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Abstract

Population dynamics studies are very important for any area-wide control program as they provide detailed knowledge about the relationship of Medfly [*Ceratitis capitata* (Wiedemann)] life cycle with host availability and abundance. The main goal of this study is to analyse seasonality of *C. capitata* in Terceira and Sao Jorge Islands (Azores archipelago) using field and laboratory data collected during (2010–2014) CABMEDMAC (MAC/3/A163) project. The results from Sao Jorge Island indicate significantly lower male/female ratio than on Terceira Island. This is an important finding specially regarding when stablishing the scenario parameters for a sterile insect technique application in each island. The population dynamics of *C. capitata* are generally linked with host fruit availability and abundance. However, on Terceira Island fruit infestation levels are not synchronized with the trap counts. For example, there was Medfly infestations in some fruits [e.g., *Solanum mauritianum* (Scop.)] while in the nearby traps there were no captures at the same time. From this perspective, it is important to denote the importance of wild invasive plants, on the population dynamics of *C. capitata*, as well important to consider the possibility of having different densities of traps according to the characteristics of each area in order to improve the network of traps surveillance's sensitivity on Terceira Island.

Key words: *Ceratitis capitata*, medfly, population dynamics, sex-ratio, fruit infestation level

The Mediterranean fruit fly, or Medfly, [*Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae)] is a major fruit fly pest species of quarantine importance capable of causing extensive damage to a wide range of cultivated and wild fruit and vegetable crops (FAO and IAEA 2013). This species is native to Africa, but due to the world fruit trade expansion and its ability to adapt to new environments (Carvalho and Aguiar 1997, Pierre 2007, FAO and IAEA 2008, Papadopoulos 2008, Sciarretta and Trematerra 2011, Radonjic et al. 2013), it has spread invasively. First, to the Mediterranean area and then to many other parts of the world, including Australasia and North and South America (FAO and IAEA 2013).

Population dynamics studies are very important for any area-wide control program as they provide detailed knowledge about seasonal patterns of fruit host preferences as well as the influence of seasonal climatic conditions on the life cycle of *C. capitata* (Amaro 2003, Aluja and Mangan 2008). These studies are carried out using trapping systems to estimate the presence, seasonal abundance and spatial distribution of adults to make predictions of fruit host infestation levels (Díaz-Fleischer et al. 2014). This information, combined with Geographic Information Systems (GIS), allows the identification of critical periods and key locations as targets for application of area-wide suppression techniques that impact pest populations at the landscape level in their most vulnerable stage (Pimentel et al. 2005, 2014b; Lopes et al. 2006b,c; Vreysen et al. 2007; Capinera 2008; Aluja and Rull 2009; Midgarden et al. 2014). Moreover, the development and use of biologically based pest management tactics, such as use of natural enemies or sterile insect technique (SIT), requires a detailed knowledge of pest biology and ecology, including life cycle, population dynamics, and interactions with the physical and biological environment, including potential competitors, predators and parasites (Capinera 2008).

Within the activities and objectives of the research projects (MAC/3.1/A1) Interfruta (2004–2006), (MAC/3.1/A4) Interfruta II (2006–2009), some studies about *C. capitata* including high density locations, dispersion and fruit infestation have been carried out

(Pimentel et al. 2005, 2014b; Lopes et al. 2006b,c; Pimentel 2010). One of the main goals of the first Interfruta project was to attend the concerns of growers, farmers, and technicians about this pest. Therefore, the first studies were made to evaluate what was the best trapping system (Nunes et al. 2005) and which orchards was this insect mainly located (Pimentel et al. 2005). Another goal was to evaluate the sexual (Costa 2007) and dispersion fitness of the sterile males, produced in Madeira's Biofactory, under Terceira's conditions (Lopes et al. 2005).

The second Interfruta project was aimed, more specifically, to an area-wide approach of this pest as it provided the opportunity to install and monitor a network of traps all around the Terceira Island from the 0 to 200 m of altitude (Lopes et al. 2009, Pimentel 2010). This study provided a better knowledge of spatial distribution of Medfly over Terceira Island, as it unveiled the ecological corridors and the main hotspots over time.

As a direct result of these projects, the research project (MAC/3/A163) CABMEDMAC (2010–2014) was initiated. The main goal was to get a better knowledge about fruit flies throughout Macaronesia, mainly, about the area-wide control strategies. In the Archipelago of the Azores, the CABMEDMAC project developed its activities on Sao Jorge and Terceira Islands. On the island of Sao Jorge, as these were the first studies to ever be made in this Island, the developed activities were related to Medfly population dynamics and sterile insect dispersion tests. In Terceira Island, the activities included the evaluation of the SIT strategy over a period, as well as, follow the population dynamics in order to keep up an updated trapping and fruits infestation record log.

Since the settlement of the Azorean Islands, horticulture has been an engine of economic development for the region, enhancing its relationship with foreign markets, e.g., through cultivation of oranges (Lopes et al. 2006a). Medfly was first reported in the Azorean Archipelago in 1829, coincident with the establishment of orange production (Quaintance 1912). Nowadays, according to Lopes et al. (2006c) and Pimentel (2010), Medfly on Terceira Island, prefers other fruits over oranges. This change in fruit host preferences, along with changes in the extent and pattern of horticultural production over the years, shows the biological adaptability of this insect to environmental changes, such as fruit availability. In fact, Pimentel (2010) recorded higher levels of infestations on fruits from *Solanum mauritianum* (L.) than on commonly attacked fruit crops, especially when there is no other fruit host nearby.

Taking into account all the work done within the INTERFRUTA projects and its results, it is the objective of the present article to analyze the population dynamics of *C. capitata* on Terceira and Sao Jorge Islands, Azores, using field and laboratory data collected during the CABMEDMAC (2010–2014) project.

Materials and Methods

The Azorean archipelago is in the middle of the North Atlantic Ocean and is sometimes in the route of tropical cyclones and lesser

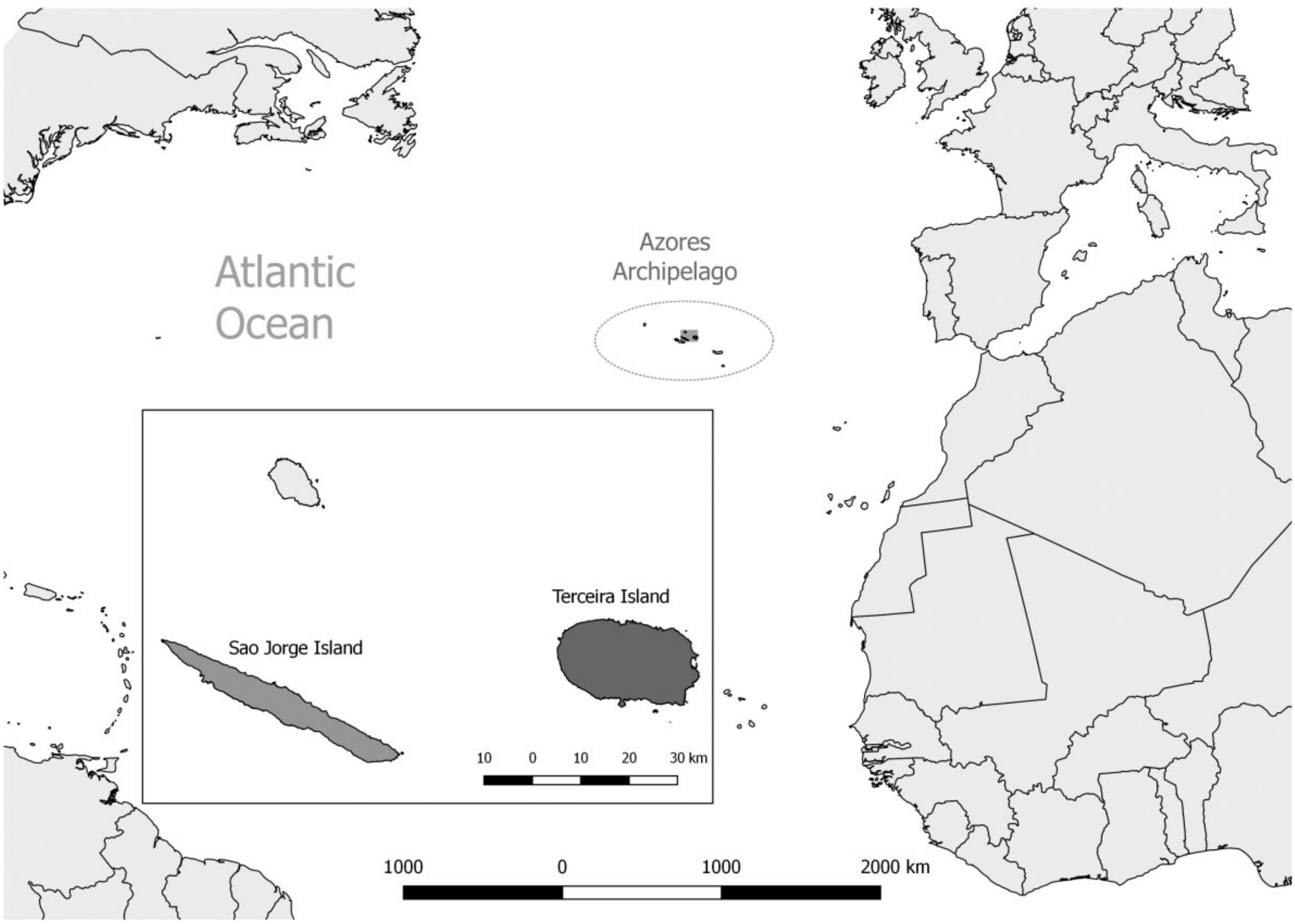
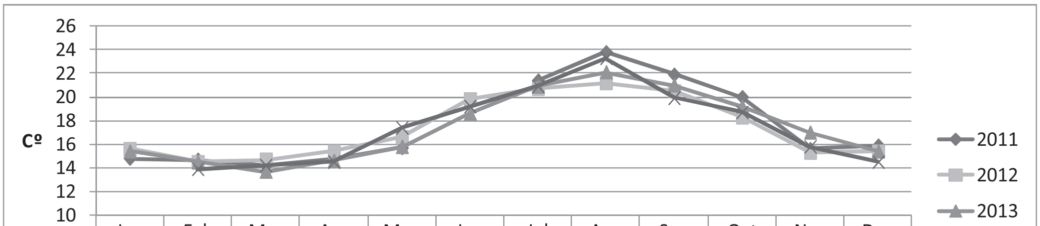


Fig. 1. Location map of Terceira and Sao Jorge Islands.

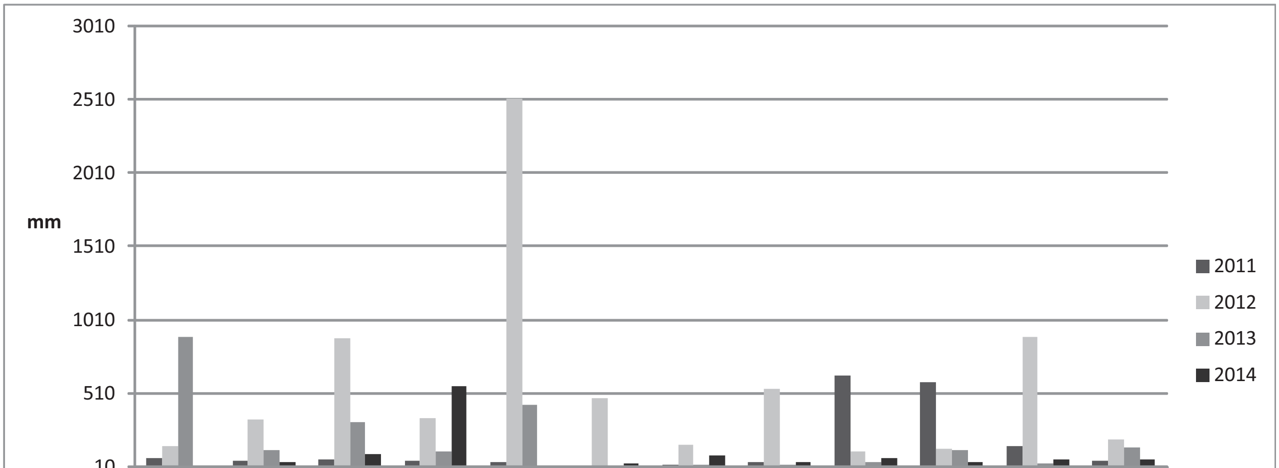
storms. These tropical circulations are predominant between September and December. This archipelago is made of nine islands and the fruit production in each island is intimately related to their own geographic location and topographic conditions (Batista et al. 2006).

Terceira and Sao Jorge Islands belong to the Central Group as it are located in a central position and the climate on these islands is characterized by mild conditions, high levels of humidity and persistent winds. Temperatures range between an annual average



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	14,8	14,7	14,2	14,8	15,7		21,4	23,8	21,9	20	15,6	15,9
2012	15,6	14,5	14,7	15,4	16,6	19,8	20,7	21,2	20,5	18,3	15,3	15,4
2013	15,4	14,5	13,7	14,6	15,8	18,6	20,9	22,1	21	19,2	17	15,4
2014		13,9	14,2	14,5	17,4	19,2	20,9	23,3	19,9	18,7	15,8	14,5

Fig. 2. Average monthly air temperature (°C) at Lajes parish on Terceira Island each year of the study (2011–2014) (Valor 2015).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	67	49	56	51	39		12	40	634	583	153	53
2012	153	332	885	345	2516	475	159	539	115	130	895	196
2013	896	125	314	117	430	7	23	25	43	127	31	137
2014		46	93	560	10	30	84	42	69	40	63	58

Fig. 3. Monthly rainfall (mm) at Lajes parish on Terceira Island each year of the study (Valor 2015).

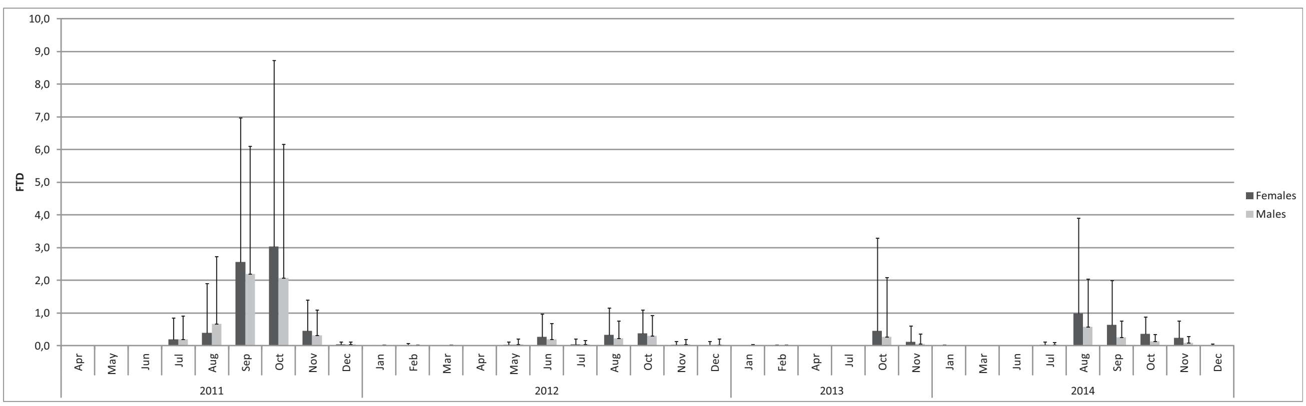


Fig. 4. Captures of males and females on Terceira Island expressed as numbers of FTD from 2011 to 2014.

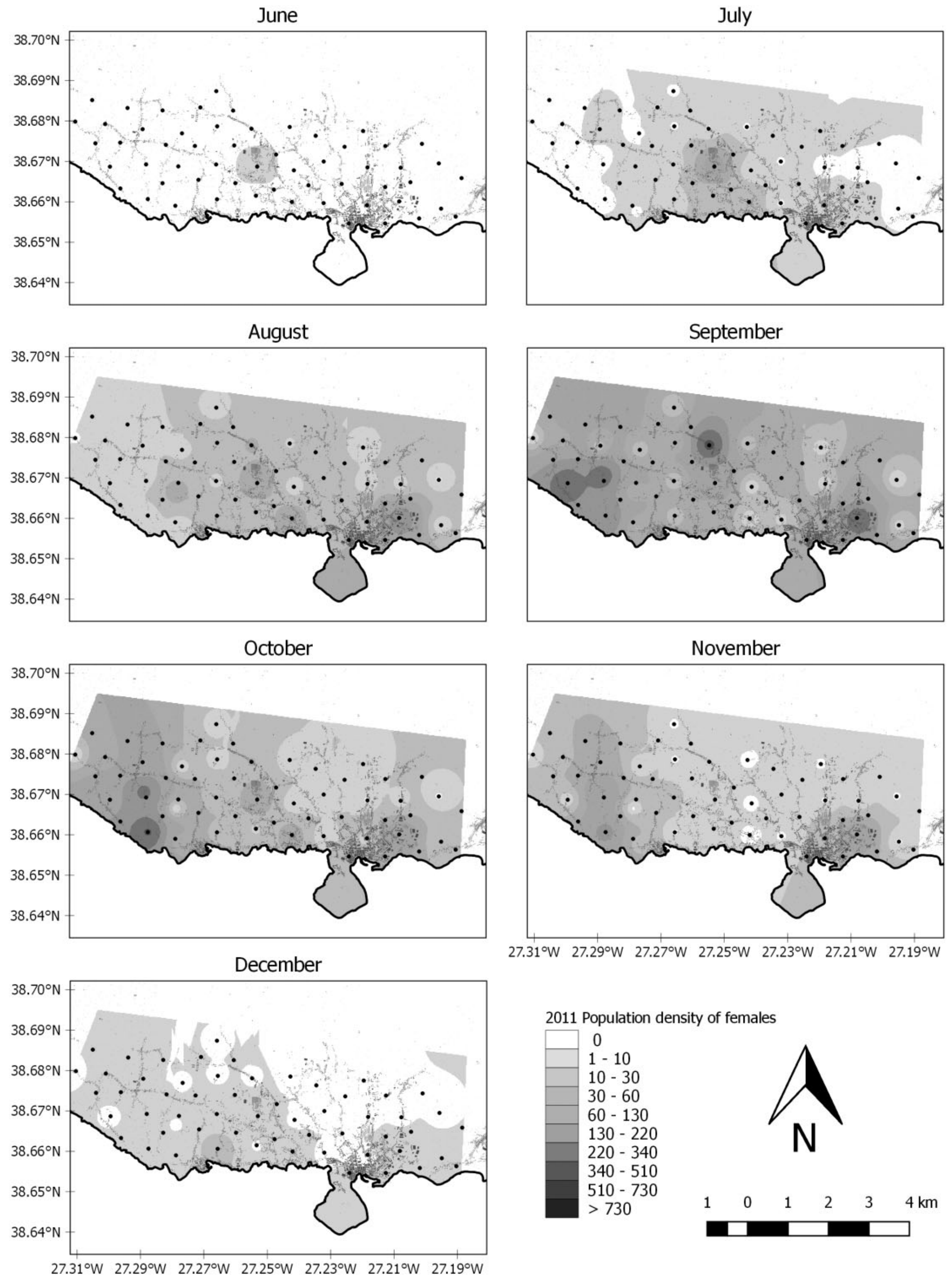


Fig. 5. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2011 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

