The spatio-temporal pattern of *Delphacodes kuscheli* (Homoptera: Delphacidae) abundance in central Argentina

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Abstract

Delphacodes kuscheli Fennah is the vector of maize rough dwarf virus, that affects maize production in central Argentina. The spatial and temporal abundance pattern of the insect vector was studied from October 1992 to November 1994, within endemic and non-endemic areas of the crop disease. Insect density was estimated every 7–15 days during spring and summer (maize season) or monthly during autumn and winter from high (6 m) and low (1.5 m) sticky traps placed at eight sampling stations along a 300 km transect. Each year, *D. kuscheli* density increased from October, peaked in December, to decrease afterwards and disappear in May. Density was lower in the nonendemic area and higher in the endemic one. The average absolute difference of density between sampling station pairs increased with the distance between the sampling stations (R^2=0.85), and the correlation of density changes decreased with the distance between the sampling stations (R^2=0.78), suggesting that the population dynamics were affected more by local than by regional factors. There was a significant correlation (with a 36 days lag) between the normalized difference vegetation index (NDVI) (calculated from 15 days maximum value composites images of NOAA-11 meteorological satellites) and *D. kuscheli* abundance. Based on this regression model, and using the time series of the satellite derived NDVI values, maps of the distribution and abundance of *D. kuscheli* within the study area for the spring and summer of 1992 were produced.

Introduction

Río Cuarto Disease (RCD) is caused by the maize rough dwarf virus – Río Cuarto strain (MRDV-RC), and has affected maize (*Zea mays*) production in the main maize growing areas of Argentina since 1967, when the disease was first reported (Lenardón, 1987). The virus is transmitted by *Delphacodes kuscheli* Fennah (Homoptera: Delphacidae) (Remes Lenicov, 1985), a species with macropterous and brachypterous adult forms. The disease has caused losses estimated at 100 million US dollars during the last 10 years (INTA, unpublished data) and, although efforts to breed MRDV-RC resistant maize strains are currently being made, no successful results have been reported. Locally, some farmers sow earlier to avoid the highest density of *D. kuscheli* and thus a high potential incidence rate of MRDV, but this strategy is not always effective, as the vector population does not peak at the same time everywhere.

The main overwintering host for the vector is oats (*Avena sativa*) (Remes Lenicov, 1991) which is generally sown in autumn and harvested in late spring, contrasting with maize which is sown in late spring and harvested in late summer. However, because of local conditions, mainly related to rainfall regimes and farmer selection of maize varieties, there is variation in the sowing dates of both crops, leading to temporal coexistence of oats and maize in some regions. The vector breeds on oats and possibly on annual and perennial weed grasses, but not on maize where it only feeds and eventually transmits the virus (Trumper *et al.*, 1991). If the maize plant is infected during the early developmental stages (3 weeks after plant emergence), the disease can be severe and, in some cases, lead to plant death (Lenardón, 1987).

The disease has an endemic focus in the Río Cuarto Department (Córdoba province), where it shows high incidence rates almost every year. In maize production areas outside the endemic region, the incidence is generally low, but can reach high values during some years.

Under laboratory conditions, *D. kuscheli* completes its life cycle in 35 days, and each female lays 7–25 eggs per day during the adult phase (Virla & Remes Lenicov, 1991), although it was shown that survival and fecundity depend on the species of host plant (Maragliano & Virla, 1992). Field data on the spatial pattern of *D. kuscheli* on maize plots showed that nearby weeds (i.e. those on the edges of the maize plots) make only a minor contribution as a source of vectors colonizing the maize plots, suggesting that insects might come from distant sources (Trumper *et al.*, 1991). The same study showed that vector density is linearly correlated with MRDV incidence on maize plots. Based on relatively few data points of presence–absence data, Remes Lenicov (1992) estimated the geographical distribution of *D. kuscheli* (that includes southern Córdoba and Santa Fe, northern La Pampa and Buenos Aires and western San Luis), although no details of population abundance were given (fig. 1).

Although it is widely accepted that the population abundance of the vector species determines the incidence levels of MRDV in maize, and that insect abundance depends primarily on the presence of appropriate host crops for the overwintering vector (especially oats), no study has yet been reported on the population ecology of the insect vector on an adequate spatial scale to elucidate quantitatively the epidemiology of MRDV-RC. This lack of investigation on a regional scale is probably related to the difficulty of obtaining reliable data on that scale. The use of remote sensing data has been increasingly used as a tool in natural resources studies on a regional scale, and in this paper we explore the approach as a complement to the study of conventional *D. kuscheli* population ecology.

