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# A GIS-BASED COST DISTANCE APPROACH TO ANALYSE THE SPREAD OF *MATSUCOCCUS FEYTAUDI* IN TUSCANY, ITALY (COCCOIDEA MATSUCOCCIDAE)

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Roversi P.F., Sciarretta A., Marziali L., Marianelli L., Bagnoli M. – A Gis-based cost distance approach to analyse the spread of *Matsucoccus feytaudi* in Tuscany, Italy (Coccoidea Matsucoccidae).

The Maritime pine bast scale *Matsucoccus feytaudi* Ducasse was introduced into south-eastern France from the Atlantic regions and since then has moved eastward to reach Tuscany, Italy, causing decay and death of thousands of hectares of pine stands. Monitoring of the pine bast scale by pheromone traps in Tuscany since 2000 has allowed us to obtain yearly data on the pest's diffusion. The data were processed by means of the Thiessen polygons algorithm to obtain the distribution of the insect. A GIS cost distance model was adopted to simulate the spread of *M. feytaudi* infestation: dominant winds were used in the least accumulative distance calculation, together with *Pinus pinaster* presence as secondary factor. The overall accuracy of the model calculated for the years 2003 to 2008 ranged between 70.0% and 81.8%; user's and producer's accuracy showed greater variability, but with good performances in the majority of cases. The use of pheromone traps and spatial analysis enabled to produce annual maps for the Tuscany, with the identification of the Maritime pine forests more susceptible to *M. feytaudi* colonization. This cartography was an important tool for regional offices in the identification of areas requiring direct forestry management.

KEY WORDS: *Pinus pinaster* Aiton, non-indigenous insects, monitoring, spatial analysis, spread management.

## INTRODUCTION

Due to the remarkable growth of international trade and human traffic around the globe in recent decades, invasions of non-indigenous species are playing an increasingly important role in the biodiversity, ecology and economy of affected areas; this is especially true for forest insects because of their effects on complex ecosystems (BROCKERHOFF *et al.*, 2006). The problems of early detection and monitoring of invasive pests have been addressed many times (MEHTA *et al.*, 2007; BOGICH *et al.*, 2008; PYŠEK and RICHARDSON, 2010). In this context, the possibility to estimate and forecast the invasion process of alien species can be of considerable importance in guiding control interventions and policy decisions (TOBIN *et al.,* 2007; LIEBHOLD and TOBIN, 2008; VAN DER GAAG *et al.*, 2010).

The Maritime pine bast scale, *Matsucoccus feytaudi* Ducasse (Rhynchota: Coccoidea Matsucoccidae), is native to the Atlantic regions of France, Spain, Portugal and Morocco, corresponding to the natural range of the Maritime pine, *Pinus pinaster* Aiton, the only food plant of this insect. The species was introduced into south-eastern France in the 1950s and from there moved into Italy in the 1970s and more recently into Corsica, becoming a destructive pest of *P. pinaster* forests (SCHVESTER *et al.*, 1970; FABRE, 1980; ARZONE and VIDANO, 1981; COVASSI and BINAZZI, 1992; JACTEL *et al.,* 1998). For Tuscany, it was first recorded in 1999 in the Montefalcone Natural Reserve (Pisa) and then started a progressive expansion into the whole region, causing the decay and death of many thousands of hectares of pine stands (BINAZZI *et al.,* 2002; BINAZZI, 2005).

*Matsucoccus feytaudi* is considered a primary pest that initiates weakening of the colonized trees not only by subtraction of phloem sap but especially by the release of toxic substances into the trees, causing tissue necrosis. The infested pines present with abundant resin flow on the trunk, yellowing and reddening of the foliage, and ultimately the loss of needles. The trees die in 3-5 years, usually due to colonization by numerous secondary corticicolous beetles (BINAZZI, 2005). The primary role of *M. feytaudi* infestations in the decay and die-off of Maritime pines from Provence to Tuscany in recent decades has long been recognized, but progress in solving the problem has been conflicting (SCHVESTER *et al.*, 1970; JACTEL *et al.*, 1998; SCHVESTER and FABRE, 2001a, b).