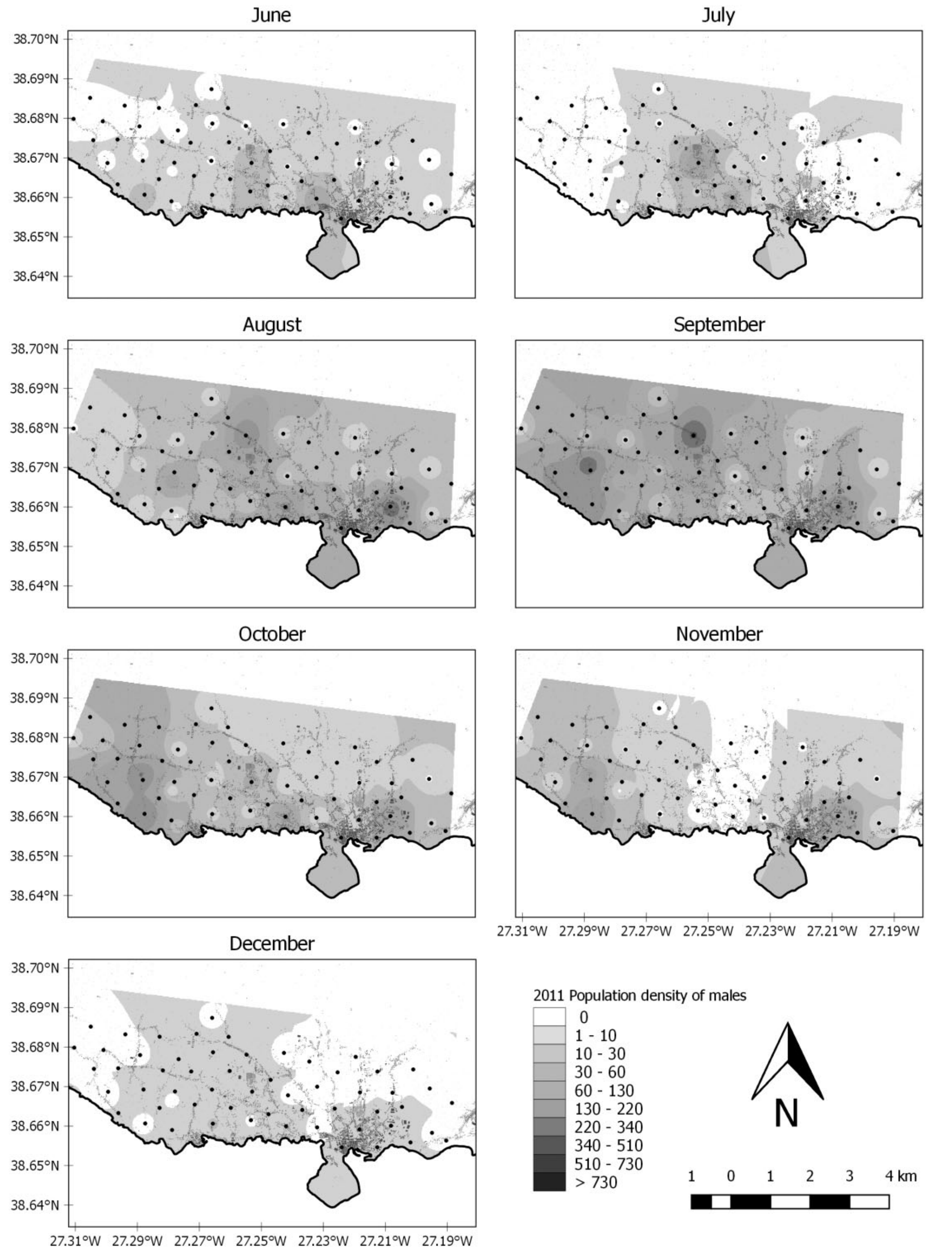


Fig. 6. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2011 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

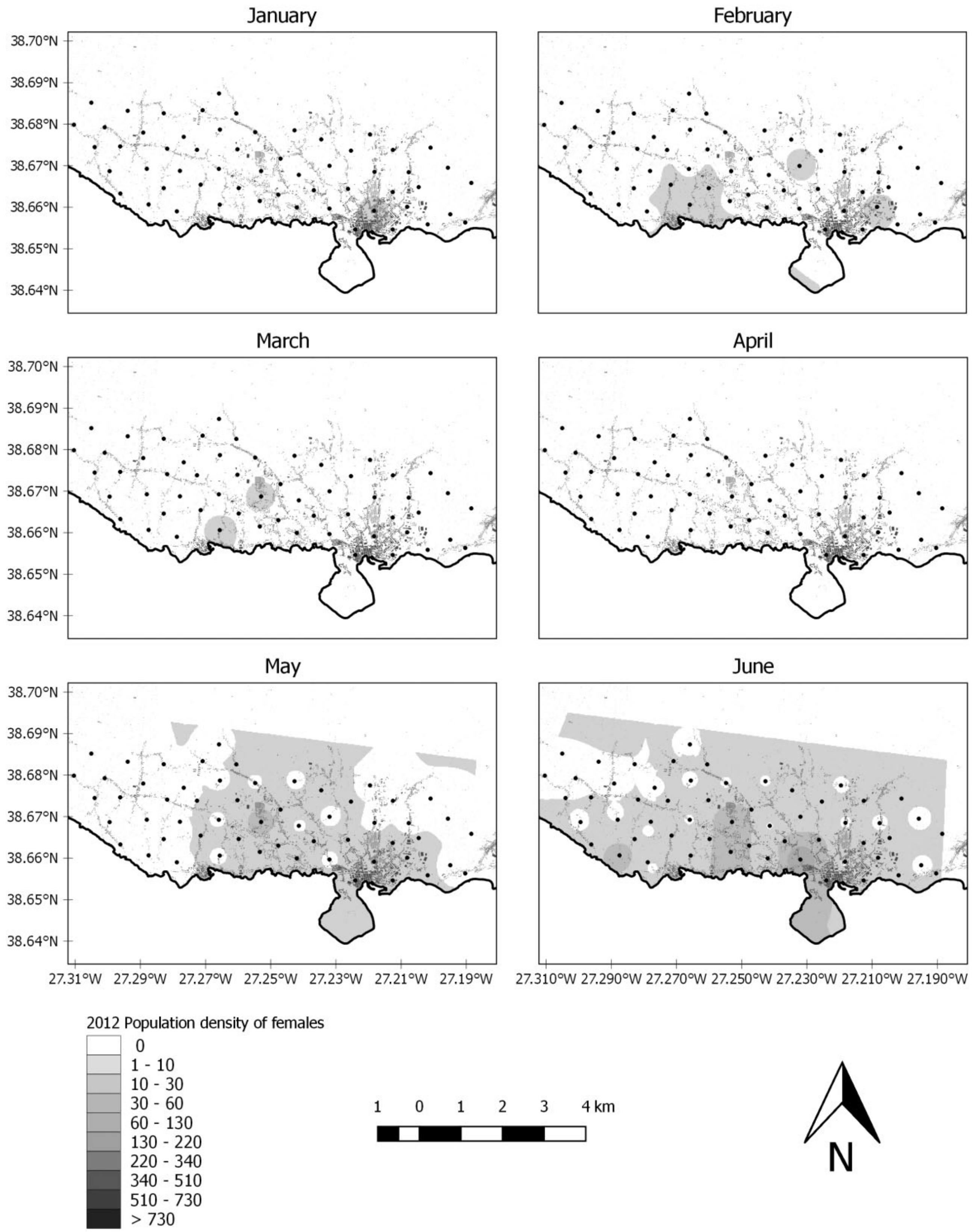


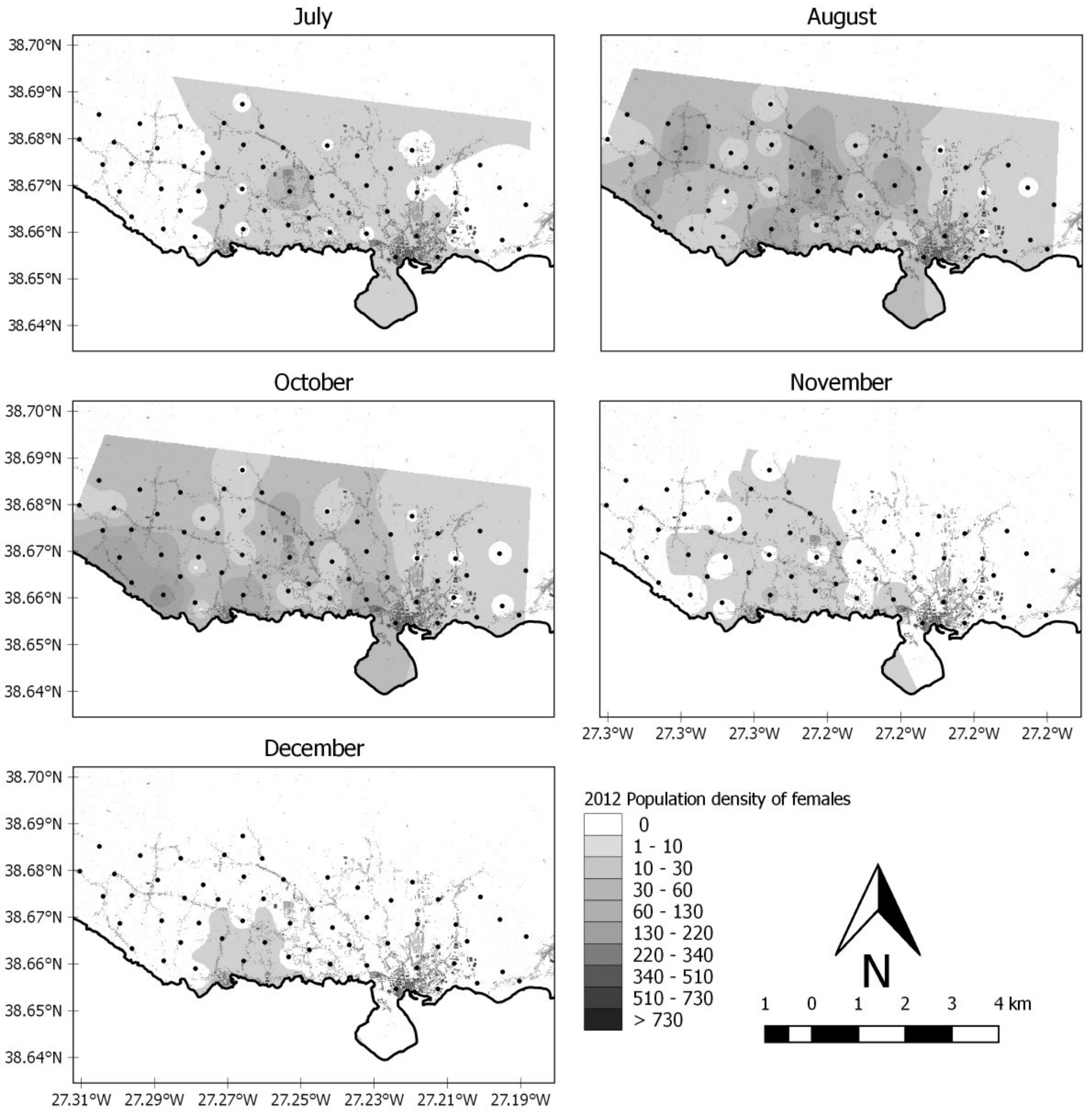
Fig. 7. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2012 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

minimum of 14°C and a maximum of 24°C. The seasonal climate characterization of the Azorean Islands is dictated by rainfall (Azevedo 1996).

The cultivated orchards on Terceira Island include apples, bananas, citrus and peaches. There are also other cultures in small orchards or home gardens. These fruits are mainly for household consumption or in some cases also for the local market, and there are figs, loquats, custard apples, guavas, passion fruits, pears, grapes, apricots, and plums.

On Sao Jorge Island there is a great variety of fruit trees, mainly on the south side of the island. There are orchards with oranges, apples, figs, coffee, olives, bananas, avocados, peaches, chestnuts, custard apples, mangos, persimmons, loquat, guavas, and tree tomatoes. The fruit production on Sao Jorge Island is mainly for household consumption, except for a small number of producers who sell their production to the local market. These are producers of apples, pears, oranges, banana, custard apples, figs, and even coffee. In both islands, many home gardens or old estates have fruit trees abandoned without any kind of pest monitoring or control.

To study the abundance and spatial distribution of the Medfly in both islands, a network of traps was installed according to the methodology used by Lopes et al. (2009). The networks of traps were spaced at ∼1 km^2 across all parts of the study areas which ranged from sea level to 200 m of altitude. The 200 m altitude was set as a



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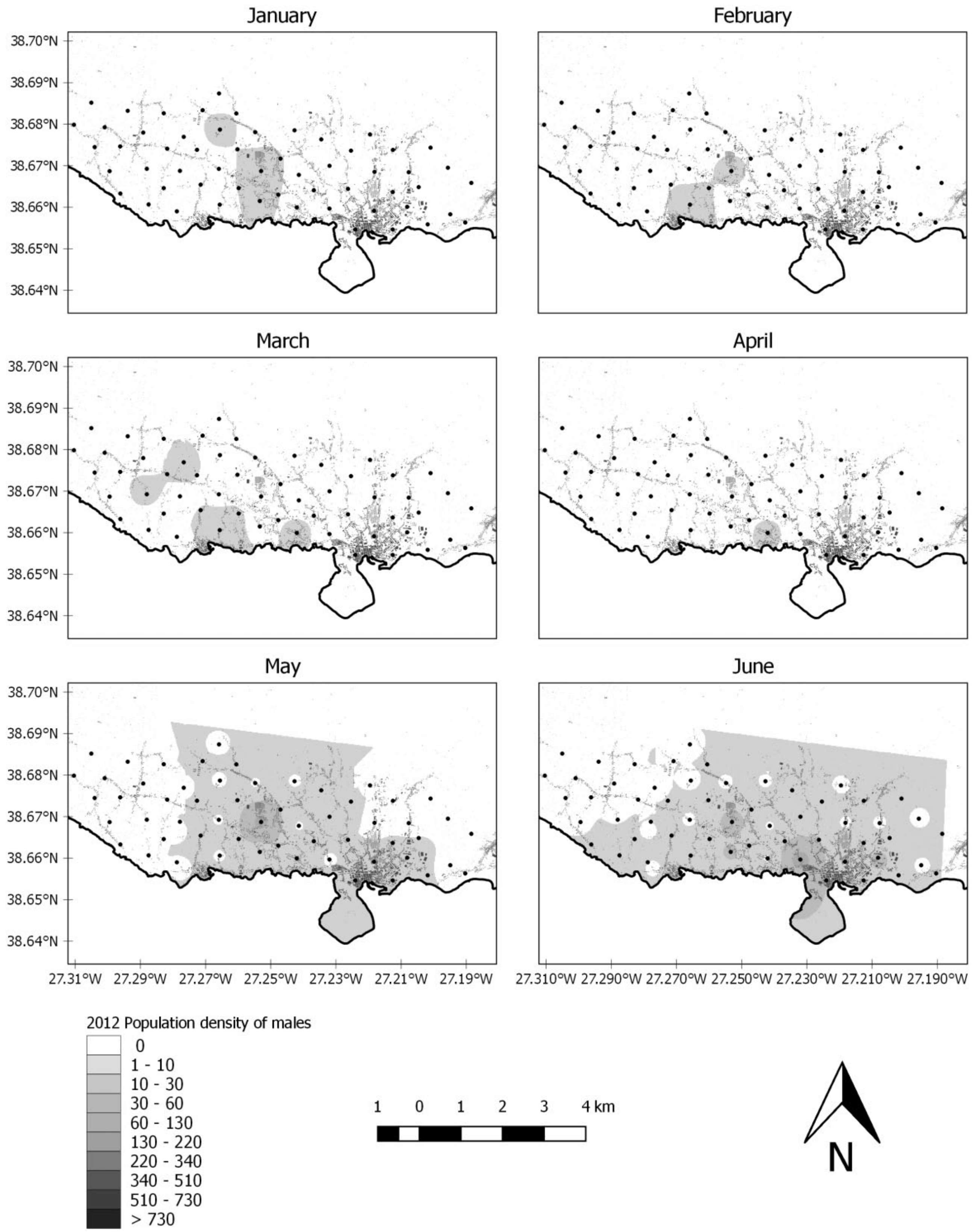


Fig. 9. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2012 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

limit based on research done by Lopes et al. (2006c), where these authors identified 200 m as the maximum altitude at which this insect was detected at this latitude. At each site there was a McPhail baited (Biosani, Palmela, PT) with Biolure MedFly lure (ammonium acetate, putrescine, and trimethylamine) and a DDVP pellet, regardless of the presence/absence of any fruit plant hosts of *C. capitata*.

Counts of wild adults of *C. capitata* in each trap were made every 15 d and the attractant was replaced every 2 months, even though, according to Ferrer Tena et al. (2007) the Biolure MedFly can withstand up to 120 d. A tight schedule was taken in consideration in the event of an unexpected situation that could delay the regular maintenance of the traps, and this way the traps would have always good conditions of attractiveness.

On Terceira Island the network was installed on the south side of the island to include the areas with highest density and annual recurrent presence of *C. capitata* (Pimentel 2010). The locations of these traps were restricted by access granted to the areas, but every effort was made to keep to the intended 1 km spacing. On this island, the study started at the beginning of April 2011 and ended at the last week of December 2014. There were 28 traps monitored for the entire time of this study on Terceira Island.

