Szyniszewska et al.: Seasonal risk of C. capitata importation via air passenger traffic

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**Analysis of seasonal risk for importation of the Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae), via air passenger traffic arriving in Florida and California**

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**Abstract**

The Mediterranean fruit fly (medfly), *Ceratitis capitata* (Wiedemann), is one of the world’s most economically damaging pests, displaying seasonal population fluctuations in response to changes in environmental conditions. It has repeatedly invaded two major agricultural states in the U.S., Florida and California, each time requiring costly eradication. One of the main pathways for its entry is fruit found in air passenger baggage. Consequently, a medfly global seasonal environmental suitability model, a global passenger flow matrix, and interception data from airports in Florida and California were used to analyze the seasonally changing risk of long distance medfly movement into these states. The predicted annual number of passengers arriving directly from medfly-infested countries into Florida in 2010 was higher compared to California, and most of the passengers came from South and Central America. Passengers destined for California from medfly-infested locations came mostly from Australia, France and El Salvador. Between 2003 and 2014, Florida had about three times more organisms intercepted in passenger baggage and identified as medfly than did California. The greatest risk of medfly introduction into Florida was during January-April and May-August, while for California it was in May-August. This analysis demonstrated how risk indicators for medfly arrival in Florida and California varied over the year and can be used to tailor surveillance at key airports.

**Keywords**

*Ceratitis capitata*, medfly, pathway analysis, seasonality

The Mediterranean fruit fly (medfly), *Ceratitis capitata* (Wiedemann), one of the world’s most destructive pests, has over 250 hosts and is present in most of Africa, the Middle East, the Mediterranean region of Europe, Central and South America, western Australia, and the Pacific region, including Hawaii (Liquido et al. 1990, Papadopoulos, Katsoyannos, Carey, et al. 2001, Papadopoulos, Katsoyannos, Kouloussis, et al. 2001, Papadopoulos et al. 2002, Bakri 2013, Badii et al. 2015). It has high dispersal capacity and the most recent molecular studies revealed its likely historical invasion pathway as being initial colonization of Europe from Africa followed by secondary colonization of Australia from Europe (Karsten et al. 2015). Subsequent invasions were attributed to expanding human mobility and global trade (Malacrida et al. 1998). The medfly has the potential to cause tremendous economic damage and its eradication is extremely expensive (Enkerlin and Mumford 1997). Historical estimates of agricultural industry losses and eradication costs due to individual incursions of the medfly into the U.S. ranged from $300,000 to $200 million between 1970 and 1990 (APHIS 1992). Medfly outbreaks in California during the period of 25 years have cost taxpayers nearly $500 million, while a single outbreak in the Tampa Bay area of Florida in 1997 resulted in $25 million spent on eradication (Cross 2004). These costs still are significantly less than the cost of potential establishment, however. If the medfly were to establish in California, long-term control costs would be enormous, and consequent imposition of a trade embargo by Asian countries on commodities from the state would result not only in additional revenue decline, but would also eliminate thousands of jobs (Siebert and Cooper 1995).

Global transportation greatly enhances the unintended spread of organisms, including invasive pest species, such as the medfly, and the volume of goods and people transported internationally is increasing every year (Klassen et al. 2002, Drake and Lodge 2004, Tatem et al. 2006a, Westphal et al. 2008, Hulme 2009, Lopes-da-Silva et al. 2014, Papadopoulos 2014). There has been a particularly rapid increase in air travel in recent decades, with 31.6 million scheduled flights worldwide in 2013, about a 2% increase from the previous year, and an estimated 3.3 billion passengers transported in 2014 (Tyler 2014). In consequence, the expanding air traffic network and volume of passengers it carries are mirrored by increasing rates of migration and dispersal of organisms (Ware et al. 2011, Tatem et al. 2012, Tatem 2014). Disease-carrying mosquitos have survived long-haul flights in aircraft cabins (Lounibos 2002, Tatem et al. 2006b, Benedict et al. 2007) and many invasive pest species are being encountered in both cargo and passenger baggage (Work et al. 2005, Liebhold et al. 2006, McCullough et al. 2006, Horton et al. 2013). Also due to the expansion of air travel, distance is posing a rapidly diminishing obstacle to the spread of invasive pests; however, the number of individuals of a species travelling on a route (a surrogate for “propagule pressure”) and the environmental conditions an invasive species encounters are considered fundamental constraints to its establishment (Levine and D’Antonio 2003, Drake and Lodge 2004, Lockwood et al. 2005, 2009, Tatem and Hay 2007, Tatem 2009) . Based on previous studies and recurrent outbreaks, there is reason to believe that medfly continues to arrive in the U.S., including Florida and California, at a sustained rate, mostly via infested fruit in passenger baggage (Liebhold et al. 2006).

While the international air travel network is constantly expanding and traffic on it increasing, the resources for surveillance are limited and there is a proliferation in the number of potentially invasive organisms being intercepted (Klassen et al. 2002, McCullough et al. 2006). The U.S. Department of Agriculture (USDA), Animal and Plant Inspection Service (APHIS) maintained a record of pest interceptions at the ports of entry, known as the PestID database (formerly Port Information Network, PIN) from 1984 to 2003 before the Department of Homeland Security (DHS) assumed responsibility for inspection activities and the database. Between 1984 and 2000, 725,000 pest interceptions were recorded in the PestID database, 73% occurring at airports and only 9% at marine ports. More than half of those interceptions were associated with small parcels and baggage carried by travelers. In total, insects represented 73.5-84.6% of the annual interceptions. Miami (MIA), New York (JFK) and Los Angeles (LAX) international airports accounted for 43% of all interceptions. In Florida, 69% of interceptions occurred in shipments that arrived from South and Central America and 22% from the Caribbean. Roughly 62% were associated with baggage, 30% with cargo and 7% with plant propagative material. When the entire contents of randomly selected cargo aircraft arriving at MIA between September 1998 and August 1999 were inspected in an attempt to detect all of the foreign insects, the infestation rate was ‘unacceptably’ high at 10.4% (Dobbs and Brodel 2004). In Southern California, arrival and detection of the medfly has remained at the same level even after its repeated eradication and associated extensive public information campaigns (Liebhold et al. 2006). The number of these medfly interceptions was positively correlated with the volume of passenger traffic from a country and negatively associated with its gross domestic product (Liebhold et al. 2006).