Early detection and risk assessment are considered a fundamental aspect of a management plan. Monitoring of adult males with pheromone traps has proved to be very effective in locating *M. feytaudi* infestations before the onset of tree decay and in implementing timely measures for prevention and control (BRANCO *et al.*, 2004; ROVERSI *et al.*, 2007; MARZIALI *et al.,* 2011). Current silvicultural practices such as selective cutting and removal of infested or sensitive trees can help in preventing the establishment of *M. feytaudi* invasion, while other control methods include mass-trapping of emerging males and use of kairomones to attract natural enemies (JACTEL *et al.*, 1998; GAULIER *et al.*, 2001; BINAZZI *et al.,* 2002; BINAZZI *et al.,* 2009).

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After the identification of the first *M. feytaudi* outbreaks in Tuscany, the need to identify the areas at greatest risk of colonization by the Maritime pine bast scale has led to the development of a model that incorporates the main factors affecting *M. feytaudi* spread after the initial colonisation in a new area with fragmented *P. pinaster* distribution.

The 3-year period of monitoring data after the identification of the first *M. feytaudi* outbreak in Tuscany, Italy (2000-2002) was considered for setting up the model parameters. From 2003 the model was validated and utilized to identify on map areas at greatest risk of colonization by the Maritime pine bast scale, to guide early warning activities in possible areas of further invasion and to evaluate the attendant outbreak probabilities.

## MATERIAL & METHODS

### STUDY AREA AND SAMPLING SITES

In Tuscany (Italy), *P. pinaster* is a forest tree largely used in reforestation for both soil protection and timber production. It forms 23,500 ha of mainly even-aged stands and is present in about 18,000 ha of broad-leaved mixed forest (MONDINO and BERNETTI, 1998). The shapefile of *P. pinaster* distribution in Tuscany was obtained by selecting the points from the Tuscany Forest Inventory (AA.VV., 1998) where Maritime pine was reported to be present, at a grid resolution of 400 m.

Entomological surveys were carried out from 2000 to 2010. In 2000-2002, 46 sampling sites were set up in the north-western part of the region, where the first record of the Maritime pine bast scale was reported in 1999. Due to expansion of the insect, sampling sites were increased to 82 (2003), 95 (2004), 134 (2005), 144 (2006-2009) and 145 (2010), covering the whole region. For each sampling station, UTM datum WGS 1984 coordinates (Zone 32T) were recorded using the Etrex Vista Global Positioning System (GPS) (Garmin, Olathe, Kansas).

### DATA COLLECTION

*Matsucoccus feytaudi* males were collected using sticky traps consisting of a 30x30 cm polycarbonate panel covered with glue on one side and baited with a synthetic sex pheromone blend containing 0.4 mg of (8E, 10E)-3,7,9-trimethyl-8,10-dodecadien-6-one (provided by the Institut National de la Recherche Agronomique, Unité de Phytopharmacie et des Médiateurs chimiques, Versailles, France). For each sampling site, a single pheromone trap was positioned on the tree trunk at about 2 m above ground. Each year, traps were positioned in January and maintained until March, for the whole duration of male flight. Pheromone dispensers were replaced monthly. At the end of the survey period, glued surfaces were removed and checked in the laboratory under a stereoscopic microscope to assess the presence of *M. feytaudi* individuals. The binary data of presence/absence, obtained for each sampling site and year, were used for subsequent spatial analyses.

### SPATIAL DISTRIBUTION ANALYSIS

Thiessen polygons were used to represent the spatial distribution of the Maritime pine bast scale. Each polygon defines an area of influence around its sampling point, so that any location inside the polygon is closer to that point than any of the other sample points (STOYAN *et al.*, 1987). Polygons corresponding to *M. feytaudi* presence areas were selected and clipped so that only areas of infestation overlaid on the Maritime pine distribution were represented on the map. The spatial analysis was carried out using GIS Arcview version 3.2 (ESRI, Redland, California).

### COST DISTANCE ANALYSIS

The range expansion of *M. feytaudi* was modelled using the Cost Distance tool in the Spatial Analyst extension of GIS Arcview version 3.2 (ESRI, Redland, California).