On Sao Jorge Island, where no prior work had been conducted on Medfly, the network of traps was installed to cover the most productive areas on both the south and north sides. There were 32 traps monitored for the entire time of this study on Sao Jorge Island, with 18 on the south side and 14 on the north side. In this island, the

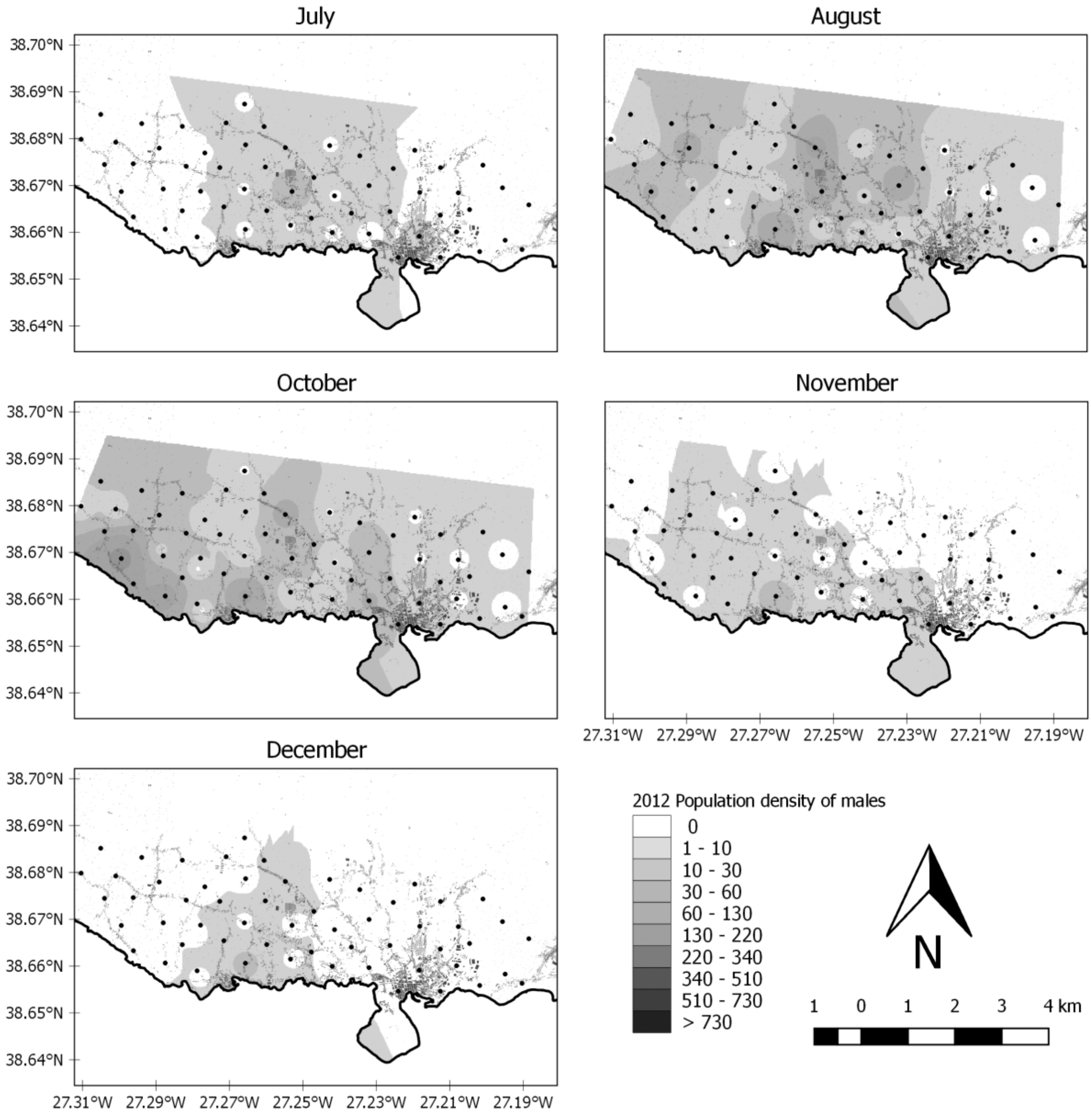


Fig. 10. Continuation of Figure 9.

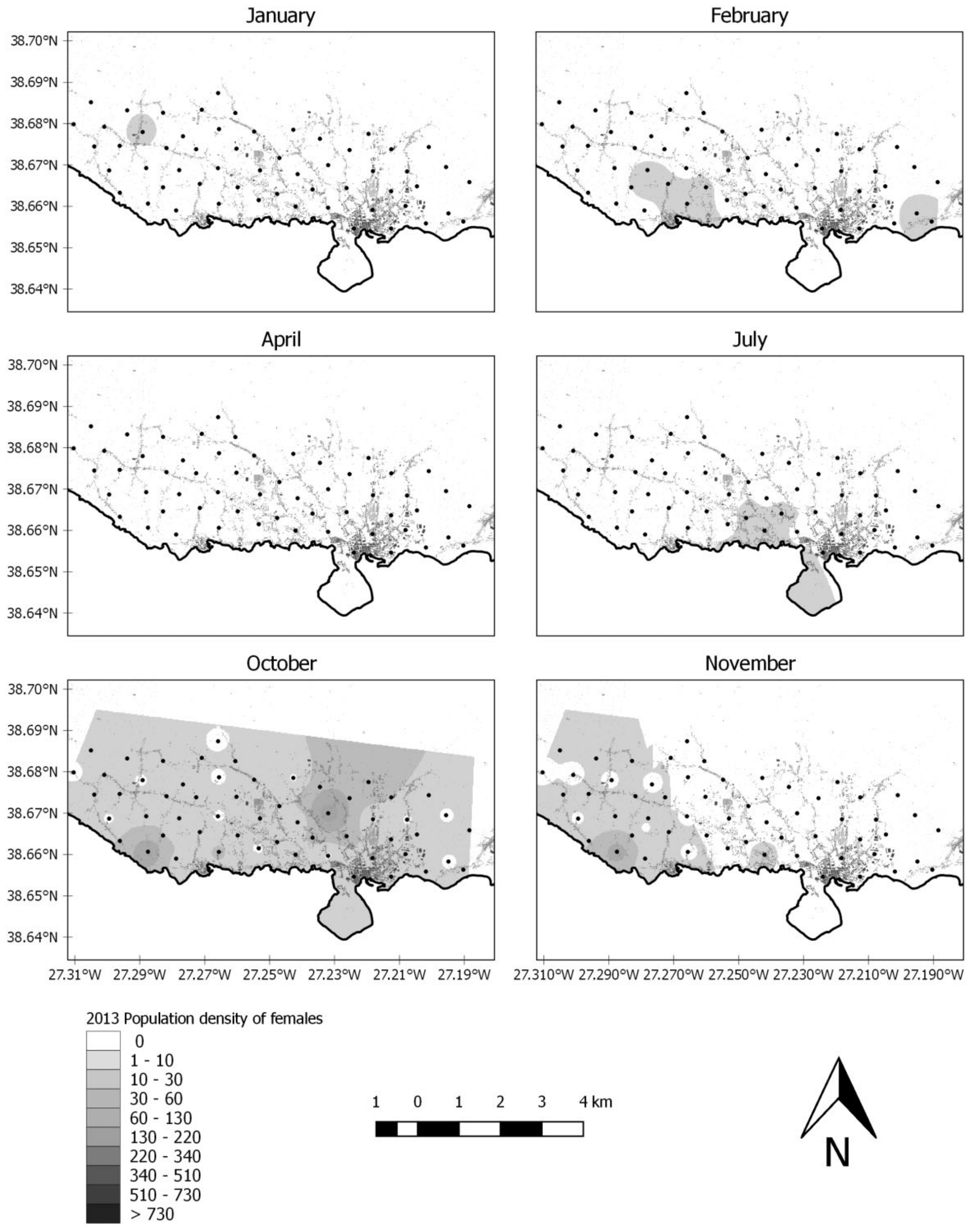


Fig. 11. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2013 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

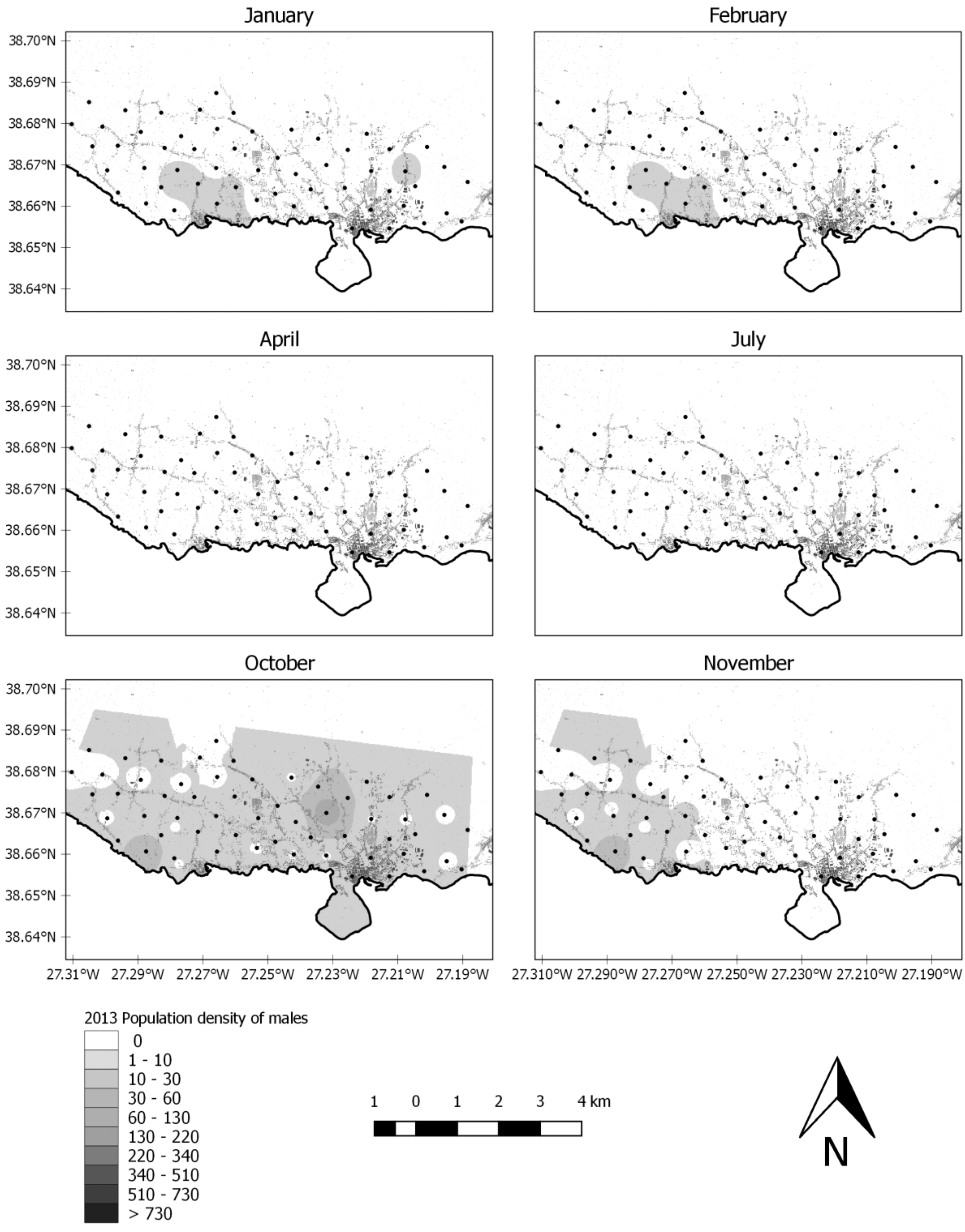


Fig. 12. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2013 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

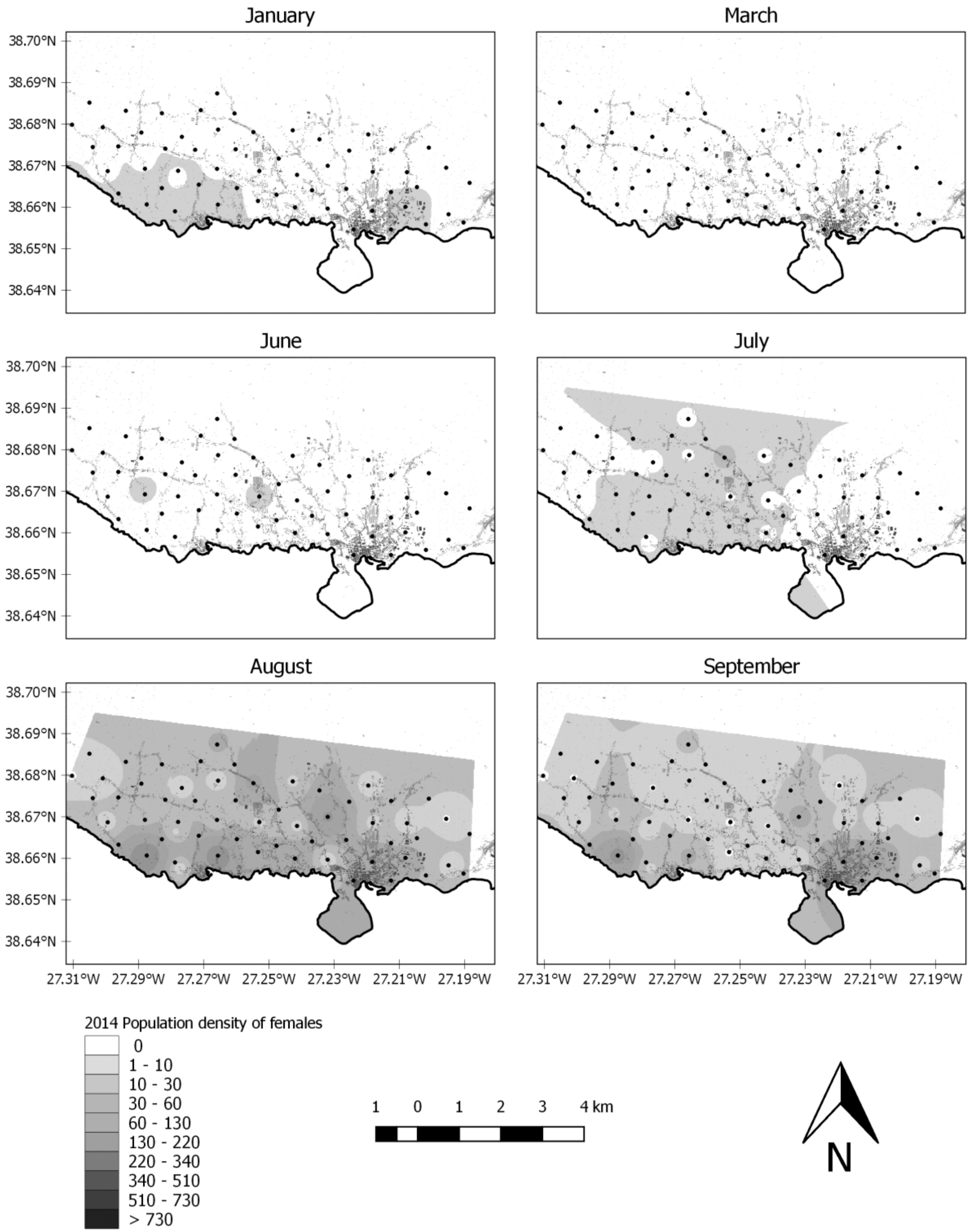


Fig. 13. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2014 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

study started at the beginning of March 2011 and ended at the last week of September 2014.

To evaluate fruit infestations on both islands, the fruits were collected, weighted, and stored following the same methodology used by Lopes et al. (2006c), every fifteen days, simultaneously with trap counting. All fruit samples were georeferenced, weighed, and stored in boxes with some substrate. The quantity of fruit sampled varied with availability.

On Terceira Island, fruit sampling was very dependent on the access we got to the fruit trees. The surveyed area, despite the mix of metropolitan and rural characteristics, has a record of permanent Medfly populations even when the rest of the island doesn't (Pimentel 2010). That's where the majority of the old farms on Terceira Island are located. The traps were placed very near the location of these fruit hosts, but never inside the perimeter of the properties for this reason.

For the spatio-temporal analysis, it was used the interpolation method called Inverse Distance Squared Weighted (IDSW). The IDSW method was introduced by Lsaaks and Srivastava (1989) and according to Kemp (2008) is one of the oldest, simplest approaches and the most readily available method. IDSW assumes that each sampled point is under a local influence that diminishes with distance. Thus, points in the near neighborhood are given high weights, whereas points at a far distance are given small weights (Lsaaks and Srivastava 1989, Shekhar and Hui 2007). For values of non-sampled points, there is an assumption that these can be approximated as a weighted average of values at sampled points according to the distances from that point, or from a given number of the closest sampled points (Kemp 2008). Weights are usually inversely proportional to a power of distance, and the most common choice by researchers is the power of 2 (Pimentel et al. 2006; Bonsignore et al. 2008; Lopes et al. 2008, 2010, 2012; Sciarretta and Trematerra 2011).

The GIS software used to perform this interpolation method was the QGIS software version 7.0.4 and the all statistical analysis was performed using the IBM SPSS Statistics software version 22.

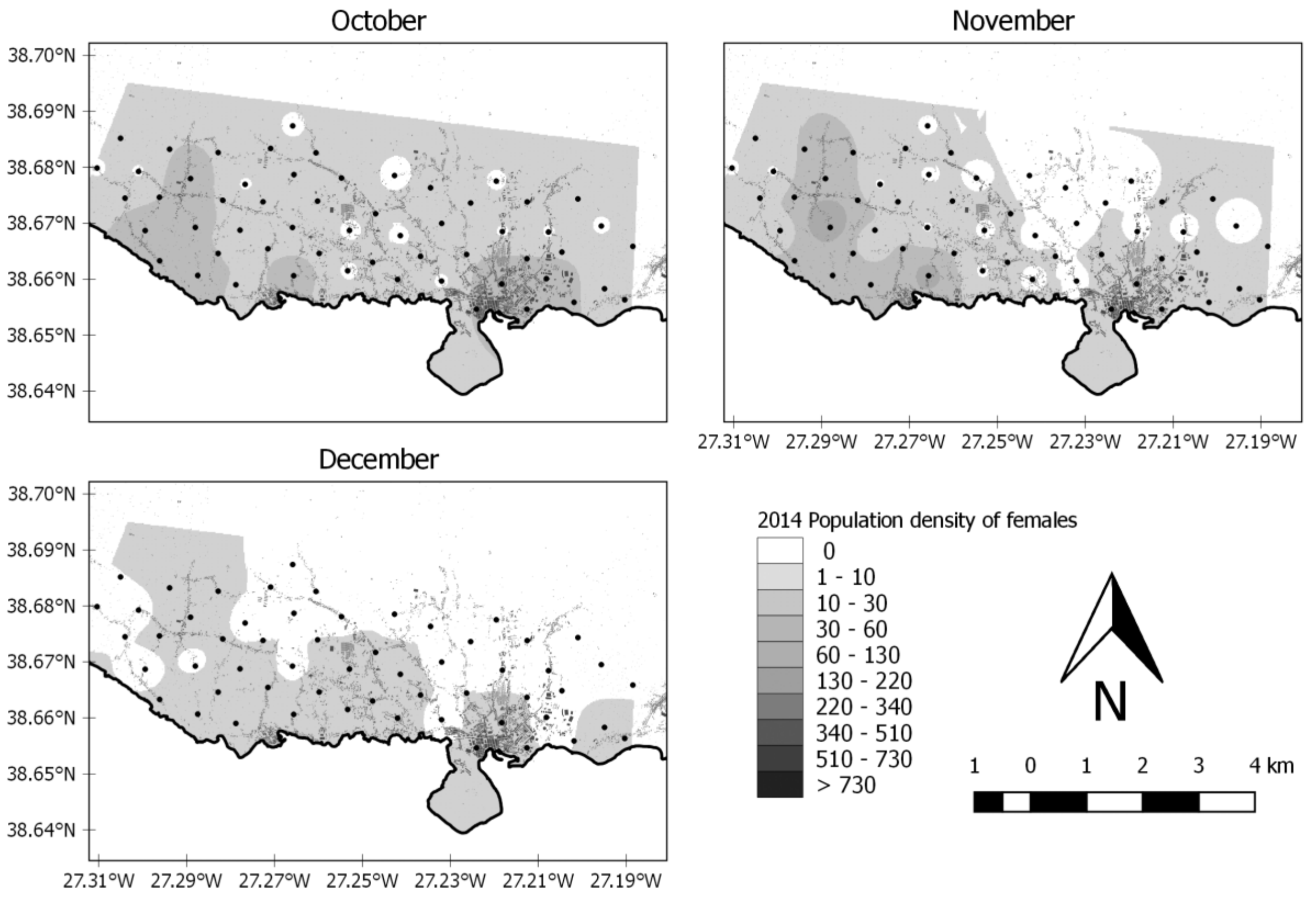
Results

The monthly average air temperatures recorded for Terceira Island (Fig. 2) over the 4 years of study followed an expected pattern. The monthly average air temperature reached a maximum in August (21.2–23.8) every year and a minimum in February (13.9–14.7).