The aim of this research was to quantify the seasonally changing risk of importing the medfly via air traffic into Florida or California, both of which are vulnerable states due to their mild climates, multiple international transportation connections, high number of international passenger arrivals, abundant commodity imports, and substantial agricultural industries. Global spatial datasets of medfly historical presence and a model of international passenger air travel, along with duration of the pest’s lifecycle and its environmental requirements, were used to estimate how various risk factors interplay in the possibility of medfly being transported. Risk factors included seasonal changes in the suitability of the environment for medfly occurrence at the departure airports and the rates and pathways of international passenger arrivals at airports in Florida and California. Arrival rates of the medfly and many other invasive organisms show strong seasonal patterns, as does their population dynamics in the countries of origin (Caton et al. 2006, Liebhold et al. 2006, Escudero-Colomar et al. 2008, Dixon et al. 2009). Specific objectives of this study were to: 1) Estimate seasonal passenger flow from the major countries connecting to airports in Florida and California, 2) Use seasonal environmental suitability models to estimate medfly population levels at locations surrounding each departure airport, 3) Calculate seasonal risk indicators for passengers departing from all or individual international airports and arriving in Florida or California potentially transporting medfly, and 4) Select a subset of high-risk medfly infested departure airports and paired arrival airports in Florida or California, and for each pair calculate annual risk indicators for medfly introductions. The resulting information can be used to deploy airport surveillance by assigning seasonal risk of medfly introduction to high-risk pathways.

**Materials and Methods**

**Airports, Flight Routes, Seat Capacities, and Passenger Flow**

Airport coordinates, city names and International Air Transport Association (IATA) airport codes were obtained for 3,416 airports from Flightstats (www.flightstats.com). The latest available information on the route and scheduled seat capacity for each flight by month for 2010 was purchased from the international OAG dataset (www.oag.com). Directly connected airport pairs were utilized to construct a table of international air travel connections to Florida or California. However, this dataset was insufficient for determining the actual passenger flow, as flights often do not operate at full seat capacity and therefore the dataset tended to provide an overestimate. Actual passenger flow data existed but remained difficult to obtain for research purposes due to prohibitive cost, requirements for confidentiality, and legal restrictions. Therefore, for the passenger flow analysis, annual and monthly open-access modelled passenger flow matrices for the global air network were utilized (Huang et al. 2013, Mao et al. 2015).

The models estimated air passenger flow as an outcome of spatial interactions between a pair of origin and destination airports, considering routes and node (region around an airport) characteristics as dependent variables. Route characteristics included measurement of the linkage between origin and destination airports such as the great circle distance, seat capacity, flight frequency, and airport link type. Due to computational power limitations, only direct flights were included in the monthly prediction (Mao et al. 2015). Estimated passenger flows for routes were constructed based on the adjacency matrix defined by the Official Airline Guide (OAG) dataset, and actual travel volumes for training and validation were obtained and assembled from various transportation organizations in the U.S., Canada and European Union (Huang et al. 2013, Mao et al. 2015). The node characteristics included socio-economic, demographic, meteorological and network characteristics. To reflect the economic status of complex hierarchical networks in which cities are situated, G-Econ data (http://gecon.yale.edu/) were extracted on local area Purchasing Power Parity (PPP) per capita based on the location of an airport. The human population surrounding each airport was obtained from the most recent Gridded Population of the World, Version 4 (GPWv4), released by the Center for International Earth Science Information Network (CIESIN 2014). The number of people residing in a 200 km buffer corresponding roughly to a 2 h travel time to an airport (Marcucci and Gatta 2011) was compared as a covariate of origin and destination airports. Other node characteristics, such as degree, capacity and centrality, were calculated as covariates for airports as well. Both the annual and the monthly models for route and node characteristics explained at least 98% of the variance in the data. For the analysis, a subset of foreign airports which connect to one of the airports in Florida or California, as indicated by modelled air traffic flow, was obtained from the monthly passenger flow matrix (Huang et al. 2013). This included the origin, final destination and predicted number of passengers taking a route monthly. Hawaii is medfly-infested but was not included in the analysis because it is not an international connection relative to the U.S. mainland and passengers undergo stringent agricultural inspection before departure.

**Seasonal Occurrence of Medfly at Departure Airports**

Seasonal environmental suitability maps were used to estimate the potential for medfly to be at high or low population levels at locations surrounding each departure airport (Szyniszewska and Tatem 2014). Records on medfly occurrence from 1980 until the present were used to model seasonal environmental suitability for the pest using the maximum entropy species distribution modelling algorithm (MaxEnt) combined with a set of seasonally changing environmental variables: minimum, mean and maximum temperature; minimum, maximum and sum of rainfall; a normalized difference vegetation index (NDVI); and a digital elevation model (DEM) (Szyniszewska and Tatem 2014). The annual model was divided into three seasons for the months of January-April, May-August and September-December. These categories described well the global seasonal activity of medfly for both the northern and southern hemispheres. The output of this analysis was used to classify infestation risk for the 200 km area around each airport in the countries where medfly is officially present (EPPO 2009, IAEA 2013). The same buffer was used in the passenger flow model to define the likely passenger cohort for each airport. Descriptive statistics (maximum, mean and standard deviation) were calculated across all grid cells per buffer. Network nodes were classified using this procedure as low risk for medfly occurrence with a weight of 0.2 if the maximum = <0.8, ͞*x* = <0.1, and *s* = <0.15. Airport regions categorized as medium risk for medfly occurrence were assigned a weight 0.6 if the maximum = <0.9, ͞*x* = <0.3, and s was not considered. In all other instances, an airport region was classified as high risk for medfly occurrence and assigned a risk weight of 1.0.

**Seasonal Risk Indicators for Passengers Arriving with Medfly**

Three risk indicator values were calculated for each individual departure airport, destination airport, and for pairs of origin-destination airports, in order to assess the risk of passengers transporting the medfly into Florida or California during three seasons. For each airport in Florida or California (*i*) and passenger departure airport (*k*), the passenger flow *pik* was calculated. This *pik* value was segregated by the three seasons (*j*) to determine the seasonally adjusted flow *pijk*. The risk indicators (*RI*) for passengers arriving with medfly from all international departure airports, including medfly infested countries, to individual airports in Florida or California (*i)* in season *j* were defined as *ARIij*. For passengers arriving in Florida or California from an individual departure airport *k* in season *j,* the risk indicators were defined as *ORIjk*. The risk indicator for arrival at a specific airport *i* in season *j* by passengers from a paired origin-departure airport *k* was defined as *AORIijk*. The notation *ojk* represents the seasonal medfly occurrence risk at the airport of origin*.* The ratio of arrivals from medfly-infested locations compared to overall international arrivals was calculated by dividing potentially infested by overall arrivals for each destination.The risk indicator values were obtained by summing the products of the derived risk weight value of medfly occurring at the origin (low=0.2, medium=0.6 and high=1.0) in each season and the passenger number on a given route for: 1) All arriving flights from international airports to the destination airport (*ARIij*), 2) All departing flights to Florida and California from an individual origin airport (*ORIjk*), and 3) For a pair of specific origin-destination airports (*AORIijk*). The sum of these products was then divided by the total number of passengers travelling on the route. The following equations were used to calculate seasonal medfly risk indicators for passengers arriving in Florida or California:

(1) 

(2) 

(3) 

**Seasonal Medfly Interceptions, Countries of Origin and Host Plants**

Medfly interception data from U.S. ports of entry documented in the PestID database for 2003-2014 were used to compare the highest volume and risk airline routes with the level of airport surveillance. The database contained records of pest interceptions from agricultural commodities in cargo, airline passenger baggage, and other conveyances. It provided detailed information on pest interceptions, such as the port of entry, date, origin of the pest, commodity, part of the plant harbouring the pest, species of the pest, and other pertinent information. However, because the PestID database was limited to actionable pests that were intercepted, lacked systematic sampling methods, was subject to varying detection priorities resulting from changing commodities and pests of concern, and did not contain records on negative inspection results, these data were not statistically valid for estimating entry rates of nonindigenous species into the U.S. (Work et al. 2005). Consequently, for specific countries and seasons, Pearson product-moment correlation coefficients were calculated to compare the risk of medfly occurrence for weight-adjusted passenger volume with the interception numbers, a measure of surveillance intensity.