The algorithm underlying the Cost Weighted Distance function is:

$$N_{i+1} = N_i + (R_i + R_{i+1})/2 \qquad [1]$$

where $i$ is the source cell, $i$+1 the target cell, $Ni$ the accumulated resistance, $Ri$ the resistance to migrate through the cell $i$. Along a diagonal direction, the cost is multiplied by $\sqrt{2}$ to compensate for the longer distance:

$$N_{i+1} = N_i + \sqrt{2}\,(R_i + R_{i+1})/2 \qquad [2]$$

The algorithm calculates the least accumulative distance to travel from one cell to another of the map (in our case, to move from the border of an infested polygon to the surrounding uninfested space), adjusting the Euclidean distance between the source cell and the given destination cell according to some cost weights (BERRY, 1993; MCGREW and MONROE, 1993). The algorithm allows the entry of multiple layers (resistance layers) under which the distance measurement is weighted: if the assigned weight is less than 1 it represents a decrease in the cost (or an acceleration factor), if it is greater than 1 it represents an increase in the cost (or a slowdown factor). As a final output, the algorithm gives the least accumulative cost distance from the border of infested areas of each cell taking into account a cost surface.

*Resistance layers.* The choice of the layers in the model and the setting up of appropriate values were established according to current knowledge on the dispersal ecology of *M. feytaudi*. In our case, dispersal takes place from April to early June and is determined mainly by the wind, which scatters the first instar nymphs. Consequently, the prevailing wind was the first layer included in the model.

For the period 1 April-15 June each year, daily data for maximum, minimum and mean wind speed (m/sec) and wind direction were obtained from the network of weather stations of the Tuscan Regional Agency for Development and Innovation in the Agro-forestry Sector (ARSIA), selecting the nearest to the *M. feytaudi* infested sampling points. To identify the prevailing wind of the period for each point, daily data were ranked according to the number of days of presence of each wind direction. Hence, the primary prevailing wind was the one blowing from a certain direction for the greatest number of days, followed by the secondary prevailing wind (Fig. I).

The other considered layer was the *P. pinaster* presence in the forest tree communities located around infested polygons, since they represent preferential corridors facilitating Maritime pine bast scale dispersal. In this case, dominant Maritime pine stands (*P. pinaster* >50%) and mixed woods (*P. pinaster* <50%) were differentiated, on the assumption that dispersal is more facilitated in the former than in the latter.

The weights of layers were obtained by calculating the maximum yearly rate of spread of *M. feytaudi* in different wind and habitat conditions. Comparisons were carried out for 2000-2001 and 2001-2002. The two individual layers were then combined to create a cost layer, which summarizes the considered factors. The cost layer is used

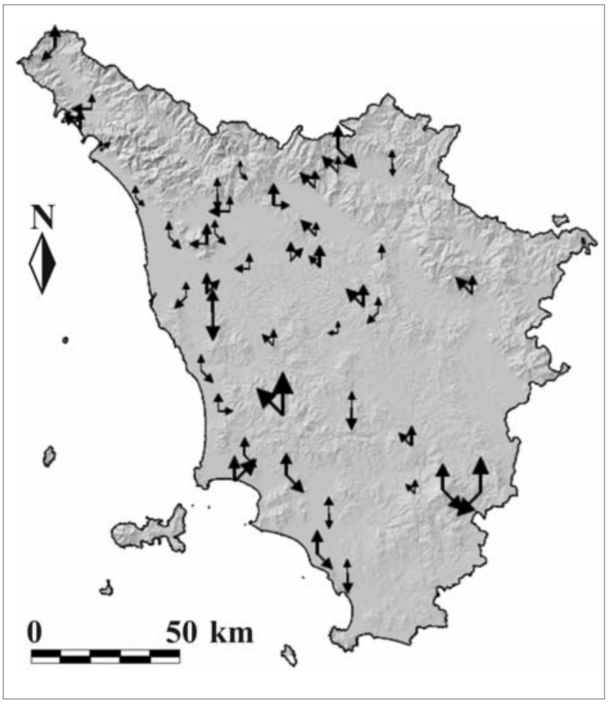


Figure I – Example of a wind map showing the direction of prevailing winds obtained from weather stations during the period 1 April-15 June 2006. The size of the arrows represents the mean wind speed calculated over the period, with values ranging between 0.8 and 4.9 m/sec.

by the model to simulate the *M. feytaudi* expansion and the result is expressed in terms of cost distance: the smaller the value, the higher the probability of colonization.

*Model validation.* To validate the predictions, the data obtained from the forecasting map were compared with the experimental data collected in year *x+1* via a 2x2 error matrix. In this way, observed presence/absence data were tabulated against those predicted by the model, and true positive (TP), false positive (FP), false negative (FN) and true negative (TN) were identified (DEDECKER *et al.,* 2007).