On Terceira Island (Fig. 4), the adult abundance peaks of *C. capitata* of 2012, 2013 and 2014 were substantially lower than that observed in 2011. The first adults of *C. capitata* were detected in June 2011 and peaked during October with 3 flies/trap/day (FTD) for females and 2.1 for males. In 2012, the Medfly population abundance peaked during October with 0.4 FTD for females and 0.3 FTD for males.

In 2013, the Medfly population abundance reached a peak of 0.5 FTD for females and 0.3 FTD for males at the end of October. In 2014, the Medfly abundance peaked in August with 1 FTD for females and 0.6 FTD for males.

From the spatio-temporal distribution of *C. capitata* population in Terceira Island (Figs. 5–16), it is possible to identify the main



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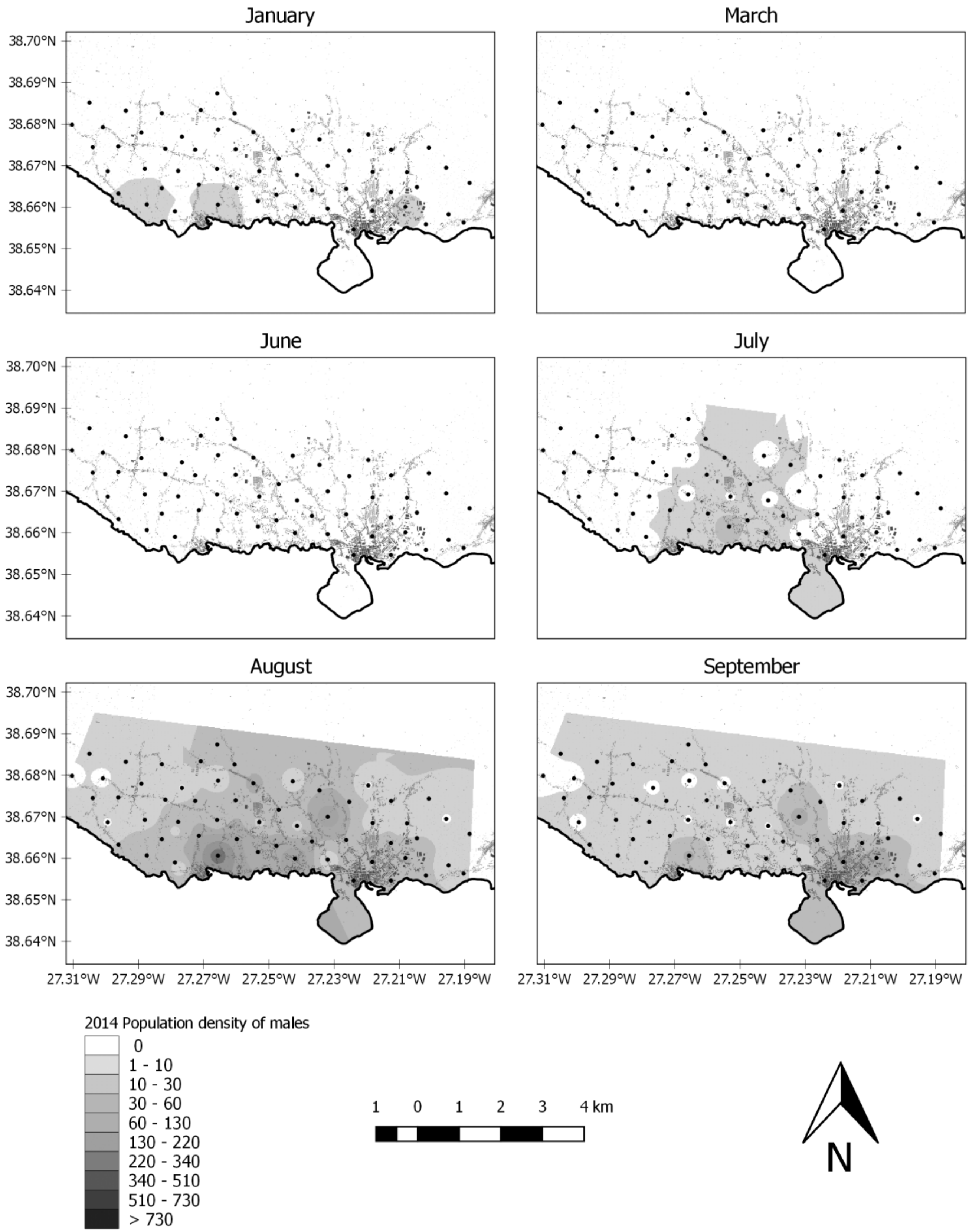


Fig. 15. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2014 monthly trap counts. Trap location, in Terceira Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

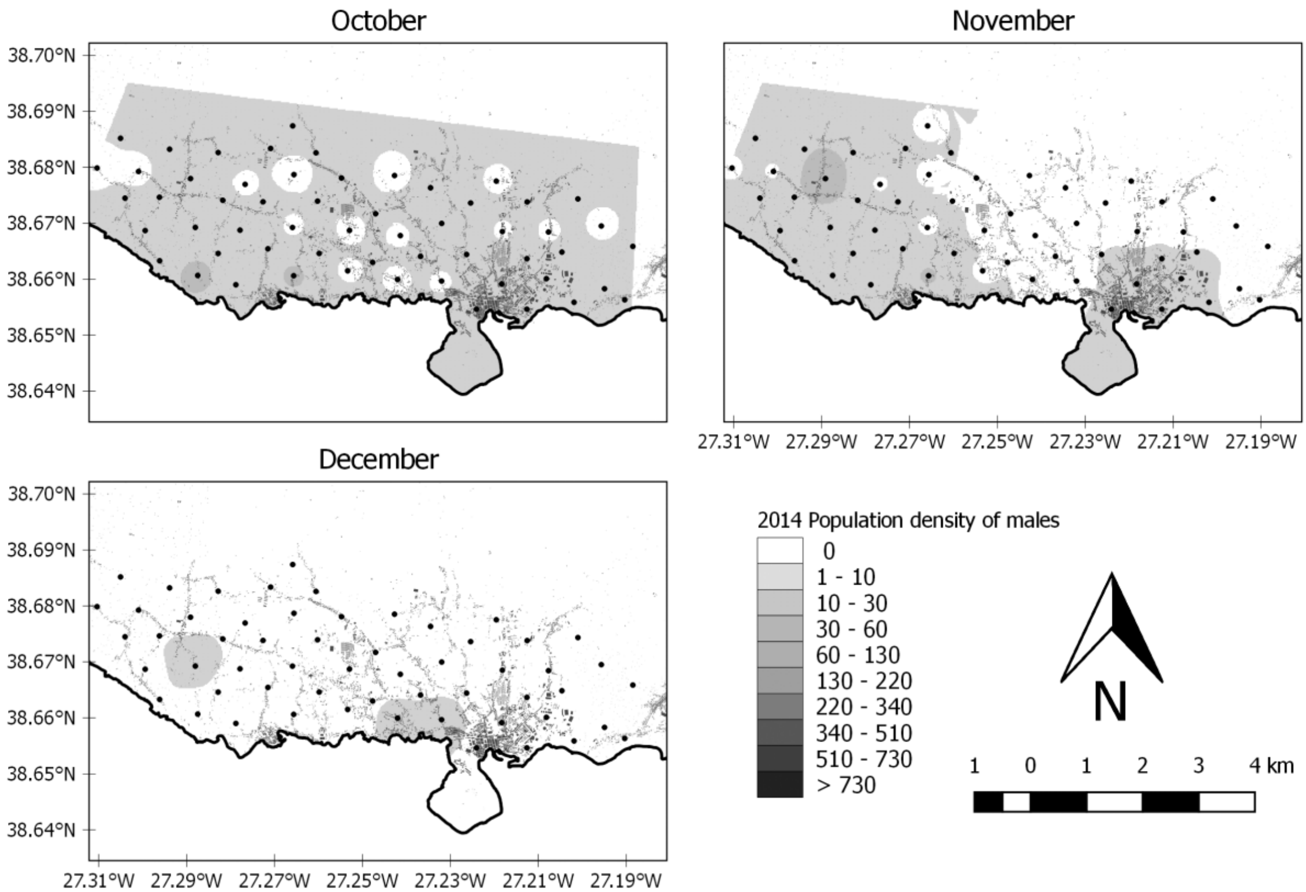


Fig. 16. Continuation of Figure 15.

hotspots of Medfly during this study. Annually, the Medfly first starts to appear mostly in the traps located at Sao Bartolomeu and Sao Mateus parishes.

The infestation of fruits (Table 1) shows the highest infestation levels in fruits of *S. mauritianum* (Scop.) and of *Eriobotrya japonica* (Thunb.) while only fruits of *Annona cherimola* (Mill.) presented no infestation.

Fruits of *E. Japonica* and of *S. mauritianum* had its higher infestation levels (411 ± 232 and 193 ± 50, respectively) in May 2012 and April 2013, respectively.

Table 1. Seasonal *C. capitata* average ± SE fruit host infestation levels expressed as Larvae per Kg of fruit in the Terceira area of study

Host fruits year and month		*P. guineense (*Sw.)	*Ficus carica* (L.)	*C. aurantium* (L.)	*E. japonica* (Thunb.)	*S. mauritianum (*Scop.)	*A. cherimola* (Mill.)
2011	May				98 ± 110		
	Sep					110 ± 90	
2012	Jan			0	5 ± 0		
	Feb			0		5 ± 5	
	Mar			0		154 ± 0	
	May				411 ± 232		
	Oct	78 ± 0	0				
	Nov			0			
	Dec			0			
2013	Jan			0	0 ± 0	13 ± 0	
	Feb			0		26 ± 0	
	Apr			1 ± 1	131 ± 171	193 ± 50	
	Jul					26 ± 6	
	Oct	105 ± 116	4 ± 8	5 ± 2		63 ± 0	0
	Nov			0			0
2014	Jan			0		0	
	Mar			0	7 ± 2	28 ± 0	
	Nov	42 ± 61	33 ± 43	0		150 ± 150	

Fruits of *Psidium guineense* (Sw.) had its higher infestation levels (105 ± 116) in October 2013 and from all the sampled fruits with infestation levels, fruits of *Citrus aurantium* (L.) had the lowest infestation levels.

During this study, especially during the first half of every year, the location of sampled fruits that had some degree of infestation was not coincident with the existence of *C. capitata* adults in the nearby traps. Fruits from *E. Japonica* sampled during 2012 January had an average infestation of 5 ± 0 larvae/kg while none of the traps nearby trapped a single female adult (Fig. 17). Similar situation happened in places where *S. mauritianum* fruits where sampled during February and March of 2012, January of 2013, January and March of 2014 (Fig. 18).

On Sao Jorge Island, the average monthly air temperature during this study was regular and accordingly to each season (Fig. 19). The monthly average air temperature reached a maximum in August (22.0–22.9) every year and a minimum in February/March (13.6–13.8).

On Sao Jorge Island (Fig. 21), the female abundance peaks of 2012–2014 were substantially lower than that observed in 2011. The first adults were recorded in April in 2011 and the population density began increasing gradually. Male adults reached a peak of 0.6 FTD in the middle of August 2011, while female adults reached a peak of 3.7 FTD in October 2011.

From November 2011 to January 2012 there was a very slow rate of population decline to an FTD of 0. In 2012 the first adult captures were in March and ended in January 2013. During this period *C. capitata* population, the females peaked on July with an FTD value of 0.6, while the males peaked on May with an FTD value of 0.1. In 2013, captures were not recorded until July and both sexes peaked twice with the same intensity. The first peak occurred in August and the second peak in November. For both peaks, the female's FTD value was 0.4, while male's FTD value was 0.1. In 2014 the first captures occurred in April and increased up to an FTD value of 1.1 in September.

From the spatio-temporal distribution of *C. capitata* population in Sao Jorge Island (Figs. 22–35), every year, the Medfly first starts to appear in the traps located at the south area of the island. At the north part, this insect only starts to appear in traps in mid year.

During this study, the location of sampled fruits that had some degree of infestation was coincident with the existence of *C. capitata* adults in the nearby traps.

The fruit infestation levels shows no infestation in fruits of *Persea americana* (C. Bauh), *A. cherimola* (Mill.), *Citrus limetta* (Risso), *Mangifera indica* (L.), *Cydonia oblonga* (Mill.), *Pyrus comunis* (L.), *Punica granatum* (L.), and *Solanum betaceum* (Cav.).

Fruits of *Coffea arabica* (L.) were the most infested (Table 3), reaching an average infestation level of 1089 ± 0 larvae/Kg in May of 2012. The fruits with the lowest infestation levels (7 ± 0) were of *Diospyros virginiana* (L.) in October 2013.

Discussion

According to previous works on Terceira Island (Lopes et al. 2009, Pimentel 2010), the adult abundance peak of *C. capitata* is normally observed from mid-September to the end of November in each year. Since the first studies conducted on Terceira, there has been always some FTD values variation between years (Pimentel et al. 2014a). However, until now, a drop in trap counts as the one observed in 2012–2014 was never observed before. On Sao Jorge Island there was also a considerable drop in trap counts after 2011 population abundance peak.

This reduction could be related to several factors. Although this is the first study conducted in Sao Jorge Island, the Medfly population abundance seems to have been affected by the same event.

According to Vieira and da (1952), when intensive and prolonged rainfall (>125mm) occurs and the air temperature is <15°C, causes high mortality of adults of *C. capitata*, mainly due to their daily inactivity. There is also a higher rate of mortality of pupae buried on the soil under these circumstances. Works of De Meyer et al. (2008) aiming to predict and compare potential geographical distributions of the *C. capitata*, has found that this species dominates at temperatures of 24–26°C and rainfall of 0–1,000 mm.

Although it was not possible to obtain weather data for the entire period of this study, for the Sao Jorge Island, the rainfall in May 2012 on Terceira Island affected to the entire Central Group (Fig. 20). Therefore, the excessive precipitation recorded in May 2012 (2,516 mm) and the heavy rainfall that was predominant during 2012, probably had a severe impact on the *C. capitata* population on both islands. Part of the life cycle is in the soil and excessive rainfall can cause waterlogging or may expose the larvae and pupae to predators. This hypothesis could explain why there was a very low *C. capitata* population peak in 2012, as opposed to the population peak in 2011.

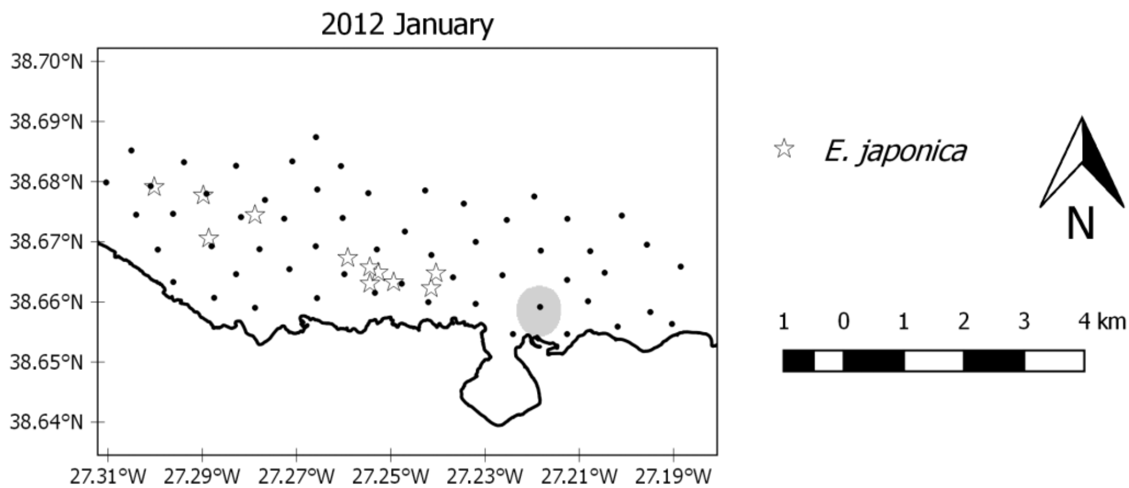


Fig. 17. Contour map of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2012 January trap counts. Trap location, in Terceira Island, is shown by spots and fruit sampling location of E. Japonica is shown by a star; x, y axes are expressed in Geographic coordinates.