**Results**

**Airports, Flight Routes, Seat Capacities and Passenger Flow**

The number of flight routes and flights between airports along with seat capacities provided a rough estimate of the potential for medfly to be transported in passenger baggage. In 2010, Miami (MIA) had 77 international direct flight connections with a total of 11.7 million seats, followed by Fort Lauderdale (FLL) with 39 routes and 2.5 million seats and Orlando (MCO) with 29 routes and 2.4 million seats. The greatest number of seats on scheduled incoming flights to Florida was from Canada (1.47 million), Puerto Rico (1.43 million), the United Kingdom (1.23 million) and the Bahamas (1.12 million). The total number of connecting countries with medfly officially present was 34, 10 and 5 for MIA, FLL and MCO, respectively. Also in 2010, flights to MIA from countries where medfly occurs officially had about 5 million seats (42.7% of total). Flights from medfly-infested countries to FLL had 417,000 seats (16.7%) and to MCO 288,000 seats (12.0%). There were multiple connections with the Caribbean region, Central and South America and Western Europe. The highest seat capacities on direct connections from medfly infested countries were from Colombia (990,000), Brazil (883,000), Venezuela (527,000), Costa Rica (457,000), and Panama (441,000). Compared with MIA, LAX had fewer direct international flights (60) but a comparable seat capacity (10.26 million). San Francisco (SFO) followed LAX with 30 direct international flights and a total of 5.4 million seats. Most of the seats on incoming flights were from Mexico (2.94 million), Canada (1.98 million), Japan (1.64 million), the United Kingdom (1.38 million), and Australia (1.23 million). The seat capacity from medfly-infested locations was 1.2 million (11.7% of total) for LAX and 239,000 (4.4%) for SFO, the primary countries of origin being France (479,000), El Salvador (283,000), Peru (140,000), Guatemala (130,000), and Switzerland (124,000). Thus, in 2010, the seat capacity on international direct flights from medfly-infested countries to Florida (MIA, FLL, and MCO) was 5.71 million (34.0% of total seats to Florida) and to California (LAX and SFO) 1.44 million (9.2% of total seats to California).

The passenger flow model provided a more precise estimate of the risk of medflies being introduced by travelers than seat capacities because it was based on actual itineraries (Mao et al. 2015). Accurate information could be derived about arrivals into Florida and California from international locations because passengers were subject to U.S. Customs and Border Protection screening at the ports of entry. In Florida, MIA (9.05 million), FLL (1.85 million), and MCO (1.96 million) received most of the international passengers with fewer than 450,000 arriving at the remaining airports. About 516,000 international passengers travelling to California arrived at airports other than LAX (7.18 million) and SFO (4.08 million), and most of them were from countries where medfly did not occur officially. The model included connections to Florida and California airports from 130 and 81 departure airports, respectively, with 44 and 14 locations where medfly occurred officially. According to the model, the number of international passengers arriving at Florida in 2010 was greatest from Canada (1.19 million), Puerto Rico (1.12 million), and the United Kingdom (989,000) (Fig. 1). The peak numbers of passengers on direct flights to Florida from medfly-infested countries were from Colombia (805,000), Brazil (684,000), and Venezuela (395,000). The numbers of passengers on flights into California were highest from Mexico (2.14 million), Canada (1.58 million), Japan (1.29 million), and the United Kingdom (1.09 million), and from medfly-infested locations Australia (994,000), France (402,000), and El Salvador (217,000).

**Seasonal Occurrence of Medfly at Departure Airports**

Medfly population levels varied seasonally at the airline flight origins, mainly in Europe, but also in Australia, and some locations in South and Central America (Figs. 2 and 3). The very low seasonal risk of medfly arriving in Florida from most of Europe in January-April was followed by an increase in May-August and a decline again in September-December. The risk of medfly-infested fruit being transported from Mediterranean countries was very high during the summer and fall months due to the high passenger volume. The medfly is extremely abundant virturally yearround in Sub-Saharan Africa from which relatively few passengers travel to Florida, and in regions of South America with continuous arrivals in Florida and California regardless of season. Eradication of the medfly from Mexico, Belize and areas of Guatemala has eliminated the risk of introductions into the U.S from those locations. The pattern of international passenger movement to California is very different than that to Florida, with most flights arriving in California from countries having minimal risk of transporting the medfly. Exceptions are Mediterranean countries and a few in South and Central America.

**Seasonal Risk Indicators for Passengers Arriving with Medfly**

*Seasonal Risk Indicators for Passengers Arriving from All and Medfly-Infested Countries to Destination Airports in Florida and California (ARIij).*

Depending on season, international airports in both Florida (MIA, FLL and MCO) and California (LAX and SFO) were subject to considerable risk of passengers arriving with medfly (Table 1). Higher *ARIij*values indicated increased risk due to more passengers arriving from locations with high or medium medfly population levels during certain seasons. The resulting *ARIij* values were highly variable for passengers arriving at the two states. MIA had the highest risk indicators for medfly introduction by passengers in Florida, between 0.38 and 0.44 depending on the season, considering all international arrivals, including locations where medfly is not established or has been eradicated. Indicators ranged from 0.84 to 0.95 for passengers who arrived at MIA from medfly-infested countries. FFL and MCO airports had comparable *ARIij* values with each airport having slightly less than 2 million passengers arriving from locations where medfly was present. In California, LAX and SFO had the highest *ARIij* values for arrivals from medfly-infested countries in May-August, 0.95 and 0.92, respectively. LAX had an *ARIij* score of 0.70 in January-April and 0.64 in September-December; whereas, scores for the respective seasons at SFO were 0.47 and 0.49. The ratio of arrivals at Florida from medfly infested locations compared to overall international arrivals was highest for MIA (0.45) followed by Orlando (0.20) and FLL (0.12). The two major airports in California, LAX and SFO, had arrival risk ratios of 0.12 and 0.05, respectively.