To assign the prediction attribute (presence / absence) estimated by the model, we operated as follows: for the prediction based on data collected in year *x*, all the survey points of year *x+1* were selected. We assigned the prediction attribute to each of them, considering as "presence" any point included in the maximum cost surface calculated by the model, whatever its value. In the validation process, the real position of the survey points, instead of Thiessen polygons, was compared with the cost surface, to have more restrictive validation results.

To verify the significance of model predictions, predicted *versus* observed cases were compared, using contingency table and $Chi^2$ analysis. The null hypothesis is that true and false observations were equally distributed in the error matrix. If the predictions were significantly more true than false, then the model validity was confirmed. The goodness of the prediction was evaluated on the basis of three performance measures: the overall accuracy, the producer's accuracy and the user's accuracy (CONGALTON, 1991). The overall accuracy was obtained from the sum of correctly classified points (TP+TN) divided by the total number of survey points (TP+FP+FN+TN). The producer's accuracy indicates the probability of a point being correctly classified and was obtained from the number of correct points in a category (TP or TN) divided by the total number of points of that category (TP+FN or FP+TN, respectively). The user's accuracy indicates the probability that a site classified by the model corresponds to the experimental datum and was obtained by dividing the correct points predicted in a category (TP or TN) by the total number of points predicted in that category (TP+FP or FN+TN, respectively).

## RESULTS

### *MATSUCOCCUS FEYTAUDI* DISTRIBUTION

The initial spread of *M. feytaudi* following the appearance in northern Tuscany in 1999 is shown in Fig. II. In 2000, two areas of invasion were active, the first in contact with the neighbouring Liguria Region (Santo Stefano in Magra), the second 70 km to the south-east

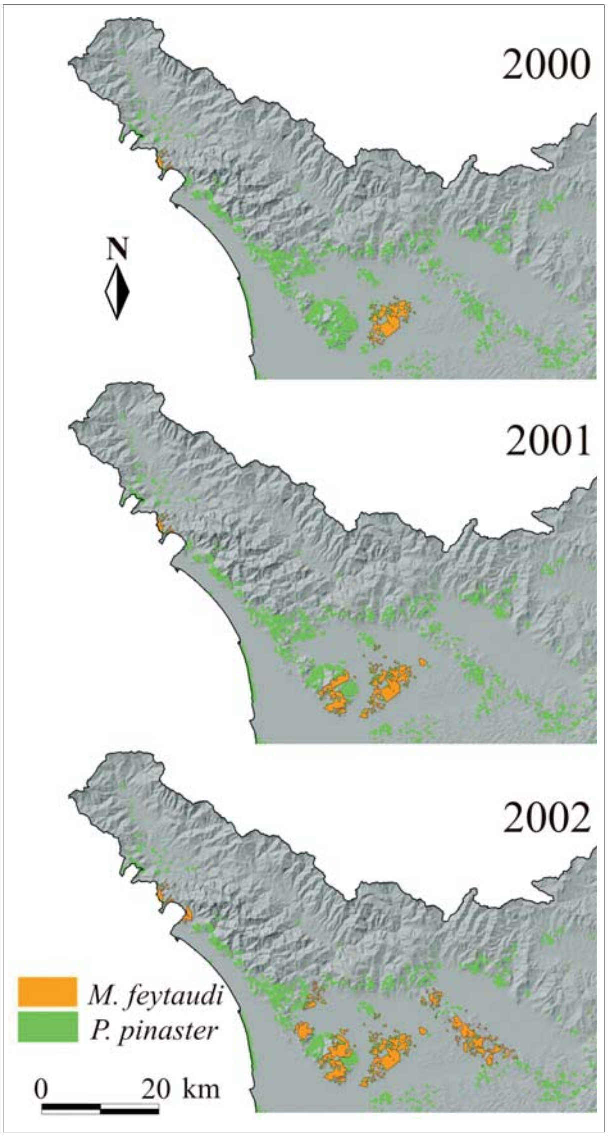


Figure II – Distribution of *M. feytaudi* in north-western Tuscany from 2000 to 2002, obtained with the Thiessen polygons procedure.