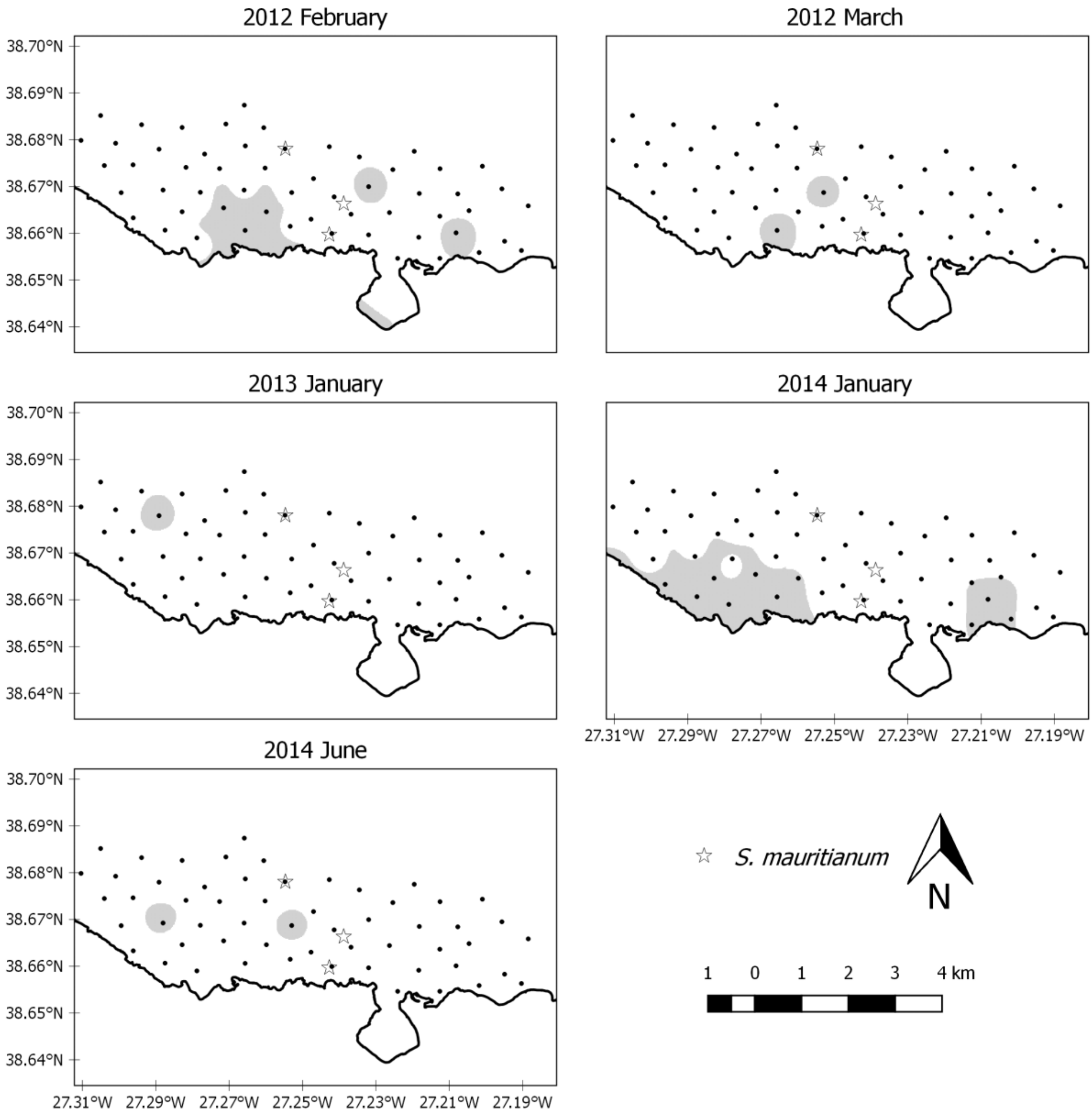


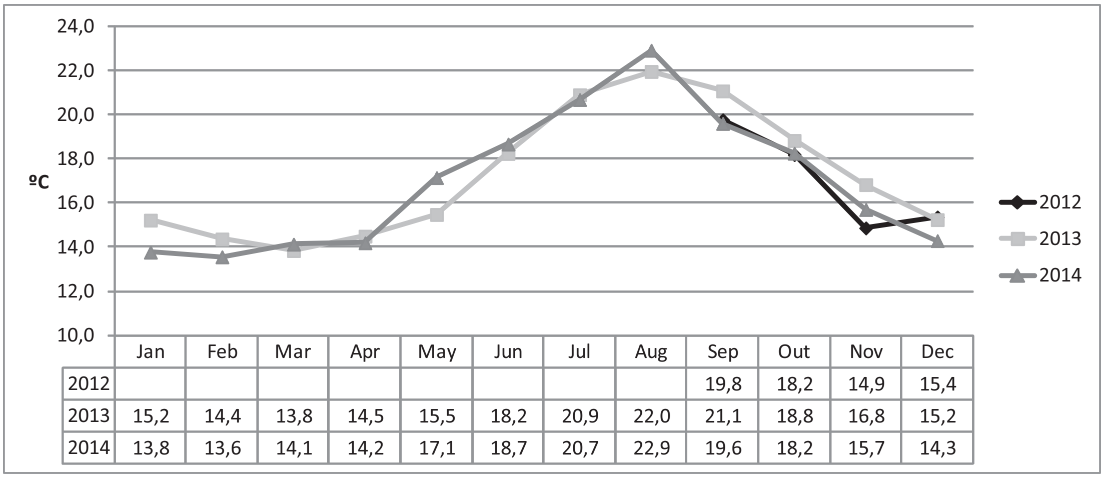
Fig. 18. Contour map of *C. capitata* (adult females) distribution obtained by IDSW procedures to trap counts. Trap location, in Terceira Island, is shown by spots and fruit sampling location of S. mauritianum is shown by a star; x, y axes are expressed in Geographic coordinates.

The Logit regression results (Table 4) suggests that trap counts were influenced by Temperature and Rainfall. The Pearson's chi-square for Terceira Island is considerably higher than the one calculated for Sao Jorge Island. The higher value for Terceira Island reveals a larger discrepancy between the observed and expected frequencies. This probably happened because the distance of the weather station to the study area in Terceira Island is bigger than the one in Sao Jorge Island.

On Terceira Island, in 2014 there has been an anticipation of the annual population abundance peak. In 2014 the adult abundance peak occurred in August as opposed to what would be expected (Lopes et al. 2009, Pimentel 2010). The year 2014 was a particular dry year compared with previous years (Fig. 3) and that could explain why, in 2014, the FTD value of population abundance peak was higher than 2012 and 2013.

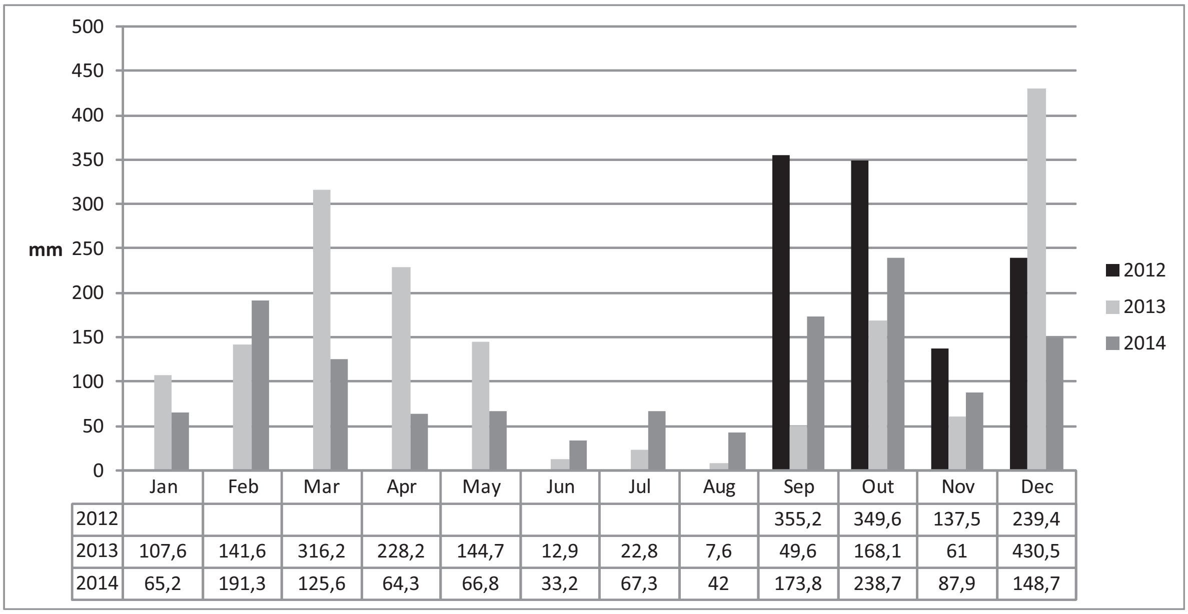
The spatio-temporal analysis has revealed how the Medfly populations are distributed over time. More importantly, it was possible to identify the main hotspots on both Islands. On Terceira Island, the main hotspots are mainly located where used to exist old larges farms that were the main fruit suppliers in 1800s for boats traveling to the United Kingdom (Lopes et al. 2006a). Although on Sao Jorge Island, the main hotspots are located in the south part of the Island and in small orchards near to the airport and two important harbors of this island.

Despite the advantages of food-based lures for capturing both females and males, these lures are very female-biased (Epsky et al.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Out	Nov	Dec
2012									19,8	18,2	14,9	15,4
2013	15,2	14,4	13,8	14,5	15,5	18,2	20,9	22,0	21,1	18,8	16,8	15,2
2014	13,8	13,6	14,1	14,2	17,1	18,7	20,7	22,9	19,6	18,2	15,7	14,3

Fig. 19. Average monthly air temperature (°C) at Manadas parish on Sao Jorge Island from 2012 to 2014. (Valor 2015).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Out	Nov	Dec
2012									355,2	349,6	137,5	239,4
2013	107,6	141,6	316,2	228,2	144,7	12,9	22,8	7,6	49,6	168,1	61	430,5
2014	65,2	191,3	125,6	64,3	66,8	33,2	67,3	42	173,8	238,7	87,9	148,7

Fig. 20. Monthly rainfall (mm) at Manadas parish on Sao Jorge Island from 2012 to 2014. (Valor 2015).

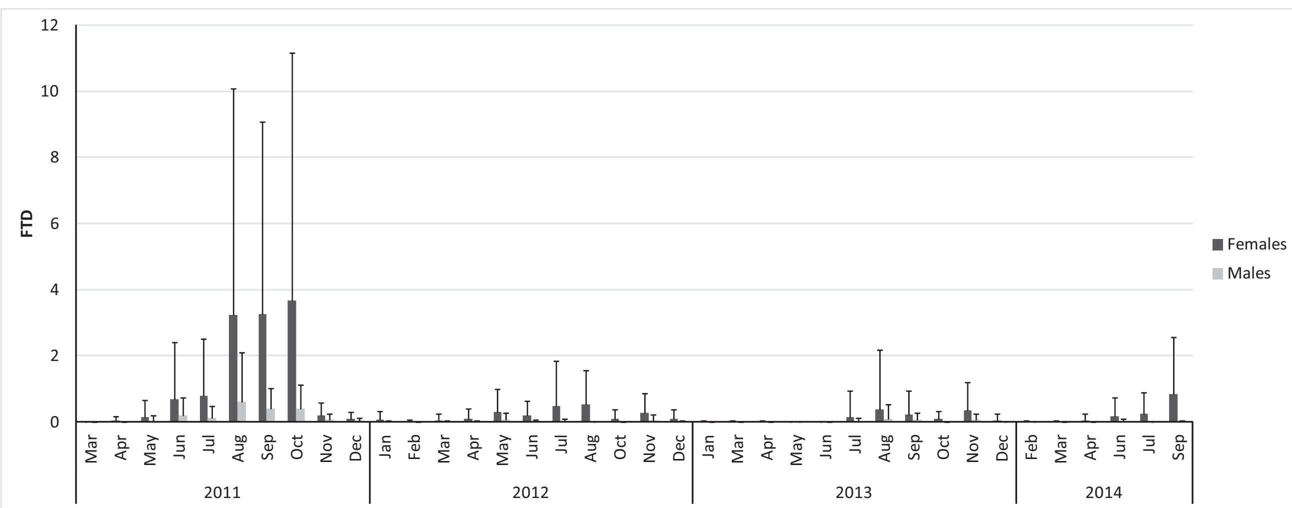


Fig. 21. Captures of males and females on Sao Jorge Island expressed as numbers of FTD from 2011 to 2014.

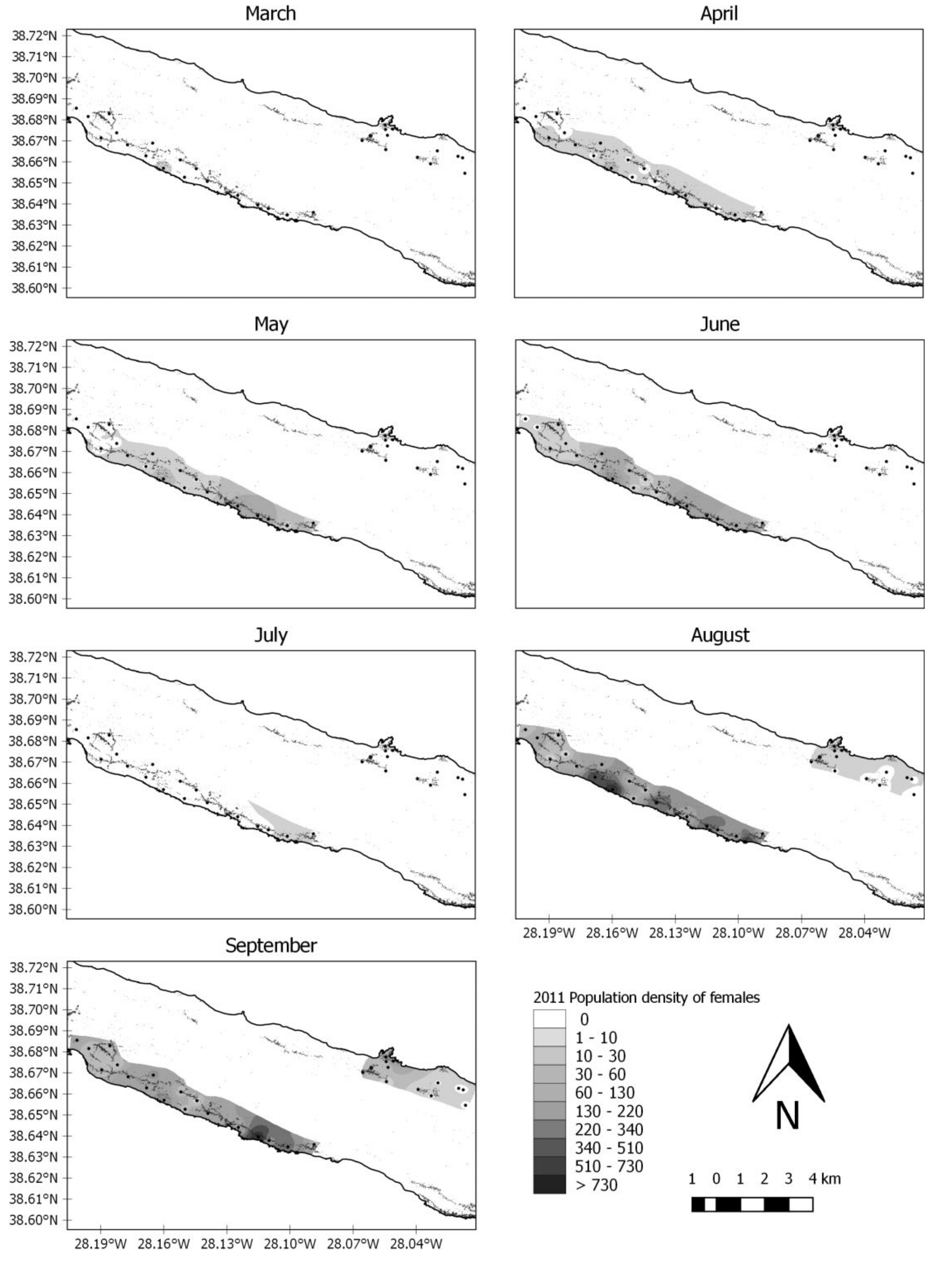


Fig. 22. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2011 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

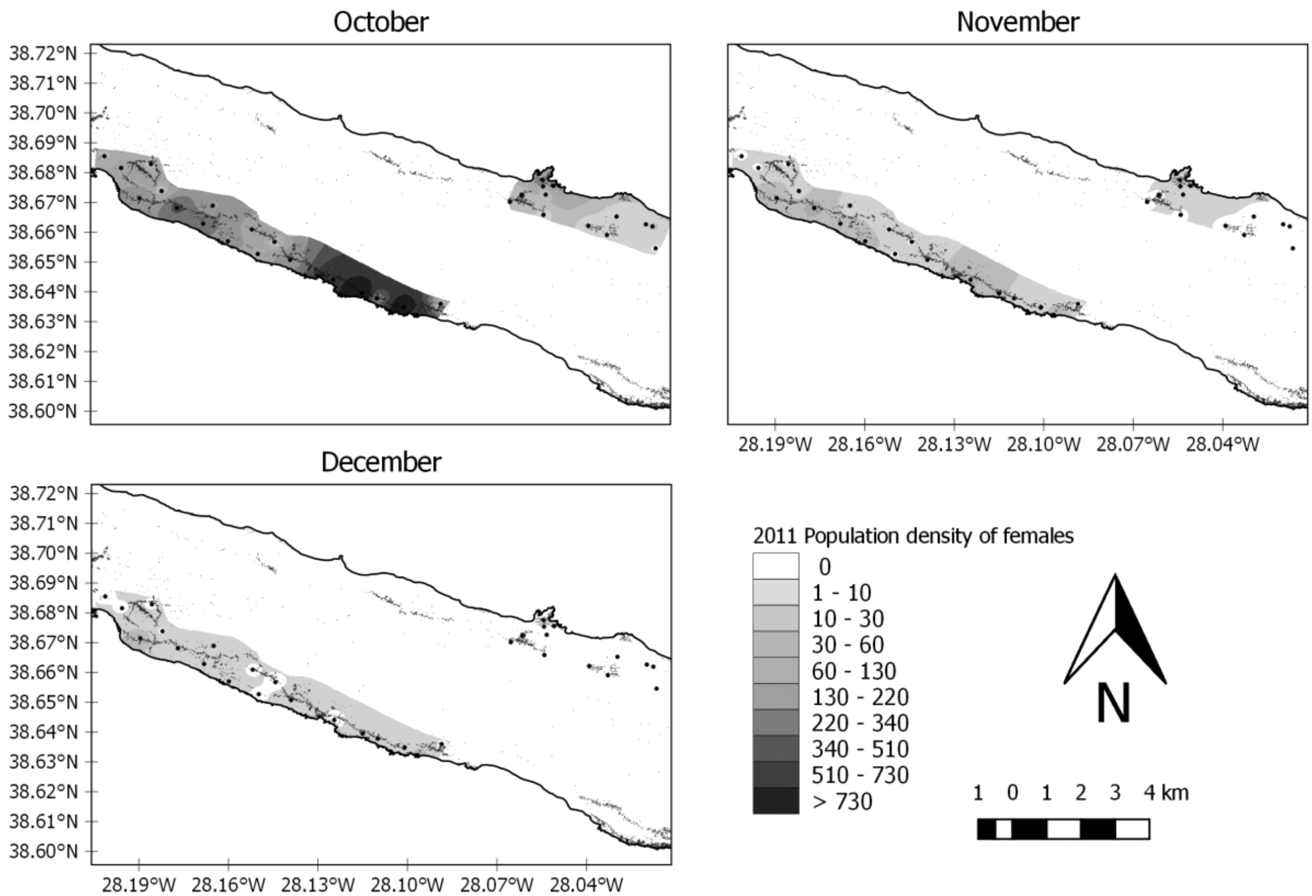


Fig. 23. Continuation of Figure 22.