*Seasonal Risk Indicators for Passengers Arriving in Florida and California from Individual Medfly-Infested Departure Airports (ORIjk).*

The highest estimated number of passengers entering Florida in 2010 came from airports in South and Central America (Bogota, São Paulo, Panama City, Caracas, San Jose, and Lima) (Table 2). Most of these airports were exposed to a high risk of medfly being carried by passengers yearround (1.0), with risk decreasing from high to medium (0.6-0.87) at some locations, predominantly due to medfly population declines at departing countries during the last four months of the year. The other main medfly-infested countries with flights to Florida included Argentina, Spain, France, Guatemala, Ecuador, Nicaragua, and Honduras. California had a greater number of passengers than Florida arriving from Europe, specifically France, Switzerland and Italy. California received flights from additional medfly-infested countries, including El Salvador, Peru, Guatemala, Brazil, Israel, Panama, Colombia, and Costa Rica. The annual risk indicator (*ORIjk*) was determined for each origin airport, a greater value indicating higher risk of medfly arrival at the destination. The *ORIjk* values ranged from 0.35 for flights from Switzerland to 1.0 for those from high risk countries.

*Seasonal Risk Indicators for Passengers Arriving in Florida and California from Pairs of Departure and Arrival Airports (AORIijk).*

Most of the passengers travelling from medfly-infested departure airports to Florida arrived at MIA, including flights from Brazil (GRU), Venezuela (CCS), Peru (LIM), Argentina (EZE) and Colombia (BOG) (Table 3). The greatest number of passenger arrivals to FLL were from Colombia (BOG) and to MCO Panama (PTY) and Brazil (GRU). The number of passengers destined for Florida decreased significantly in September-December for MIA-LIM, MIA-EZE, FLL-SJO and FLL-MDE. The (*AORIijk*) values were high (1.0-0.86) for all pairs of airports, except Medellin, Colombia (MDE)-FLL at 0.74. The passenger volume into California was highest for France (CDG)-LAX at nearly 290,000 per year. Totals above 100,000 were estimated for El Salvador (SAL)-LAX, Peru (LIM)-LAX and France (CDG)-SFO. El Salvador (SAL)-SFO and Switzerland (ZRH)-SFO had less than 50,000 passengers per year. The *AORIijk* values for pairs of airports in California were highest (0.86-0.88) for SAL-LAX, LIM-LAX and SAL-SFO and lowest (0.38-0.67) for CDG-LAX, CDG-SFO, and ZRH-SFO.

**Seasonal Medfly Interceptions, Countries of Origin, and Host Plants**

According to the PestID database for 2003-2014, medflies were intercepted in passenger baggage 548 times in Florida and 194 times in California. The average number of medflies intercepted annually was greatest for MIA (42.41), LAX (8.9) and SFO (7.25). Florida had a range of 8-91 interceptions annually between 2003 and 2014, while California had 0-52. For four years, including 2013, no medflies were found in passenger baggage in California, and only 2 were encountered in 2014. Florida had 73 and 35 recoveries, respectively, during those years. The peak year was 2011 for both states. For the period, Peru (95) was the most common origin of medfly intercepted in Florida, followed by Spain (76), Bolivia (50) and Ecuador (45). Romania (31), Nicaragua (26), Nigeria (26), and Portugal (23), 67.9% for the 8 countries. Fewer medflies intercepted in Florida were from Lebanon (16), El Salvador (11), France (13), Venezuela (15), Egypt (13), Algeria (2), and Cameroon (4). The primary sources of medfly intercepted in California were Australia (50), Nigeria (42), Israel (29) and Spain (25), 75.25% for the 4 countries. Considerably fewer were intercepted from Lebanon (5), El Salvador (8), France (3), Algeria (10), Ghana (7), Tunisia (2), Armenia (5),Cameroon (6), Greece (1) and Iran (1). Medfly interceptions occured throughout the year in Florida, with a total for the 2003-2014 period peaking in July (66) and September (77), but remaining at a relatively high level in November (60), December (46) and February (48). A somewhat lower level of interceptions was reported for January (38), April (43), May (44), June (34), August (42), and October (39). The lowest level was in March (18). California interceptions peaked in June (62) and July (58), with a second surge in October (27) and to a lesser extent November (14). The remaining months had <10 interceptions, except there were none in April and September. Overwhelmingly, the most common host for medfly intercepted from flights to Florida was peach (133), followed by guava (35), mango (46), quince (36), plums/cherries (33), orange (31), and mandarin orange (23). Fewer were found in peppers (14), lemon/lime (19), custard apple (19), apple (7), garcinia (15), sapodilla (13), fig (12), pomegranate (8), and pepper tree fruit (10). Most medflies intercepted in California were from guava (50) and peppers (49). Only peach (15), orange (17), apple (24), rough lemon (11), and pomegranate (10) exceeded 9 interceptions.

Pearson correlation coefficient values (*r*) were calculated to explore the relationship between the number of intercepted organisms and the predicted number of passengers on the routes of interest. There was a weak negative relationship between the cumulative number of medflies from individual departure countries intercepted at airports during 2003-2014 and the weighted number of predicted passengers arriving in Florida from these locations (*r* = -0.21). California had a strong negative relationship (*r* = -0.97), although because interception data were limited, only four origin-destination pairs could be compared. In 2010, there was a positive correlation between the total number of intercepted medflies and the predicted number of passengers arriving at the five main airports in Florida and California (MIA, FLL, MCO, LAX and SFO) (*r* = 0.78), and an even stronger correlation when comparing the interception counts with the risk indicator weighted number of passengers (*r* = 0.98) or annual ARI values (*r* = 0.81). A strong relationship also occurred between the seasonal number of intercepted medflies and the seasonal predicted number of passengers (*r* = 0.75) and weighted number of passengers (r = 0.93) arriving at the five main airports in Florida and California. When examined by state, the relationship between the weighted seasonal passenger number versus the seasonal number of intercepted medflies was stronger in Florida than California, *r* = 0.97 and 0.52, respectively.

**Discussion**

The purpose of this study was to quantify the seasonal risk of importing the medfly into Florida or California through air transportation. We approached it by determining seasonal passenger flow between major connecting countries and airports in Florida and California, estimating seasonal medfly population levels at the origin airports, identifying high-risk departure airports and flight routes, and using this information to calculate seasonal and annual risk indicators for passengers arriving from these airports with medfly. The indicators of seasonal risk were compared with seasonal medfly interceptions at airports in Florida and California that included data on the countries of origin and host plants. Since it is estimated that approximately 2.9 million passengers arrive annually in Florida and 1.6 million in California from medfly-infested countries, the risk of medfly entry is potentially very high. By assigning seasonal risk of medfly introduction to high-risk flights arriving from medfly-infested countries, airport surveillance personnel should be able to concentrate their effort where it is most needed. Therefore, based on predicted passenger traffic for 2010, pest exclusion activities in Florida should focus on flights from Colombia, Brazil, Venezuela, Costa Rica, Panama and Ecuador primarily arriving at MIA and in California on flights from Australia, France and El Salvador arriving at LAX (Fig. 1). Even though Florida received a higher number of passengers from medfly-infested countries, it has had fewer outbreaks compared to California (Thomas et al. 2010). Perhaps this is because medfly populations at origin locations of passenger influx to Florida have been decreasing, e.g., Mexico, Belize and Chile where the medfly has been eradicated.