(Montefalcone). In 2001 and 2002, *M. feytaudi* spread eastward and westward, especially from the Montefalcone focus. The mean annual spread of *M. feytaudi*, calculated by measuring all distances observed between the boundary of a polygon infested in year *x* and the boundary of a polygon that became infested in year *x+1*, was 7.7 ± 0.6 km/year (n=9) and 8.0 ± 1.5 km/year (n=11) in 2000-2001 and 2001-2002, respectively.

In 2003, new invaded areas were observed in other sectors of the region, such as Farma-Merse in central-southern Tuscany, well over 50 km from areas already infested in the previous year (Fig. III).

The long-distance spread of *M. feytaudi* was facilitated by the presence of sawmills, which received wood with infested bark from areas even tens of kilometres away, allowing them to trigger new outbreaks of infestation. In the following years (2004-2008), *M. feytaudi* expanded its range according to the natural expanding factors. From 2010, most of the Tuscan sectors with *P. pinaster* stands were colonized by *M. feytaudi,* both along the coast and in the inner areas, while the spread in previously invaded areas of northern Tuscany was almost completed (Fig. III).

COST DISTANCE MODEL

The maximum annual distances travelled by *M. feytaudi* were observed in the 2001-2002 comparison. In the presence of tailwind and the absence of *P. pinaster*, the distance was 15.4 km/year (eastward); in the absence of tailwind and the presence of Maritime pine stands, it was 10 km/year (westward); in absence of both tailwind and *P. pinaster*, it was 7.5 km/year (northward). No tailwind was observed in the direction of Maritime pine stands. These results were used to select the appropriate weights in the cost distance model.

The prevailing wind weight was determined by dividing the distance travelled without tailwind (7.8 km) by the tailwind distance travelled in one year by *M. feytaudi* (15.4 km); the resulting value of 0.5 means that cost distance along the tailwind direction was half the Euclidean distance. A wind influence map was prepared by digitizing the polygons situated in the direction of the prevailing winds in sectors surrounding already infested areas. These polygons were assigned the value of 0.5.

In a similar way we calculated the weight for dominant Maritime pine stands: the cost distance along the *P. pinaster* direction decreased to 25% of the Euclidean distance and thus a value of 0.25 was assigned. For mixed woods, assuming that the low presence of *P. pinaster* would slow the scale's spread, we assigned a halved weight of 0.12.

The two individual layers were then combined into the cost layer by subtracting single weights to 1, the neutral value for the algorithm. As an example, if we have a polygon with both prevailing wind and dominant Maritime pine stands, the cost layer will have a value of 0.25, representing a path that is very preferential with respect to the other.

The forecasting map showing the cost surface elaborated by the model for the years 2003-2008 was obtained each year based on the 2002-2007 data (Fig. IV). The results of the validation process are shown in Table 1. $Chi^2$ analysis resulted significant for all years except 2008. In general, the overall accuracy ranged between 70.0% and 81.8%, while both the user's and producer's accuracy showed greater variability, albeit with good performances in the majority of cases. In particular, very high performances were obtained for the producer's accuracy predicted presence (75.0% - 100%) and user's accuracy predicted absence (87.5% - 100%). Lower performances were obtained for user's accuracy predicted presence, especially in 2007 and 2008 with 33.3% and 14.3%, respectively.