2014). When the female population peak occurred on October 2011, the catch of females was about nine times more than males. On Terceira Island, the female captures are normally at most two times more than male captures (Lopes et al. 2006c), and depending on the weather and landscape conditions, sometimes more males than females are caught (Pimentel 2010, Pimentel et al. 2014b). Epsky et al. (1999) evaluated female-targeted trapping systems for this species and 43–90% of the total captures were female adults. Therefore, considering that the same lures were used in both Islands, the results suggest a higher concentration of females on Sao Jorge, than on Terceira Island.

On Terceira Island, the fruits of *S. mautitianum* are the only ones that have no commercial value and; however, these are one of the most infested. These results supports the argument already suggested in other studies (Lopes et al. 2006c, 2009; Medeiros et al. 2007; Pimentel 2010; Pimentel et al. 2014b) about the great importance of this invasive species in the maintenance of populations of the Medfly. This invasive plant is present practically all over any area, either private or in the public domain, such as streams banks. The fruits of *C. aurantium* (L.) were one of the most sampled fruits and the low infestation level probably indicates a very low success rate of larval survival despite the several visible puncture signals on the fruit skin. Fruits of *A. cherimola* were the only sampled fruits with no infestation, although this fruit is on the list of the potential fruit hosts on Terceira Island (Lopes et al. 2006c).

Comparing Table 1 results with the ones in Figure 4 and with the monthly average air temperatures in Figure 19, one obvious result stands out. Papadopoulos et al. (1998) studied the temporal changes in the composition of the overwintering larval population of *C. capitata* and came to the conclusion this insect can successfully overwinter in cold temperate areas, where subfreezing temperatures are frequently observed over the long winter period accompanied by a long absence of suitable host trees.

Based on the life cycle of this insect and the weather conditions typical of the Azorean Archipelago, the lack of captures during the winter/spring, while there are fruits infested (Table 1), could be attributed to the low air temperatures and the excessive rainfall characteristic of the season (Bodenheimer 1951, Fletcher 1989, Meats 1989, Liu et al. 1995, Aluja and Rull 2009). Another reason commonly cited to justify the low catch of adults in traps at this time of the year is the unavailability of mature fruit hosts (Papadopoulos 2005, Lopes et al. 2006b, Medeiros et al. 2007, Oliveira and Medeiros 2009, Papachristos and Papadopoulos 2009, Pimentel 2010, Radonjic et al. 2013).

Although these are all valid assumptions, one must consider the possibility of abiotic factors interfering with the trap's attractant volatilization rate and on the daily adult of *C. capitata* activity patterns.

Air temperature inside a trap will regulate the volatilization rate of the attractant odours. Therefore, the radius of effectiveness of food attractants might be directly related with air temperatures (Heath et al. 1995, Díaz-Fleischer et al. 2014). This could mean that traps will likely not be able to attract the already low number adult abundance mainly because volatile compounds are not dispersing at

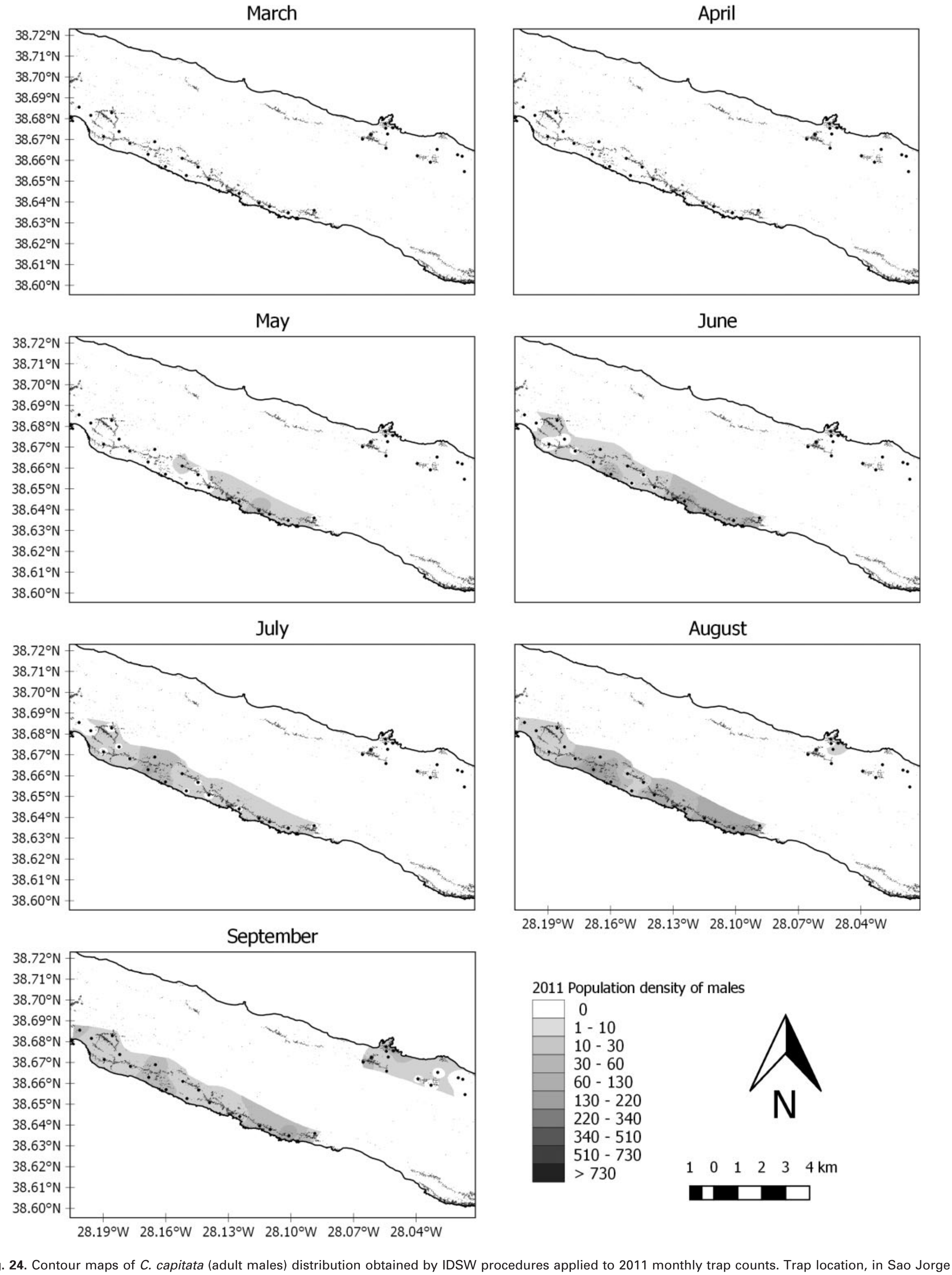


Fig. 24. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2011 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

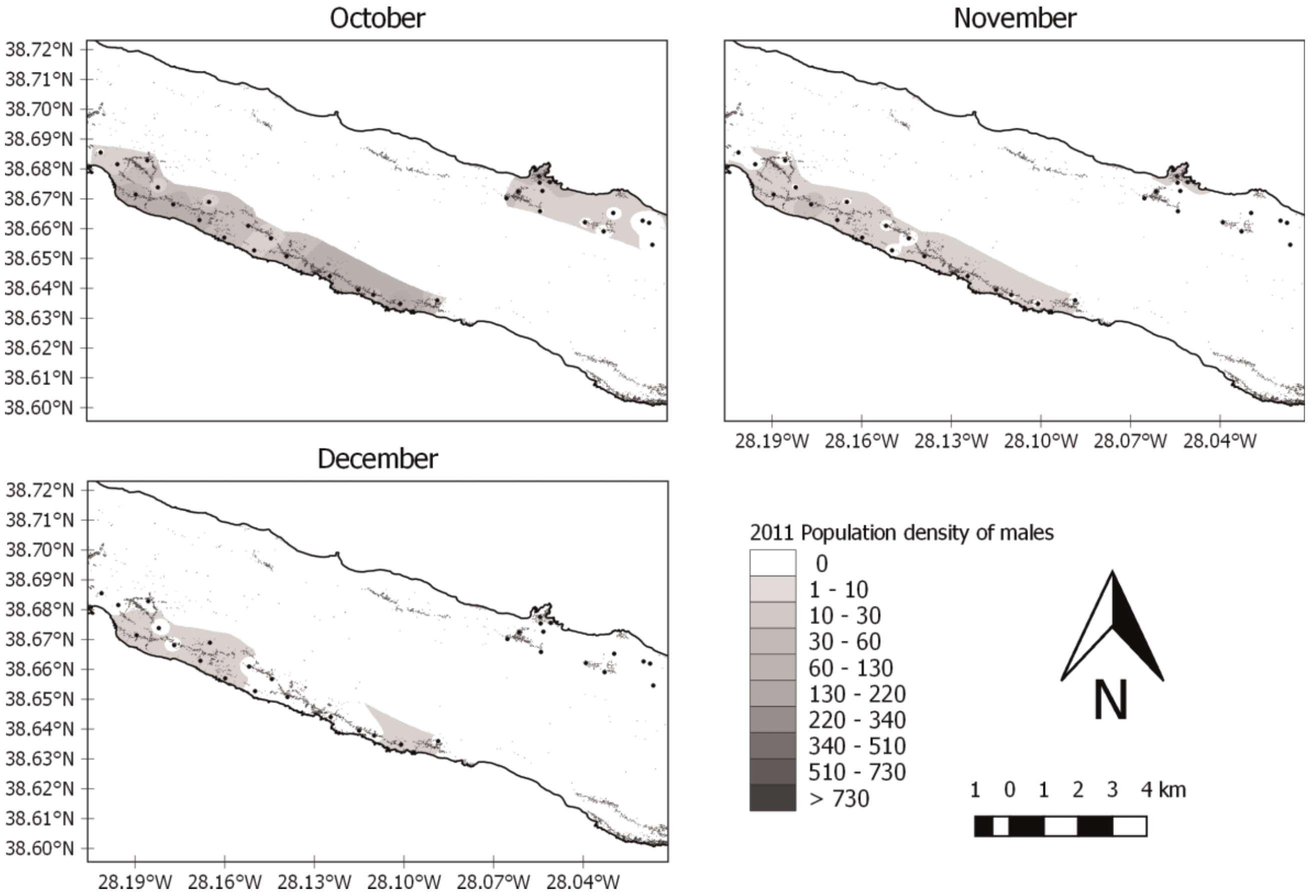


Fig. 25. Continuation of Figure 24.

the best possible rate and the adult Medflies are not as active as they would be with warmer air temperatures (Vieira and da 1952; Abed-Aall et al. 2014).

According to Nyamukondiwa et al. (2013), individuals of *C. capitata* expressing a temperature sensitive lethal mutation show greater critical thermal maxima and greater longevity under field conditions than reference individuals. However, further research on this subject is required to determine the presence of such mutation in the *C. capitata* populations present in the Azorean Islands.

Nevertheless, there are some adults of *C. capitata* somewhere during the winter season. Another possibility for this could come from Terceira's climate, which is also characterized by some microclimates where these adults could find some refuge from the harsh weather conditions. These microclimates can differ in air temperature and amount of Rainfall as a direct consequence of the island topography and wind direction. As a consequence, this could maintain the population abundance at a certain levels until May/June of the next year when it is normal to start capturing adults (Pimentel 2010).

Comparing the sampled fruits on Terceira Island (Table 1) with the ones sampled in Sao Jorge Island (Tables 2 and 3) the latter are very distinct from those on Terceira Island. Although fruit production on Sao Jorge is more directed to household consumption and the local market, the great variety of sampled fruits, as well as the infestation levels over the year, supports the possibility of having adults Medflies during the winter. This possibility is supported by the FTD values in Figure 21. On Sao Jorge Island, the present study took place in rural areas, meaning there is a considerable area of vegetation capable of providing shelter and ecological corridors, as happens in some areas on Terceira Island (Pimentel et al. 2014b). Also, most of the traps were placed inside orchards with living fences, which could buffer any interference of the air temperature (McAneney et al. 1990, Dias et al. 2006) on the volatile compounds involved in host and mate attraction.

According to Batista et al. (2006) the geographic location and topographic conditions of each Azorean island provides a different climate condition that affects fruit production. Furthermore, considering all the fruit hosts present, there are also significant yearly variations amongst individual fruit trees, which can add to the uncertainty of population levels from year to year.

Conclusions

The diversity of fruit hosts on Sao Jorge Island seems to provide sufficient opportunity for the Medfly to complete its life cycle during the even the harshest weather conditions. Both islands in the study have Medfly population peaks in October. But in 2012, the heavy rainfall probably had impact on the life cycle of Medfly, by causing high mortality in all life stages, this exceptional event affected population density levels into 2013.

The results from Sao Jorge Island indicate significantly lower male/female ratio than on Terceira Island. This is an important finding specially regarding when establishing the scenario parameters for a SIT application in each island. This still needs to be confirmed and evaluate the sex-ratio in other islands.

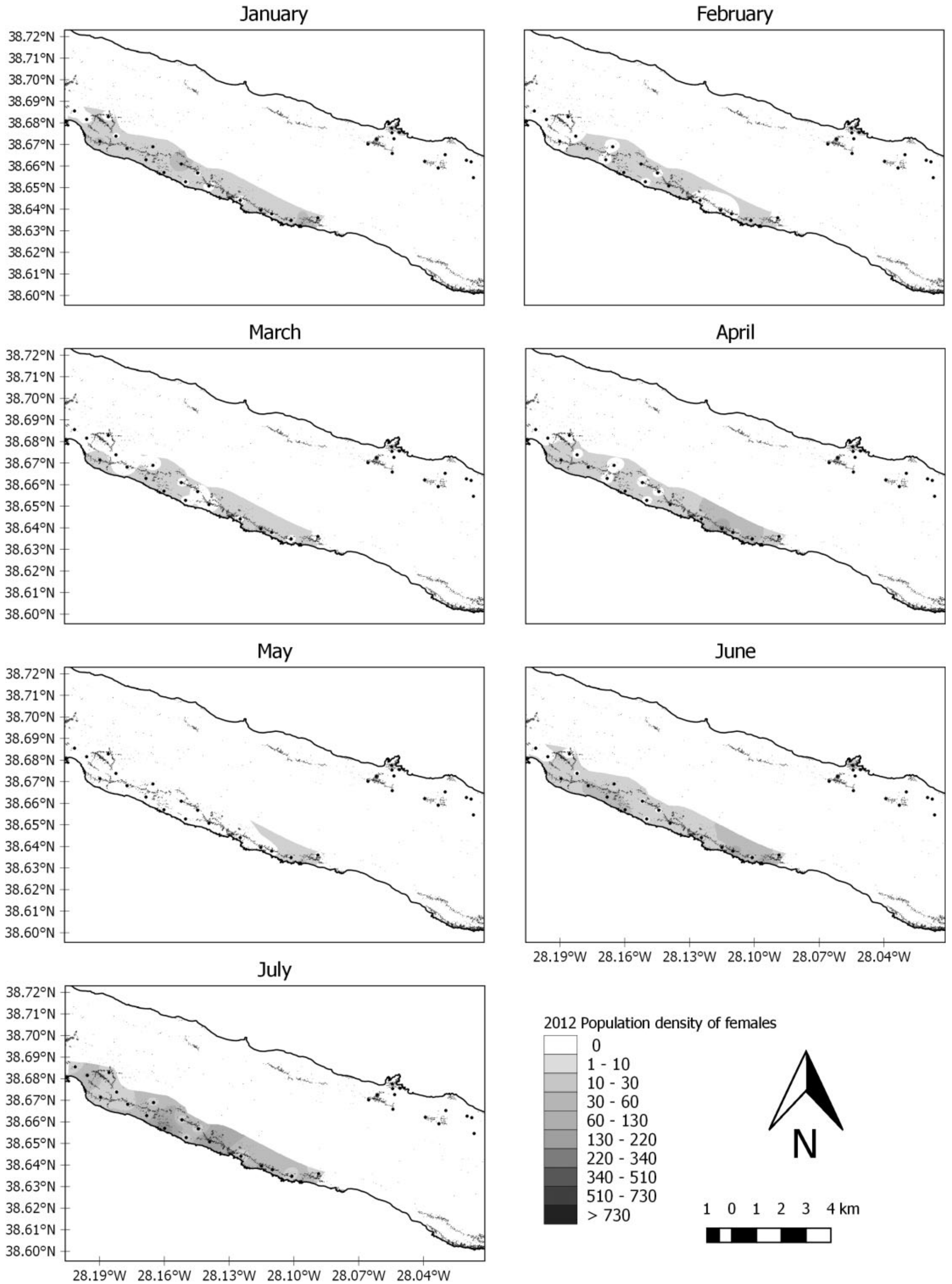


Fig. 26. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2012 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

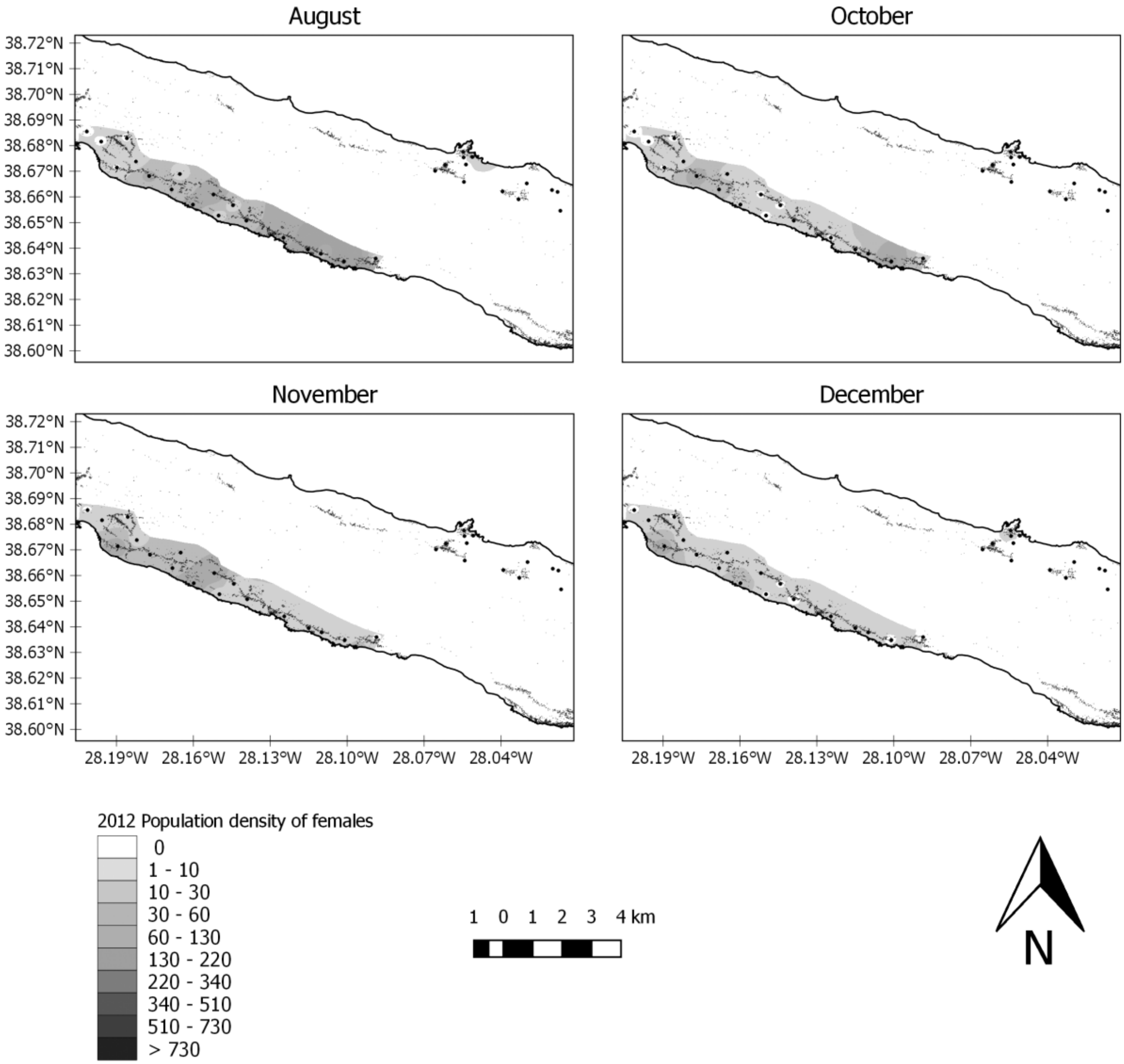


Fig. 27. Continuation of Figure 26.