The risk of medfly being introduced is not constant throughout the year. The probability of introducing medfly into Florida airports from medfly-infested countries is higher in January-April and May-August than in September-December (Table 1). Risk peaks in California during May-August. Another essential criterion for deploying surveillance resources is the specific airport where a flight originates during a season. Specific Central and South American countries are implicated as likely sources of medfly (Figs. 2 & 3, Table 2). This analysis was refined further by pairing departure and arrival airports, so that high-risk sources of medfly could be linked to the pathways for possible transport of the pest (Table 3). The results indicated that DHS personnel at Florida (MIA) should be extra vigilant in inspecting passengers and their baggage from Brazil (GRU), Venezuela (CCS), Argentina (EZE) and Colombia (BOG), and placing priority on flights arriving from BOG at FLL and Panama (PTY) at MCO. Inspection intensity at LAX would vary by season but should emphasize Salvador (SAL) and Peru (LIM). Inspectors at SFO should carefully screen flights from SAL.

The number of intercepted medflies did not correlate consistently with pairs of origin-destination airports. This could be because the interception data covered a period of twelve years; whereas, the predicted passenger number model was based on one-year data. However, in other situations there were strong positive relationships between the number of seasonal passengers, risk indicator values and intercepted organisms. Weighting the number of passengers by risk indicator values tended to improve the Pearson correlation coefficients in every instance, suggesting that the risk values accounted for some of the risk of medfly importation by specific routes. There was a strong relationship between the weighted number of arriving passengers and number of medfly interceptions at both Florida and California. However, the connection between passenger numbers and medfly interceptions could be strengthened further by obtaining more information on medfly carry rates for the passengers on incoming flights. Moreover, there is a need for a more systematic approach to sampling incoming passenger luggage, an increase in sampling intensity, and additional interception records, including negative outcomes.

This study was based on two novel models, one to define the seasonal and spatial variability in medfly abundance and the other for estimating seasonal variation in airline passenger volume. The seasonal medfly environmental suitability model was built with MaxEnt, relying on the most comprehensive dataset of medfly occurrence yet assembled (Szyniszewska and Tatem 2014). The database contained 2,328 unique geo-located entries on medfly detection sites from 43 countries and nearly 500 unique localities. This medfly occurrence data and a set of environmental variables were used to create three sets of seasonal environmental suitability maps (Jan-Apr, May-Aug and Sep-Dec) for the pest (Figs. 2 & 3). The second model was based on the global passenger flow matrix which illustrates monthly variation in passenger volume on the world airline network for airports serving cities with populations of 100,000 or more (Mao et al. 2015). These two models provided a means of assessing how a set of primary factors contributed to seasonally changing risk of medfly importation into specific airports in Florida and California, and thus can serve to enhance exclusion of this pest.

The models were subject to a range of uncertainties and limitations. Information was missing from many locations, sampling methodology was inconsistent, and there were many undefined factors that influenced estimates of medfly occurrence and seasonal abundance. The passenger flow model also did not account for longer, more complex itineraries which are common for passengers travelling internationally. Regardless of their limitations, however, these models can be used to generate risk indicators for a wide range of pests, target interventions, regulate trade, define data acquisition requirements at ports of entry, and be incorporated into risk assessments for commodity importation. Moreover, in the event that an alien pest is discovered, these models in concert with molecular genetic analyses (Kirk et al. 2013, Karsten et al. 2015) provide a means to determine its probable source and pathway of invasion.

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**References Cited**

**APHIS**. **1992**. Risk assessment, Mediterranean fruit fly. Planning and Risk Analysis Systems. Policy and Program Development. Animal and Plant Health Inspection Service USDA, Washington D.C.

**Badii, K. B., M. K. Billah, K. Afreh Nuamah, D. Obeng Ofori, and G. Nyarko**. **2015**. Review of the pest status, economic impact and management of fruit-infesting flies (Diptera: Tephritidae) in Africa. Afr. J. Agric. Res. 10: 1488–1498.

**Bakri, A.** **2013**. Geographical distribution map of the Mediterranean fruit fly Ceratitis capitata (Wiedemann). Designed by FAO/IAEA. (https://nucleus.iaea.org/sites/naipc/twd/Picture%20Gallery/Forms/DispForm.aspx?ID=131).

**Benedict, M. Q., R. S. Levine, W. A. Hawley, and L. P. Lounibos**. **2007**. Spread of the tiger: global risk of invasion by the mosquito Aedes albopictus. Vector-Borne Zoonotic Dis. 7: 76–85.

**Caton, B. P., T. T. Dobbs, and C. F. Brodel**. **2006**. Arrivals of hitchhiking insect pests on international cargo aircraft at Miami International Airport. Biol. Invasions. 8: 765–785.

**CIESIN**. **2014**. Gridded Population of the World, Version 4 (GPWv4), Preliminary Release 2 (2010).

**Cross, E.** **2004**. Mediterranean fruit flies attempt to sneak in—again. Cust. Bord. Prot. TODAY.

**Dixon, A. F. G., A. Honěk, P. Keil, M. A. A. Kotela, A. L. Šizling, and V. Jarošík**. **2009**. Relationship between the minimum and maximum temperature thresholds for development in insects. Funct. Ecol. 23: 257–264.

**Dobbs, T. T., and C. F. Brodel**. **2004**. Cargo Aircraft as a Pathway for the Entry of Nonindigenous Pests into South Florida. Fla. Entomol. 87: 65–78.

**Drake, J. M., and D. M. Lodge**. **2004**. Global hot spots of biological invasions: Evaluating options for ballast–water management. Proc. R. Soc. Lond. B Biol. Sci. 271: 575.

**Enkerlin, W., and J. Mumford**. **1997**. Economic Evaluation of Three Alternative Methods for Control of the Mediterranean Fruit Fly (Diptera: Tephritidae) in Israel, Palestinian Territories, and Jordan. J. Econ. Entomol. 90: 1066–1072.

**EPPO**. **2009**. Data Sheets on Quarantine Pests: Ceratitis capitata,.

**Escudero-Colomar, L. A., M. Vilajeliu, and L. Batllori**. **2008**. Seasonality in the occurrence of the Mediterranean fruit fly [Ceratitis capitata (Wied.)] in the north‐east of Spain. J. Appl. Entomol. 132: 714–721.