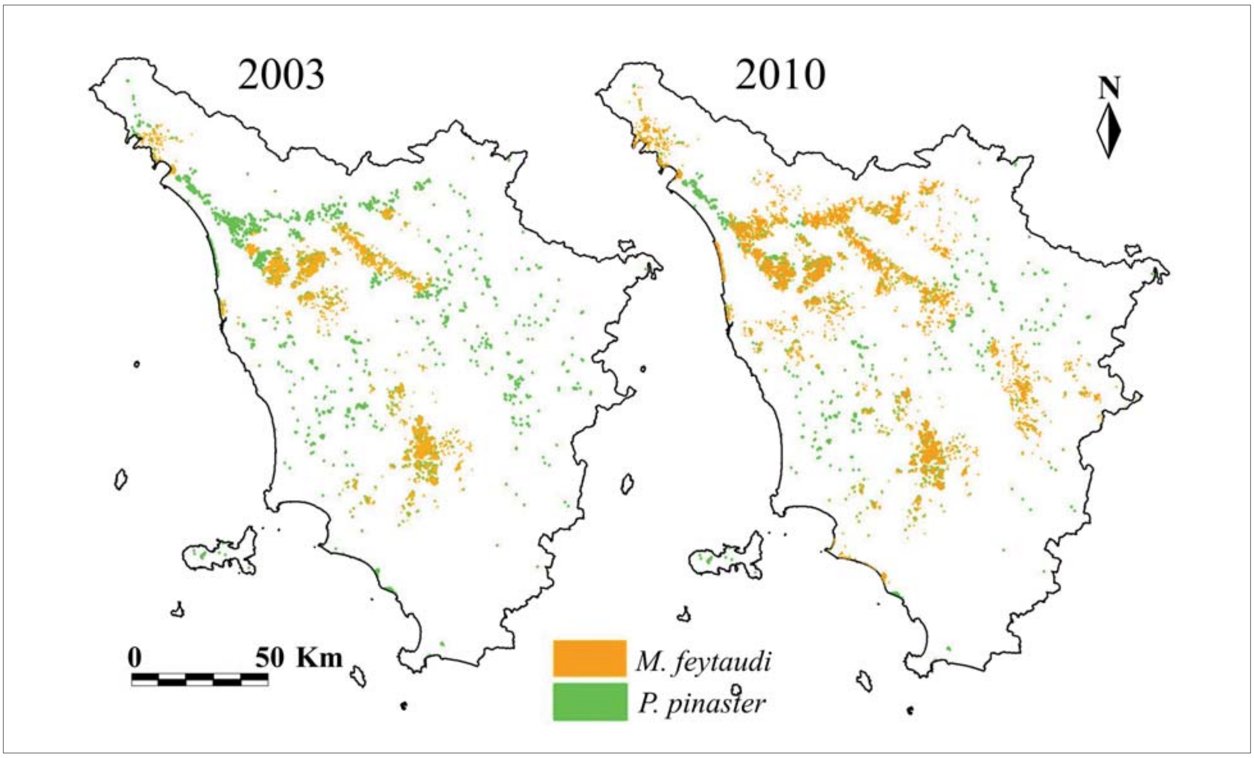


Figure III - Distribution of *M. feytaudi* in Tuscany for the years 2003 and 2010, obtained with the Thiessen polygons procedure.