The seasonality of *C. capitata* are generally linked with host fruit availability and abundance. However, fruit infestation levels are not synchronized with the trap counts, especially if these occur in winter/spring season. Fruit infestations in some fruits (e.g., fruits of *S. mauritianum* and *E. japonica*) occurred even while there were no trap captures at the same time. From this perspective, it is important to recognise the real importance of the invasive plants on the population dynamics of *C. capitata*. It is also important to consider the possibility of having different densities of traps according to the characteristics of each area in order to improve the network of traps surveillance's sensitivity on Terceira Island.

Although it is not possible for an adult of *C. capitata* to fly or even be dragged by the wind to another island, the daily regular maritime and air transport between islands makes it possible to reach any other island easily. Therefore, without an efficient control at airports and harbours, this can be a serious threat to any area-wide control program in any Island due to the high potential of reinvasion.

Despite the economic importance of fruit production of each island of the Azores Archipelago, the results of this study, mainly about the sex-ratio and the spatial distribution of this pest in both islands, has demonstrated the importance of this type of work to be conducted in other islands. Therefore, before any plan of control can be implemented, it is imperative for further investigation regarding *C. capitata* overwintering and behaviour on the other Azorean Islands. In particular, the relationship with host availability and abundance based on geographic distribution needs to be integrated with climatic data to develop predictions of the population dynamics.

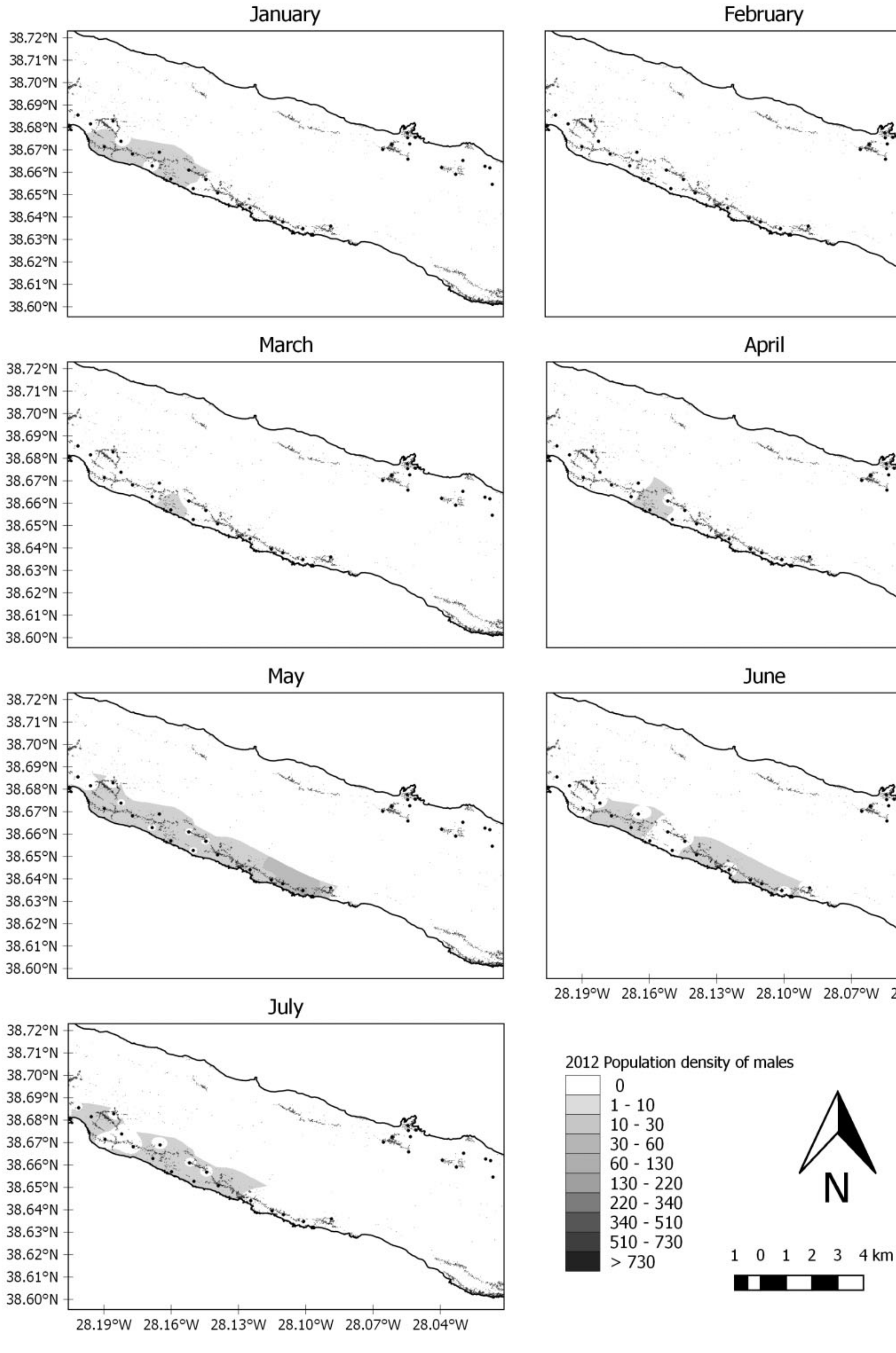


Fig. 28. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2012 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

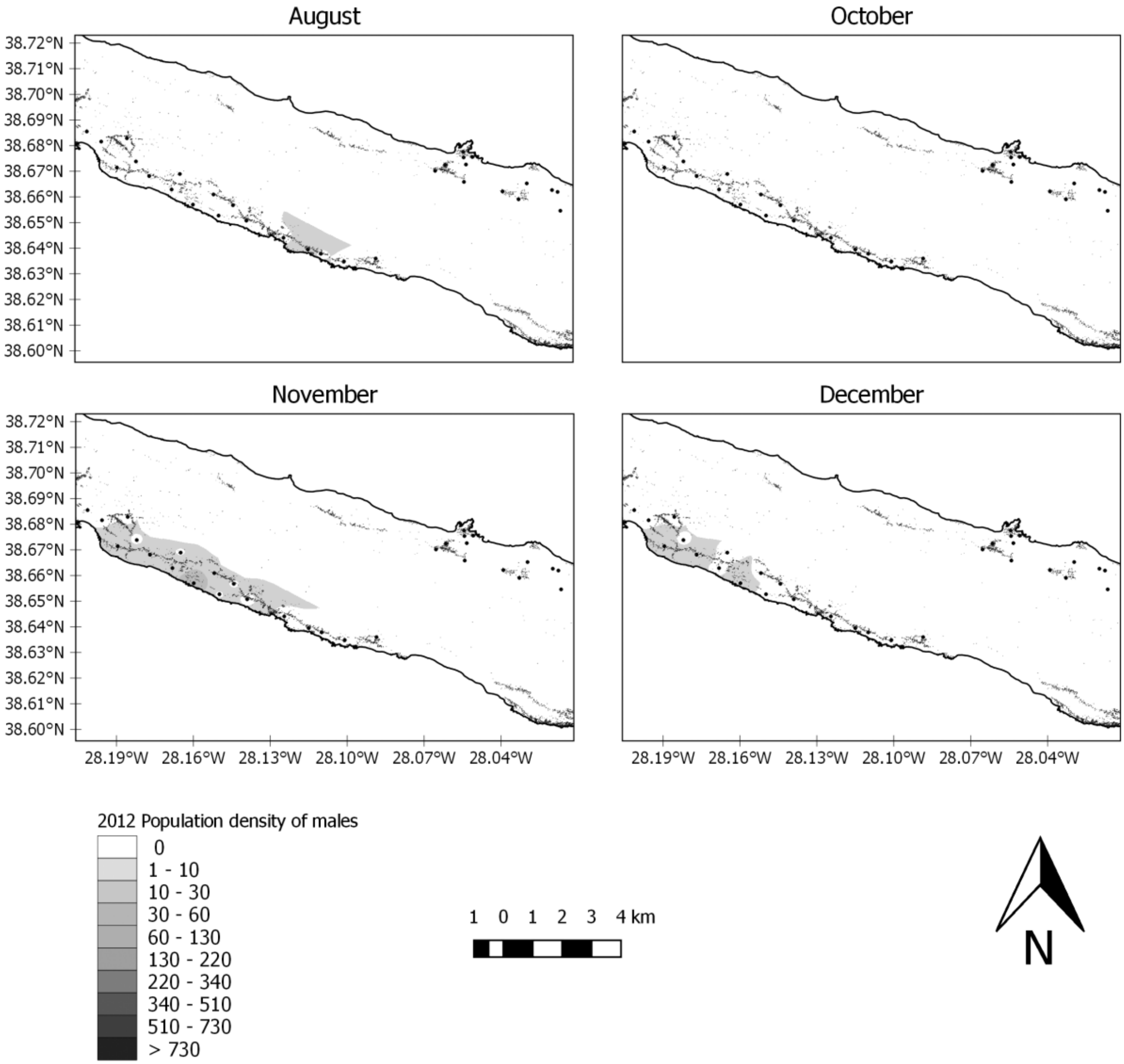


Fig. 29. Continuation of Figure 28.

Acknowledgments

We thank the technician Jorge Azevedo for his indispensable collaboration in field and laboratory work in Sao Jorge Island. A very special thanks to the land owners, fruit producers and growers that allowed us to set up traps in their properties orchards and sample mature fruits during the whole period of this study. We thank the Agrarian Services of Terceira's Island in the person of Jorge Tiago for providing the transportation necessary for all fieldwork during the whole period of this study. We thank Professor Paulo Fialho for providing us the weather information data.

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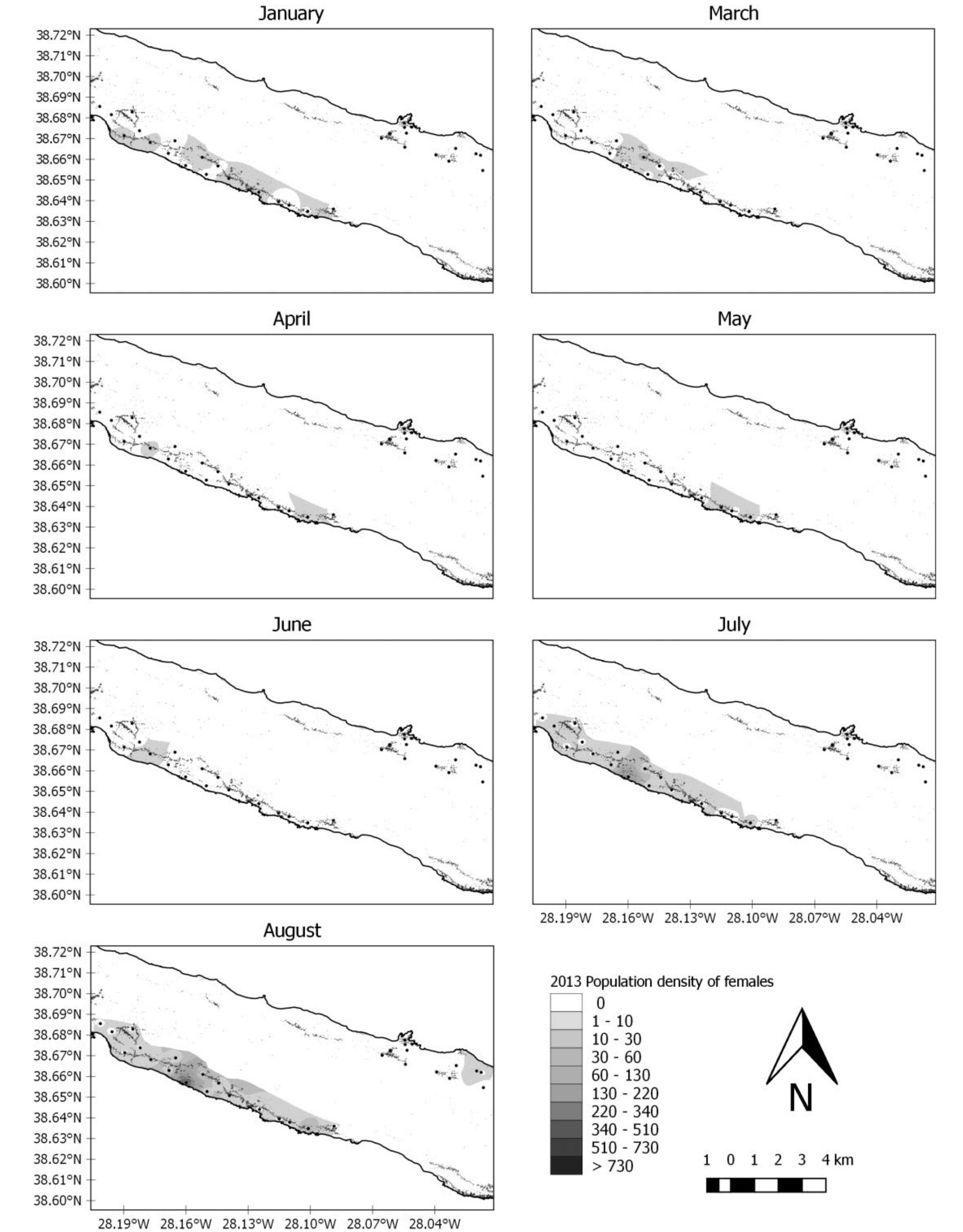

Fig. 30. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2013 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

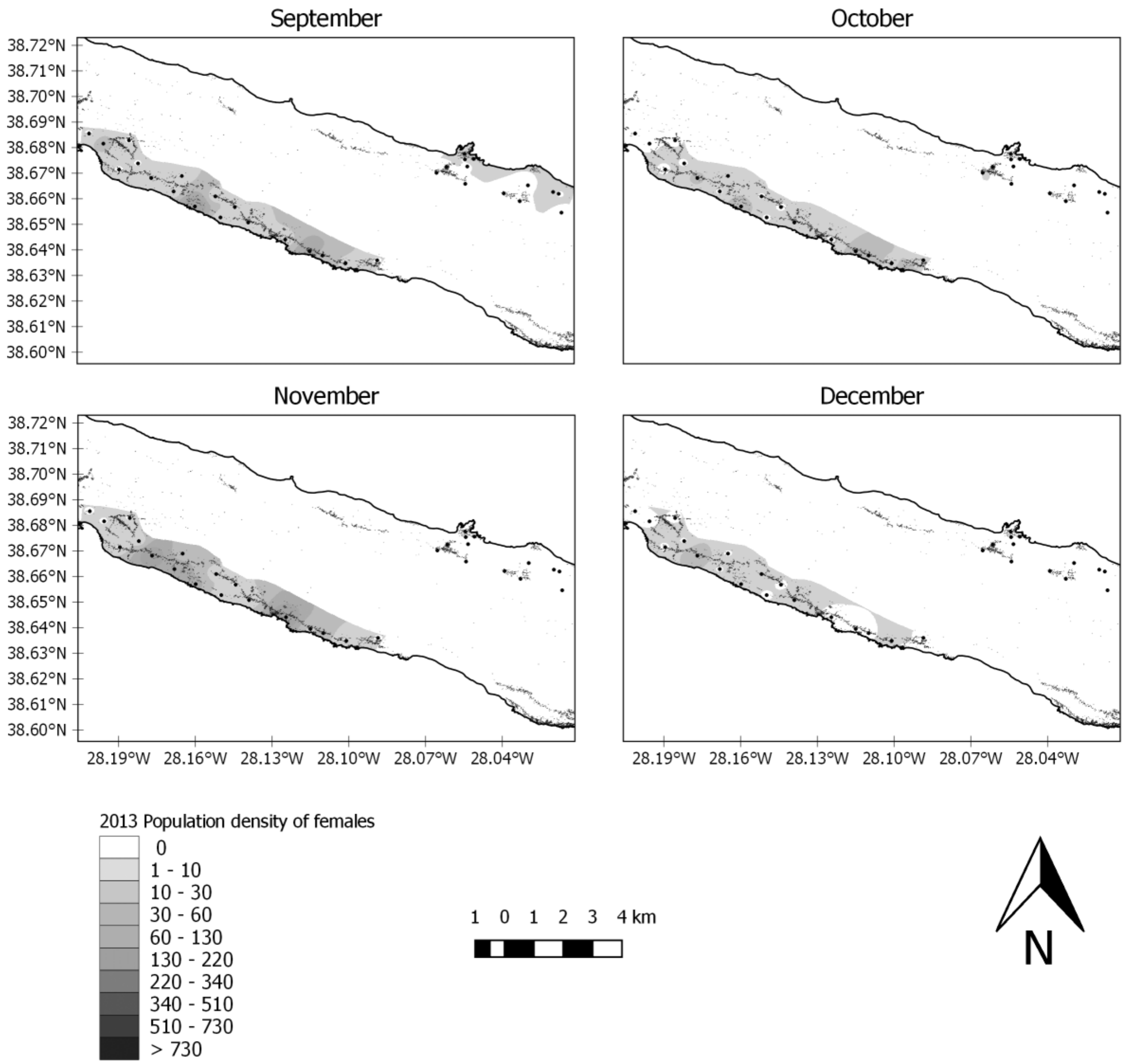

Fig. 31. Continuation of Figure 30.