**Horton, D. R., T. M. Lewis, and T. T. Dobbs**. **2013**. Interceptions of Anthocoridae, Lasiochilidae, and Lyctocoridae at the Miami Plant Inspection Station (Hemiptera: Heteroptera). Fla. Entomol. 96: 482–497.

**Huang, Z., X. Wu, A. J. Garcia, T. J. Fik, and A. J. Tatem**. **2013**. An Open-Access Modeled Passenger Flow Matrix for the Global Air Network in 2010. PLoS ONE. 8: e64317.

**Hulme, P. E.** **2009**. Trade, transport and trouble: managing invasive species pathways in an era of globalization. J. Appl. Ecol. 46: 10–18.

**IAEA**. **2013**. Tephritid Workers Database. (http://nucleus.iaea.org/sites/naipc/twd/Pages/default.aspx).

**Karsten, M., B. Jansen van Vuuren, P. Addison, and J. S. Terblanche**. **2015**. Deconstructing intercontinental invasion pathway hypotheses of the Mediterranean fruit fly (Ceratitis capitata) using a Bayesian inference approach: are port interceptions and quarantine protocols successfully preventing new invasions? Divers. Distrib. 21: 813–825.

**Kirk, H., S. Dorn, and D. Mazzi**. **2013**. Molecular genetics and genomics generate new insights into invertebrate pest invasions. Evol. Appl. 6: 842–856.

**Klassen, W., C. F. Brodel, and D. A. Fieselmann**. **2002**. Exotic pests of plants: current and future threats to horticultural production and trade in Florida and the Caribbean Basin. MICRONESICA-AGANA-. 35: 5–27.

**Levine, J. M., and C. M. D’Antonio**. **2003**. Forecasting Biological Invasions with Increasing International Trade. Conserv. Biol. 17: 322–326.

**Liebhold, A. M., T. T. Work, D. G. McCullough, and J. F. Cavey**. **2006**. Airline baggage as a pathway for alien insect species invading the United States. Am. Entomol. 52: 48–54.

**Liquido, N. J., R. T. Cunningham, and S. Nakagawa**. **1990**. Host Plants of Mediterranean Fruit Fly (Diptera: Tephritidae) on the Island of Hawaii (1949-1985 Survey). J. Econ. Entomol. 83: 1863–1878.

**Lockwood, J. L., P. Cassey, and T. Blackburn**. **2005**. The role of propagule pressure in explaining species invasions. Trends Ecol. Evol. 20: 223–228.

**Lockwood, J. L., P. Cassey, and T. M. Blackburn**. **2009**. The more you introduce the more you get: the role of colonization pressure and propagule pressure in invasion ecology. Divers. Distrib. 15: 904–910.

**Lopes-da-Silva, M., M. M. Sanches, A. R. Stancioli, G. Alves, and R. Sugayama**. **2014**. The Role of Natural and Human-Mediated Pathways for Invasive Agricultural Pests: A Historical Analysis of Cases from Brazil. Agric. Sci. 2014.

**Lounibos, L. P.** **2002**. Invasions by insect vectors of human disease. Annu. Rev. Entomol. 47: 233–266.

**Mao, L., X. Wu, Z. Huang, and A. Tatem**. **2015**. Modeling monthly flows of global air travel passengers: An open-access data resource. J. Transp. Geogr. 48: 52–60.

**Marcucci, E., and V. Gatta**. **2011**. Regional airport choice: Consumer behaviour and policy implications. J. Transp. Geogr. 19: 70–84.

**McCullough, D. G., T. T. Work, J. F. Cavey, A. M. Liebhold, and D. Marshall**. **2006**. Interceptions of nonindigenous plant pests at US ports of entry and border crossings over a 17-year period. Biol. Invasions. 8: 611–630.

**Papadopoulos, N. T.** **2014**. Fruit Fly Invasion: Historical, Biological, Economic Aspects and Management, pp. 219–252. *In* Shelly, T., Epsky, N., Jang, E.B., Reyes-Flores, J., Vargas, R. (eds.), Trapp. Detect. Control Regul. Tephritid Fruit Flies. Springer Netherlands.

**Papadopoulos, N. T., B. I. Katsoyannos, and J. R. Carey**. **2002**. Demographic Parameters of the Mediterranean Fruit Fly (Diptera: Tephritidae) Reared in Apples. Ann. Entomol. Soc. Am. 95: 564–569.

**Papadopoulos, N. T., B. I. Katsoyannos, J. R. Carey, and N. A. Kouloussis**. **2001**. Seasonal and Annual Occurrence of the Mediterranean Fruit Fly (Diptera: Tephritidae) in Northern Greece. Ann. Entomol. Soc. Am. 94: 41–50.

**Papadopoulos, N. T., B. I. Katsoyannos, N. A. Kouloussis, J. Hendrichs, J. R. Carey, and R. R. Heath**. **2001**. Early Detection and Population Monitoring of Ceratitis capitata (Diptera: Tephritidae) in a Mixed-Fruit Orchard in Northern Greece. J. Econ. Entomol. 94: 971–978.

**Siebert, J. B., and T. Cooper**. **1995**. If medfly infestation triggered a trade ban: Embargo on California produce would cause revenue, job loss. Calif. Agric. 49: 7–12.

**Szyniszewska, A. M., and A. J. Tatem**. **2014**. Global Assessment of Seasonal Potential Distribution of Mediterranean Fruit Fly, Ceratitis capitata (Diptera: Tephritidae). PLoS ONE. 9: e111582.

**Tatem, A. J.** **2009**. The worldwide airline network and the dispersal of exotic species: 2007–2010. Ecography. 32: 94–102.

**Tatem, A. J.** **2014**. Mapping population and pathogen movements. Int. Health. 6: 5–11.

**Tatem, A. J., and S. I. Hay**. **2007**. Climatic similarity and biological exchange in the worldwide airline transportation network. Proc. R. Soc. B Biol. Sci. 274: 1489 –1496.

**Tatem, A. J., Z. Huang, A. Das, Q. Qi, J. Roth, and Y. Qiu**. **2012**. Air travel and vector-borne disease movement. Parasitology. 139: 1816–1830.

**Tatem, A. J., D. J. Rogers, and S. I. Hay**. **2006a**. Global transport networks and infectious disease spread. Adv. Parasitol. 62: 293–343.

**Tatem, A. J., D. J. Rogers, and S. I. Hay**. **2006b**. Estimating the malaria risk of African mosquito movement by air travel. Malar. J. 5: 57.