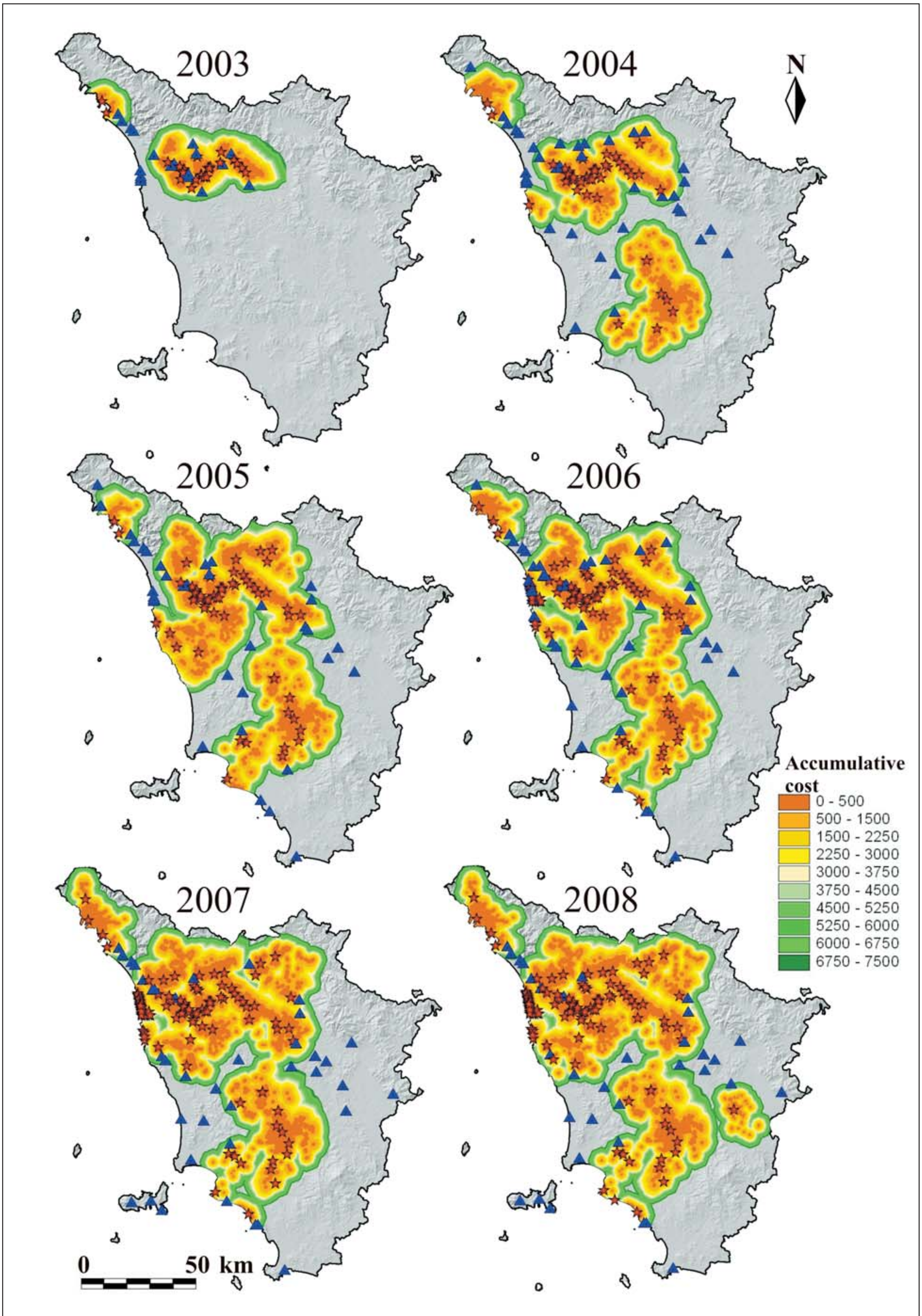


Figure IV – Map of the accumulative cost for the spread of *M. feytaudi* in Tuscany from 2003 to 2008. Blue triangles and red stars represent sampling sites where *M. feytaudi* was absent or present, respectively.

*Table 1* – Two-dimensional error matrices used to validate the forecast model of *Matsucoccus feytaudi* for the years 2003-2008 and $X^2$ analysis results.

| *Year* | *Predicted* | *Observed* | | | | |
|---|---|---|---|---|---|---|
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2003* | No presence | 21 | 1 | 22 | *95.5%* | *72.7%* |
| | Presence | 11 | 11 | 22 | *50.0%* | |
| | Total | 32 | 12 | 44 | | $X^2$ |
| | *Producer's accuracy* | *65.6%* | *91.7%* | | | 11.46** |
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2004* | No presence | 21 | 3 | 24 | *87.5%* | *81.8%* |
| | Presence | 5 | 15 | 20 | *75.0%* | |
| | Total | 26 | 18 | 44 | | $X^2$ |
| | *Producer's accuracy* | *60.8%* | *83.3%* | | | 13.37** |
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2005* | No presence | 9 | 1 | 10 | *90.0%* | *73.8%* |
| | Presence | 10 | 22 | 32 | *68.8%* | |
| | Total | 19 | 23 | 42 | | $X^2$ |
| | *Producer's accuracy* | *47.4%* | *95.7%* | | | 10.62** |
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2006* | No presence | 14 | 0 | 14 | *100%* | *71.7%* |
| | Presence | 13 | 19 | 32 | *59.4%* | |
| | Total | 27 | 19 | 46 | | $X^2$ |
| | *Producer's accuracy* | *51.9%* | *100%* | | | 14.10** |
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2007* | No presence | 14 | 1 | 15 | *93.3%* | *75.0%* |
| | Presence | 5 | 4 | 9 | *44.4%* | |
| | Total | 19 | 5 | 24 | | $X^2$ |
| | *Producer's accuracy* | *73.7%* | *80.0%* | | | 4.84* |
| | | No presence | Presence | Total | *User's accuracy* | *Overall accuracy* |
| *2008* | No presence | 13 | 0 | 13 | *100%* | *70.0%* |
| | Presence | 6 | 1 | 7 | *14.3%* | |
| | Total | 19 | 1 | 20 | | $X^2$ |
| | *Producer's accuracy* | *68.4%* | *100%* | | | 1.97 |