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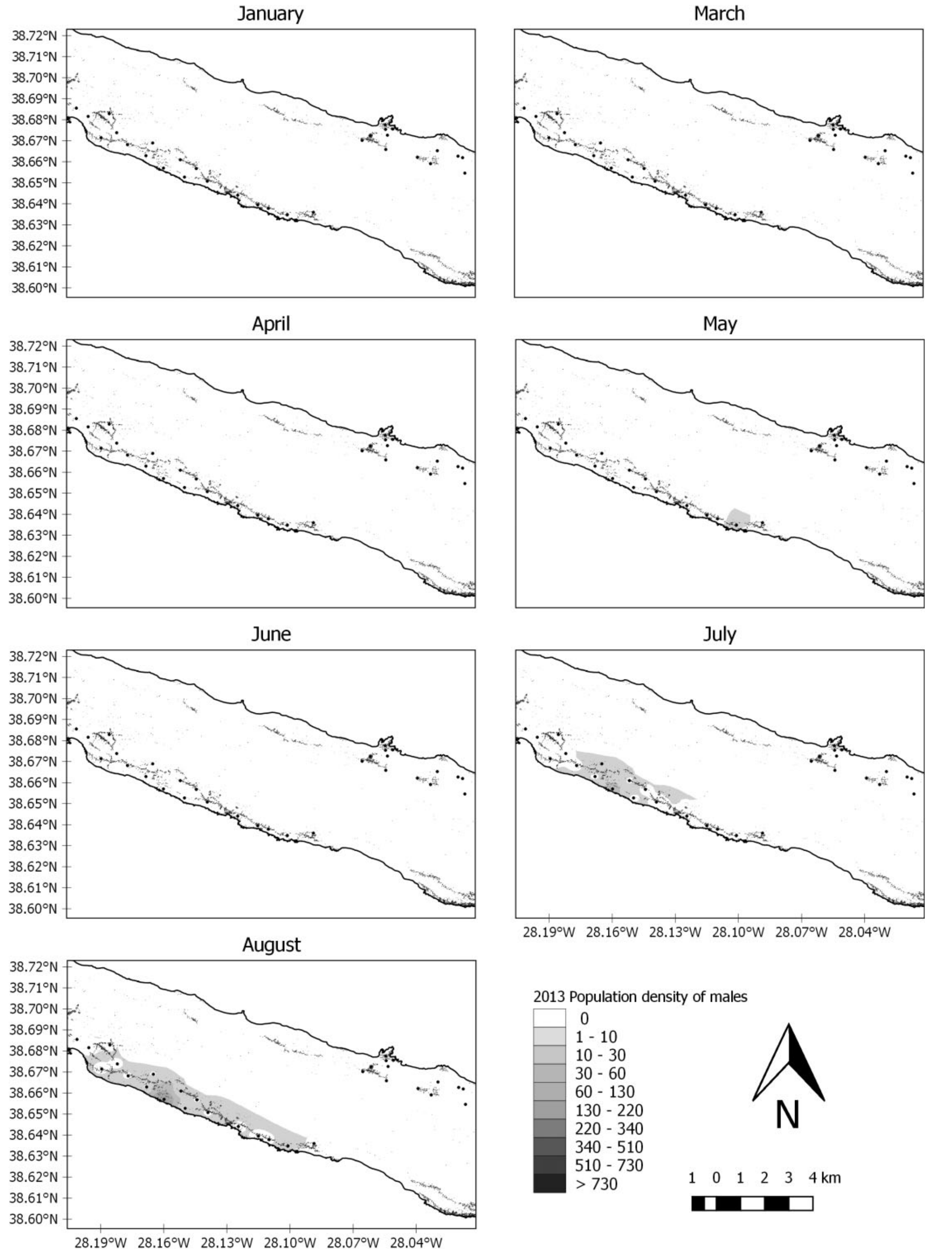

Fig. 32. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2013 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

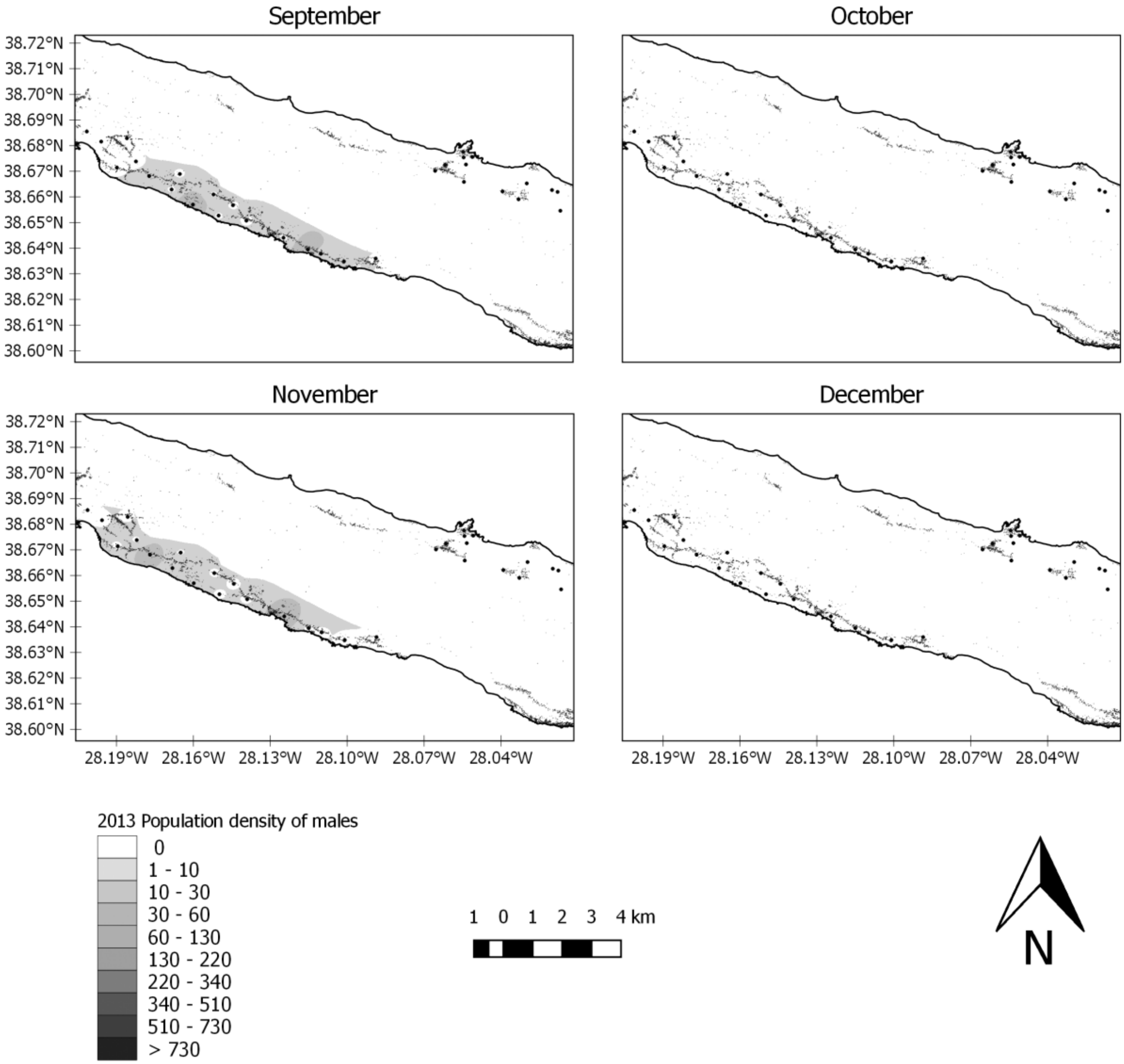

Fig. 33. Continuation of Figure 32.

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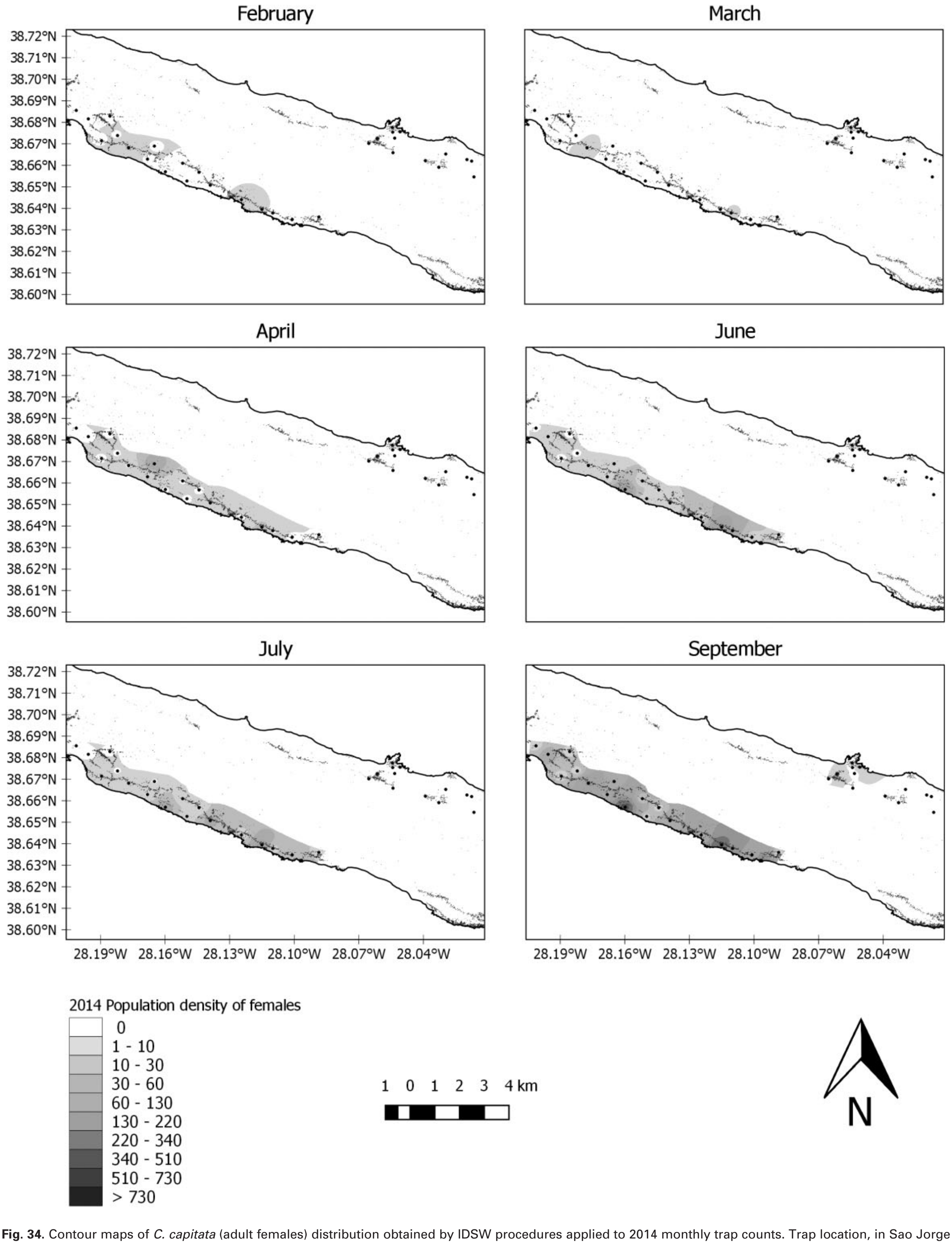

Fig. 34. Contour maps of *C. capitata* (adult females) distribution obtained by IDSW procedures applied to 2014 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

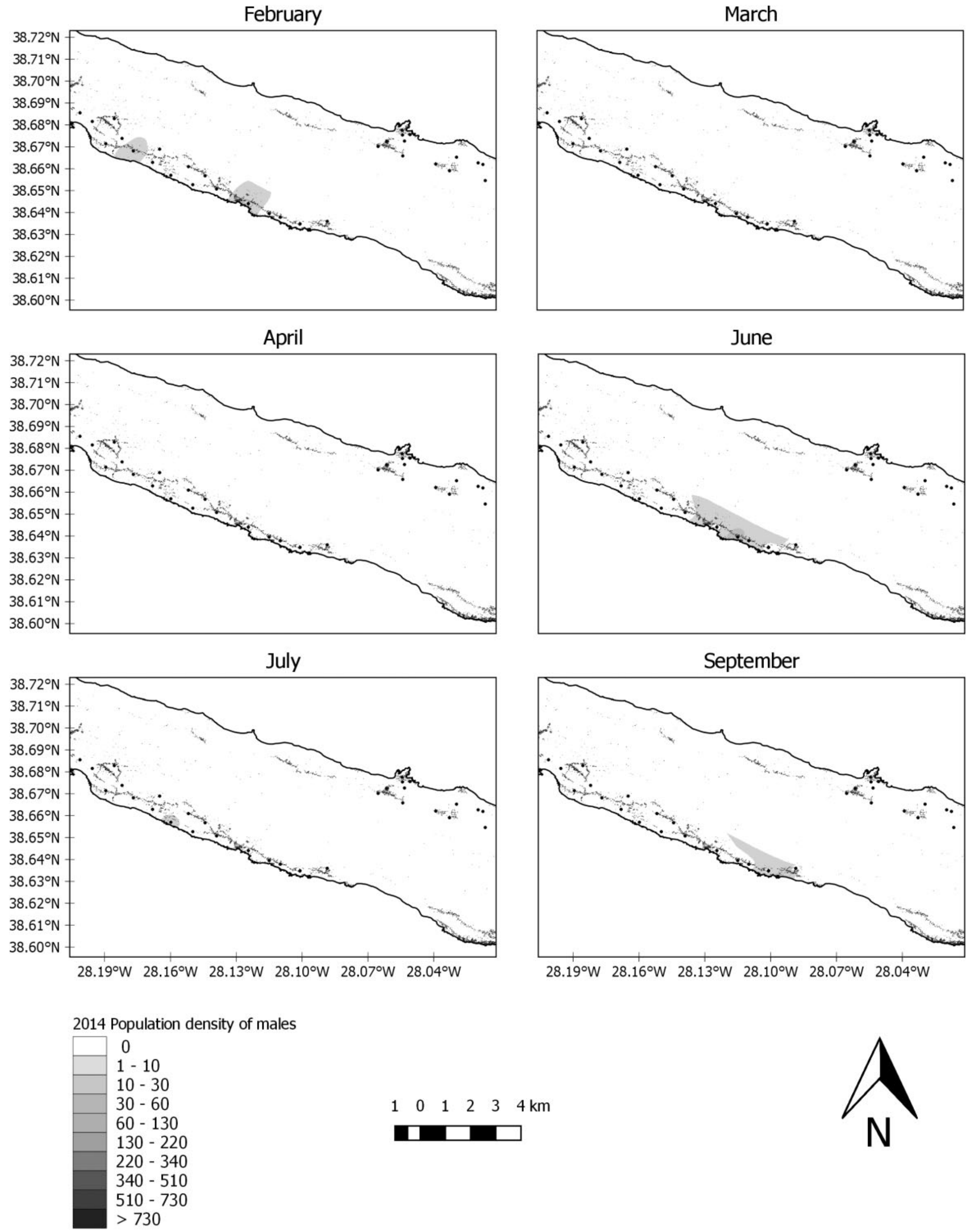

Fig. 35. Contour maps of *C. capitata* (adult males) distribution obtained by IDSW procedures applied to 2014 monthly trap counts. Trap location, in Sao Jorge Island, is shown by spots; x, y axes are expressed in Geographic coordinates.

Table 2. Seasonal *C. capitata* average ± SE fruit host infestation levels expressed as larvae per Kg of fruit in the Sao Jorge areas of study

Year and month host fruits	2011									
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P. americana (C. Bauh)								0		
Prunus domestica (L.)					122 ± 0		0			
A. cherimola (Mill.)		0								
P. guineense (Sw.)							238 ± 0	162 ± 80	85 ± 33	
Corynocarpus laevigatus (Forster)					300 ± 4	0				
C. arabica (L.)					50 ± 0					
D. virginiana (L.)								0		
F. carica (L.)						202 ± 127	119 ± 191	27 ± 41	15 ± 0	
Psidium guajava (L.)										0
Citrus sinensis (L.) Osbeck	14 ± 0	3 ± 5	5 ± 11	2 ± 3	6 ± 6			5 ± 8	2 ± 3	2 ± 3
C. aurantium (L.)		2 ± 3	13 ± 26	3 ± 0						
C. limetta (Risso)										
Malus domestica (L.)						1 ± 3	4 ± 8	2 ± 4		
Citrus reticulata (Blanco)										
M. indica (L.)										
C. oblonga (Mill.)						0				
Arbutus unedo (L.)							370 ± 0			
Prunus persica var. *nucipersica*				129 ± 81						
E. japonica (Lindl.)		153 ± 170	48 ± 34							
P. comunis (L.)						0	0			
P. persica (L.) Batsch			116 ± 61							
P. granatum (L.)							0			
S. betaceum (Cav.)								0	0	
Vitis vinifera (L.)							38 ± 50			

Table 3. Continuation of Table 2

Year and MonthHost fruits	2012					2013				
	Jan	Feb	Mar	Apr	May	Jun	Aug	Sep	Oct	Nov
P. americana (C. Bauh)										
Prunus domestica (L.)										
A. cherimola (Mill.)										
P. guineense (Sw.)									168 ± 168	
C. laevigatus (Forster)										
C. arabica (L.)					1089 ± 0					
D. virginiana (L.)									7 ± 0	
F. carica (L.)							254 ± 63	164 ± 69	38 ± 0	
P. guajava (L.)	21 ± 0									
C. sinensis (L.) Osbeck	1 ± 2	0	0		0				0	0
C. aurantium (L.)										
C. limetta (Risso)						0				
M. domestica (L.)							5 ± 2	1 ± 1		
C. reticulata (Blanco)									30 ± 4	
M. indica (L.)									0	
C. oblonga Mill.										
A. unedo L.										
P. persica var. *nucipersica*										
E. japonica (Lindl.)		11 ± 6	34 ± 0	0 ± 0						
P. comunis (L.)										
P. persica (L.) Batsch					0 ± 0					
P. granatum (L.)										
S. betaceum (Cav.)										
V. vinifera (L.)										

Performing a Logit regression analysis (Table 4) with the Temperature and Rainfall as predictor variables of the monthly trap counts for both island, results shows a statistical significant (P-value < 0.05) relationship between the predictor variables and the monthly trap counts. The slope of the predictive variables in both islands is positive. The Pearson's chi-square for Terceira Island is 447.79 while for Sao Jorge Island is 37.87.

Table 4. Logit regression results of medflies trap counts with the Temperature and Rainfall as predictor variables of the monthly trap counts

Island	Variable	*n*	slope	SE	Pearson's chi-square	Sig.
Terceira	Temperature	36	14.49	±11.17	447.79	<0.001
	Rainfall		0.49	±0.14		0.001
	Constant		−19.76	±1.74		<0.001
Sao Jorge	Temperature	20	21.67	±5.27	37.87	<0.001
	Rainfall		3.45	±0.46		<0.001
	Constant		−34.47	±6.75		<0.001

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