**Thomas, M. C., J. B. Heppner, R. E. Woodruff, H. V. Weems, G. J. Steck, and T. R. Fasulo**. **2010**. Mediterranean Fruit Fly, Ceratitis capitata (Wiedemann) (Insecta: Diptera: Tephritidae). US Dep. Agric. UFIFAS Ext. Serv. Univ. Fla. IFAS Fla. M Univ. Coop. Ext. Program Boards Cty. Comm. Coop. EENY-214 IN371 Orig. Publ. 2001 DPI Entomol. Circ. 4 230 273. (https://edis.ifas.ufl.edu/in371).

**Tyler, T.** **2014**. IATA Annual Review 2014.

**Ware, C., D. M. Bergstrom, E. Müller, and I. G. Alsos**. **2011**. Humans introduce viable seeds to the Arctic on footwear. Biol. Invasions. 14: 567–577.

**Westphal, M. I., M. Browne, K. MacKinnon, and I. Noble**. **2008**. The link between international trade and the global distribution of invasive alien species. Biol. Invasions. 10: 391–398.

**Work, T. T., D. G. McCullough, J. F. Cavey, and R. Komsa**. **2005**. Arrival rate of nonindigenous insect species into the United States through foreign trade. Biol. Invasions. 7: 323–332.

**Table 1.** Risk indicators for passengers arriving from all and medfly infested countries to destination airports in Florida and California during 2010.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| IATA airport  code1 | All international arrivals  (*ARIij*)2 | | | Arrivals from countries with medfly (*ARIij*) | | | | | | Estimated annual passenger volume from all countries3 | Estimated annual passenger volume from medfly countries | Arrival risk ratios4 |
| Jan - Apr | May -Aug | Sep -Dec | Jan -Apr | | May -Aug | | Sep -Dec | |
| Florida | | | | | | | | | | | | |
| MIA | 0.41 | 0.44 | 0.38 | 0.93 | 0.95 | | 0.84 | | 20,112,118 | | 9,050,453 | 0.45 |
| FLL | 0.11 | 0.11 | 0.14 | 1.00 | 1.00 | | 0.92 | | 16,293,958 | | 1,955,275 | 0.12 |
| MCO | 0.17 | 0.21 | 0.19 | 1.00 | 0.96 | | 0.88 | | 9,236,560 | | 1,847,312 | 0.20 |
| California | | | | | | | | | | | | |
| LAX | 0.08 | 0.12 | 0.08 | 0.70 | 0.95 | | 0.64 | | 67,883,825 | | 8,146,059 | 0.12 |
| SFO | 0.02 | 0.05 | 0.02 | 0.47 | 0.92 | | 0.49 | | 85,513,100 | | 4,275,655 | 0.05 |

1International Air Transport Association (IATA) airport codes: MIA (Miami), FLL (Fort Lauderdale), MCO (Orlando), LAX (Los Angeles) and SFO (San Francisco).

2*ARIij* indicates the ratio of estimated passenger number weighted by seasonal risk of medfly presence at a departing flight location divided by the estimated seasonal passenger total for all international arrivals or the international arrivals from medfly infested locations. Higher *ARIij* scores indicate higher risk of medfly arrival relative to passenger volume.

3Passenger volume was derived from the worldwide airline network, Vbd-air.com (Mao et al. 2015).

4Arrival risk ratios are the number of passengers arriving from locations where medfly was present divided by the total estimated number of international passengers arriving at a given airport.

**Table 2.** Risk indicators for passengers with medfly departing from airport locations infested with medfly and arriving in Florida and California in 2010.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Country | IATA airport code1 | | Seasonal risk of medfly at a departing flight location2 | | | Total estimated passenger number3 | Annual  origin  risk  indicator  (*ORIjk*)4 |
| Jan-Apr | May-Aug | Sep-Dec |
| Florida | | | | | | | |
| Colombia | | BOG | 1.0 | 1.0 | 1.0 | 413,039 | 1.00 |
| Brazil | | GRU | 1.0 | 1.0 | 1.0 | 406,040 | 1.00 |
| Panama | | PTY | 1.0 | 1.0 | 1.0 | 336,481 | 1.00 |
| Venezuela | | CCS | 1.0 | 1.0 | 1.0 | 332,507 | 1.00 |
| Costa Rica | | SJO | 1.0 | 1.0 | 0.6 | 301,482 | 0.87 |
| Peru | | LIM | 1.0 | 1.0 | 0.6 | 289,895 | 0.87 |
| Argentina | | EZE | 1.0 | 1.0 | 1.0 | 259,388 | 1.00 |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Country | IATA airport code1 | | Seasonal risk of medfly at a departing flight location2 | | | Total estimated passenger number3 | Annual  origin  risk  indicator  (*ORIjk*)4 |
| Jan-Apr | May-Aug | Sep-Dec |
|  | | | | | | | |
| Spain | | MAD | 0.6 | 0.6 | 1.0 | 210,268 | 0.74 |
| France | | CDG | 1.0 | 1.0 | 0.6 | 186,429 | 0.60 |
| Guatemala | | GUA | 1.0 | 1.0 | 0.6 | 177,542 | 0.87 |
| Ecuador | | UIO | 1.0 | 1.0 | 1.0 | 166,530 | 1.00 |
| Colombia | | MDE | 1.0 | 0.6 | 0.6 | 154,854 | 0.73 |
| Nicaragua | | MGA | 1.0 | 1.0 | 0.6 | 154,013 | 0.87 |
| Brazil | | GIG | 1.0 | 1.0 | 1.0 | 140,064 | 1.00 |
| Honduras | | SAP | 1.0 | 1.0 | 0.6 | 136,945 | 0.86 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Country | IATA airport code1 | Seasonal risk of medfly at a departing flight location2 | | | Total estimated passenger number3 | Annual  origin  risk  indicator  (*ORIjk*)4 |
| Jan-Apr | May-Aug | Sep-Dec |
| California | | | | | | |
| France | CDG | 0.2 | 1.0 | 0.6 | 401,918 | 0.66 |
| El Salvador | SAL | 1.0 | 1.0 | 0.6 | 217,318 | 0.87 |
| Peru | LIM | 1.0 | 1.0 | 0.6 | 112,141 | 0.86 |
| Switzerland | ZRH | 0.2 | 0.6 | 0.2 | 103,667 | 0.35 |
| Guatemala | GUA | 1.0 | 1.0 | 0.6 | 98,120 | 0.87 |
| Brazil | GRU | 1.0 | 1.0 | 1.0 | 54,449 | 1.00 |
| Israel | TLV | 0.6 | 0.6 | 0.6 | 49,245 | 0.60 |
| Panama | PTY | 1.0 | 1.0 | 1.0 | 46,234 | 1.00 |
| Colombia | BOG | 1.0 | 1.0 | 1.0 | 30,083 | 1.00 |
| Country | IATA airport code1 | Seasonal risk of medfly at a departing flight location2 | | | Total estimated passenger number3 | Annual  origin  risk  indicator  (*ORIjk*)4 |
| Jan-Apr | May-Aug | Sep-Dec |
| Italy | FCO | 0.6 | 1.0 | 1.0 | 25,388 | 1.00 |
| Costa Rica | SJO | 1.0 | 1.0 | 0.6 | 21,836 | 0.87 |

1International Air Transport Association (IATA) airport codes for departure airports with the most passengers arriving at Florida and California in 2010.