* *P<0.05;* ** *P<0.01*

## DISCUSSION

Cost distance analysis has recently been used to model the habitat connectivity and dispersal activity of various animal species, for example to predict the presence of the butterfly *Pararge aegeria* L. in isolated habitats, to develop macroinvertebrate migration models for habitat restoration management, to model the dispersal invasion of the bark beetle *Xyleborus glabratus* Eichhoff in U.S. forests, to evaluate the colonization of cotton fields by herbivores and their natural enemies, and to model the dispersal ability of *Phlebotomus perniciosus* Newstead under changing climatic conditions (CHARDON *et al.*, 2003; DEDECKER *et al.,* 2007; KOCH and SMITH, 2008; PEROVIĆ *et al.,* 2010; FISCHER *et al.*, 2011). The advantage of this approach is that geographical information and behavioural aspects are included in the model, allowing the measurement of species dispersal and connectivity between population patches in fragmented and heterogeneous landscapes, assuming that least costs correspond to the minimum efforts for a species to disperse. The choice and setting up of the layers in the model are considered the principal constraint for cost distance analysis, often requiring detailed knowledge of the biology and ecology of the investigated species.

We utilized the initial 3 years of monitoring data to calculate the annual rate of spread related to the wind directions. Although this area is relatively small, in terms of forest landscape structure and connectivity, it can be considered representative of the rest of Tuscany forests, except for some zones limited to the coast. The resulting distances, included in our model, fell in the range reported by other authors (JACTEL *et al.,* 1998; GAULIER *et al.*, 2001; SCHVESTER and Fabre, 2001a), i.e. between 2 and 10 km according to local conditions.

We decided to use the maximum distance travelled by the insect under different wind conditions instead of the mean values in order to have a precautionary outcome of the model, with a map showing a larger cost area. Moreover, all sampling points falling within the cost area were included in the validation of the model, also those in zones with very high cost distance values (and thus with a very low probability of being found positive). This resulted in a slight over-estimation of the model, as can be seen in the error matrix in which some estimated presences were not confirmed by the field observations (FP). In general, however, the reliability of the maps was very high. For example, the model faithfully described the process of expansion since the first outbreak of infestation in 2000 at the border with Liguria (Santo Stefano in Magra), which after eight years still does not appear to have rejoined the infested areas in the south despite the presence of Maritime pine forests.

The rapid invasion of *M. feytaudi* into Tuscany was determined by the combination of natural spread, linked to the transport of nymphs by the wind, and the movement of pine logs from areas already infested to pest-free territories (BINAZZI, 2005; ROVERSI *et al*., 2010).

This was particularly evident in 2003, when new advanced outbreaks were almost always near sawmills or lumberyards. Symptomatic of this are the captures of *M. feytaudi* males in a sampling area in the southern part of the region free from *P. pinaster* but with a vast timber storage zone (data not published). Although long-distance dispersal via human traffic cannot be predicted by the model, this limitation does not appear to restrict its validity for practical applications; in fact this human-assisted infestation was readily detected because main sawmills and lumberyards in the Region were regularly monitored after the appearance of *M. feytaudi* in Tuscany. On the contrary, it appeared problematic to monitor and control the naturally spread process in areas becoming year by year more extended.

Once the Maritime pine bast scale arrived in a new area, the anemophilous spread was described by the model with a high degree of reliability. The combined use of pheromone traps and spatial analysis for forecasting purposes enabled us to produce annual maps for the entire Tuscany region in the period 2002-2008. In these maps, accumulated cost distances can be considered as probability levels of *M. feytaudi* colonisation. The Maritime pine forests were found to be more susceptible each year to *M. feytaudi* colonization. After 2008, most Tuscan areas with *P. pinaster* were colonized by *M. feytaudi*, while areas not yet invaded were pinpointed; hence the model maps have substantially outlived their predictive function.

Since the detection of *M. feytaudi* in Tuscany, a monitoring project named "Extensive Monitoring System of Tuscany Forests (META)", supported by the European Agricultural Fund for Rural Development, was activated, aimed at provide a database gathering knowledge of the updated phytosanitary status of the Tuscan forests, to establish the best plant protection practices carried out in the public and private forests and, in the specific, to support feasible actions in pine forests infested with *M. feytaudi*. In this context, the availability of the model cartography was an important tool for the identification of areas requiring high-priority forestry management activities (ROVERSI *et al*., 2010).

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