2Seasonal risk of medfly presence at a departing flight location was derived from the medfly environmental suitability model (Szyniszewska and Tatem 2014). Based on the predicted values for a 200k buffer surrounding the airport of origin, the risk was classified as high (1.0), medium (0.6) or low (0.2).

3Number of passengers arriving on direct flights from all international origin locations to Florida and California derived from the monthly global passenger flow matrix (Vbd-air.com) (Mao et al. 2015).

4*ORIjk* represents the ratio of estimated passenger number arriving from a given airport weighted by seasonal risk of medfly presence at a departing flight location divided by the total estimated passenger number arriving from that location. Higher *ORIjk* scores indicate greater annual risk of medfly arrival relative to total estimated passenger number.

**Table 3.** Risk indicators for passengers with medfly departing from airport locations infested with medfly and arriving at specific airports in Florida and California in 2010.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| IATA airport code1 | | Seasonal risk of medfly at a departing flight location2 | | | | Estimated number of passengers3 | | | | Annual  Risk  Indicator  *AORIijk*4 |
| Origin | Destination | Jan-  Apr | May-  Aug | | Sep-  Dec | Jan-  Apr | May-Aug | Sep-Dec | Total |
| Florida | | | | | | | | | | |
| GRU | MIA | 1.0 | | 1.0 | 1.0 | 111,695 | 114,978 | 114,051 | 340,724 | 1.00 |
| CCS | MIA | 1.0 | | 1.0 | 1.0 | 110,849 | 111,948 | 109,710 | 332,507 | 1.00 |
| LIM | MIA | 1.0 | | 1.0 | 0.6 | 84,997 | 97,832 | 56,062 | 276,265 | 0.86 |
| EZE | MIA | 1.0 | | 1.0 | 1.0 | 88,575 | 99,461 | 71,352 | 259,388 | 1.00 |
| BOG | MIA | 1.0 | | 1.0 | 1.0 | 82,020 | 84,996 | 85,961 | 252,977 | 1.00 |
| BOG | FLL | 1.0 | | 1.0 | 1.0 | 39,061 | 41,823 | 37,168 | 118,052 | 1.00 |
| SJO | FLL | 1.0 | | 1.0 | 0.6 | 18,393 | 19,572 | 5,849 | 47,714 | 0.92 |
| MDE | FLL | 1.0 | | 0.6 | 0.6 | 12,376 | 7,808 | 5,570 | 34,672 | 0.74 |
| PTY | MCO | 1.0 | | 1.0 | 1.0 | 28,171 | 28,922 | 29,402 | 86,495 | 1.00 |
| IATA airport code1 | | Seasonal risk of medfly at a departing flight location2 | | | | Estimated number of passengers3 | | | | Annual  Risk  Indicator  *AORIijk*4 |
| Origin | Destination | Jan-  Apr | May-  Aug | | Sep-  Dec | Jan-  Apr | May-Aug | Sep-Dec | Total |
|  | | | | | | | | | | |
| GRU | MCO | 1.0 | | 1.0 | 1.0 | 20,483 | 22,690 | 21,982 | 65,155 | 1 |
| BOG | MCO | 1.0 | | 1.0 | 1.0 | 14,022 | 14,863 | 13,125 | 42,010 | 1 |
| California | | | | | | | | | | |
| CDG | LAX | 0.2 | 1.0 | | 0.6 | 14,845 | 114,555 | 60,519 | 289,648 | 0.66 |
| SAL | LAX | 1.0 | 1.0 | | 0.6 | 50,374 | 64,136 | 32,617 | 168,872 | 0.87 |
| LIM | LAX | 1.0 | 1.0 | | 0.6 | 35,331 | 38,023 | 23,272 | 112,141 | 0.86 |
| CDG | SFO | 0.2 | 1.0 | | 0.6 | 5,674 | 49,061 | 20,902 | 112,270 | 0.67 |
| SAL | SFO | 1.0 | 1.0 | | 0.6 | 14,271 | 19,474 | 8,820 | 48,446 | 0.88 |
| ZRH | SFO | 0.2 | 0.6 | | 0.2 | 0 | 9,603 | 3,945 | 35,733 | 0.38 |

1International Air Transport Association (IATA) airport codes: GRU (Brazil), CCS (Venezuela), LIM (Peru), EZE (Argentina), BOG (Colombia), SJO (Costa Rica), MDE (Colombia), PTY (Panama), CDG (France), SAL (El Salvador), ZRH (Switzerland), MIA (Miami), FLL (Fort Lauderdale), MCO (Orlando), LAX (Los Angeles) and SFO (San Francisco). Origin-destination airports were selected based on the highest number of passengers arriving to Florida and California.

2Seasonal risk of medfly presence at a departing flight location was derived from the medfly environmental suitability model ((Szyniszewska and Tatem 2014). Based on the predicted values for a 200k buffer surrounding the airport of origin, the risk was classified as high (1.0), medium (0.6) or low (0.2).

3Number of passengers arriving based on a given pair of origin-destination airports derived from the monthly passenger flow matrix (Vbd-air.com) (Mao et al. 2015).

3*AORIijk* calculations were based on the number of passengers per season on the origin-destination route weighted by the relative risk of seasonal medfly presence at the origin location. Higher *AORIijk* scores indicate higher risk of medfly arrival.

**Figure Captions**

**Fig. 1.** Countries with the greatest number of passenger arrivals at international airports in Florida and California, respectively, during 2010 that accounted for 70% and 90% of the total incoming passenger volume according to the global passenger flow matrix (Mao et al. 2015). Medfly is reported to be present in countries marked with an asterisk. Airport codes: MIA (Miami), FLL (Fort Lauderdale), MCO (Orlando), LAX (Los Angeles), and SFO (San Francisco).

**Fig. 2.** Three panel map illustrating the seasonal volume of passenger flow to Florida during 2010. The predicted passenger volume was obtained from vbd-air.com (Mao et al. 2015) and adjusted for risk of medfly occurrence. Medfly presence or absence was classified according to the European and Mediterranean Plant Protection Organization and International Atomic Energy Agency (EPPO 2009, IAEA 2013).

**Fig. 3.** Three panel map illustrating the seasonal volume of passenger flow to California during 2010. The predicted passenger volume was obtained from vbd-air.com (Mao et al. 2015) and adjusted for risk of medfly occurrence. Medfly presence or absence was classified according to the European and Mediterranean Plant Protection Organization and International Atomic Energy Agency (EPPO 2009, IAEA 2013).

Fig. 1.

Fig. 2

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Fig. 3.

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