The aim of this work was to study the spatio-temporal pattern of *D. kuscheli* abundance in the central and south-western region of Córdoba province, and to explore the utility of low resolution satellite imagery as a complement to field studies in the understanding of the ecology of this vector insect on a regional scale.

Methods

The study was carried out in the central and south-western region of Córdoba province in central Argentina. The area is mainly flat agricultural land, with two main rivers flowing from the northwest to the southeast. Over the last 20 years, Río Cuarto Disease has shown the highest incidence rates within the Río Cuarto Department (see fig. 1), and lower rates elsewhere.

D. kuscheli *data*

Insects were collected along a *c.* 300 km transect, from Manfredi in the northeast to Mercedes in the southwest (fig. 1). From northeast to southwest, the transect starts in a RCD nonendemic area, crosses the highest RCD endemic area and ends in a periodically high RCD incidence area. Because of regional variation in land productivity, agriculture tends to be highly intensive in the northern part of the transect (land parcels are small and used continuously through the year to cultivate different crop species; cattle breeding is infrequent) and extensive in the south (land parcels are large and used primarily for cattle breeding), (Indec, 1988). Eight sampling stations were located at approximately the same distance from each other (20–50 km) along the study transect. At each sampling station, one high and five low sticky traps were located at 6 and 1.5 m above the ground, respectively. The high trap consisted of a metal cylinder 50 cm high and 15 cm in diameter, whereas the low one consisted of a metal cylinder 20 cm high and 8 cm in diameter. A plastic film coated with an adhesive was placed around the cylinders. The plastic films were replaced by clean ones every 7–15 days during the maize season (October–January) and monthly outside the maize season (February–September). The exposed films were processed in the laboratory under a stereomicroscope to record the insects to species, according to Remes Lenicov (1992). The study was carried out from October 1992 to November 1994.

Satellite images

116 images high resolution picture transmission mode from the AVHRR (Advanced Very High Resolution Radiometer) on board the NOAA-11 satellite (National Oceanographic and Atmosphere Administration) scanning Argentina, (northwest corner 30°S, 65°W; southeast corner 35°S, 60°W) available during the period 01/Aug/1992 to 30/Nov/1993 were used for analysis. Data from channels 1 and 2 (Ch1 and Ch2, visible and near infrared channels of the satellite sensor), calibrated according to Teillet & Holben (1994) were used to calculate the normalized difference vegetation index (NDVI=[Ch2–Ch1]/[Ch1+Ch2], ranging from –1 to +1) on pixel cells of 2.2 by 2.2 km (because of the resampling procedure used by the reception station, the original resolution of 1.1 by 1.1 km was halved). The NDVI is one of the most widely used indexes derived from satellite imagery, as it is a good indicator of the green biomass covering the ground (Justice *et al.*, 1986). The highest value of the NDVI (=+1) represents the highest reflectance value from a ground patch (the pixel size of the AVHRR image) completely covered with green vegetation; a low NDVI value would indicate bare soil, water and/or clouds.

Although widely used, NDVI values are affected by a number of factors that decrease the value of the reflected energy from the ground, that could lead to important errors. Among these factors, the sensor vision angle, the sun angle and the variation of the atmospheric conditions (especially the presence of clouds) were identified as the main ones. To decrease the importance of this source of error, the method of the Maximum Value Composite (MVC), proposed by Holben (1986) was used. Given a time series of NDVIs for a particular ground location, the method assumes that the highest NDVI value within a relatively short time period, represents the real NDVI of that period for the location. Lower values would indicate 'contamination' of the sensor reception by one or more of the mentioned factors. The selection of the time period length to calculate the maximum NDVI is critical for the numerical analysis. Periods that are too long could produce 'oversmoothed' series that will miss important short-term variation. Periods that are too short will not eliminate the variation produced by clouds or other atmospheric factors. There is no rule to define the length of the period to calculate a cloud-free composite image, but experience showed that periods of 5–7 days are good choices for a wide variety of uses.

Because of the temporal resolution of the data, we grouped the insect data at 15 day intervals with the days

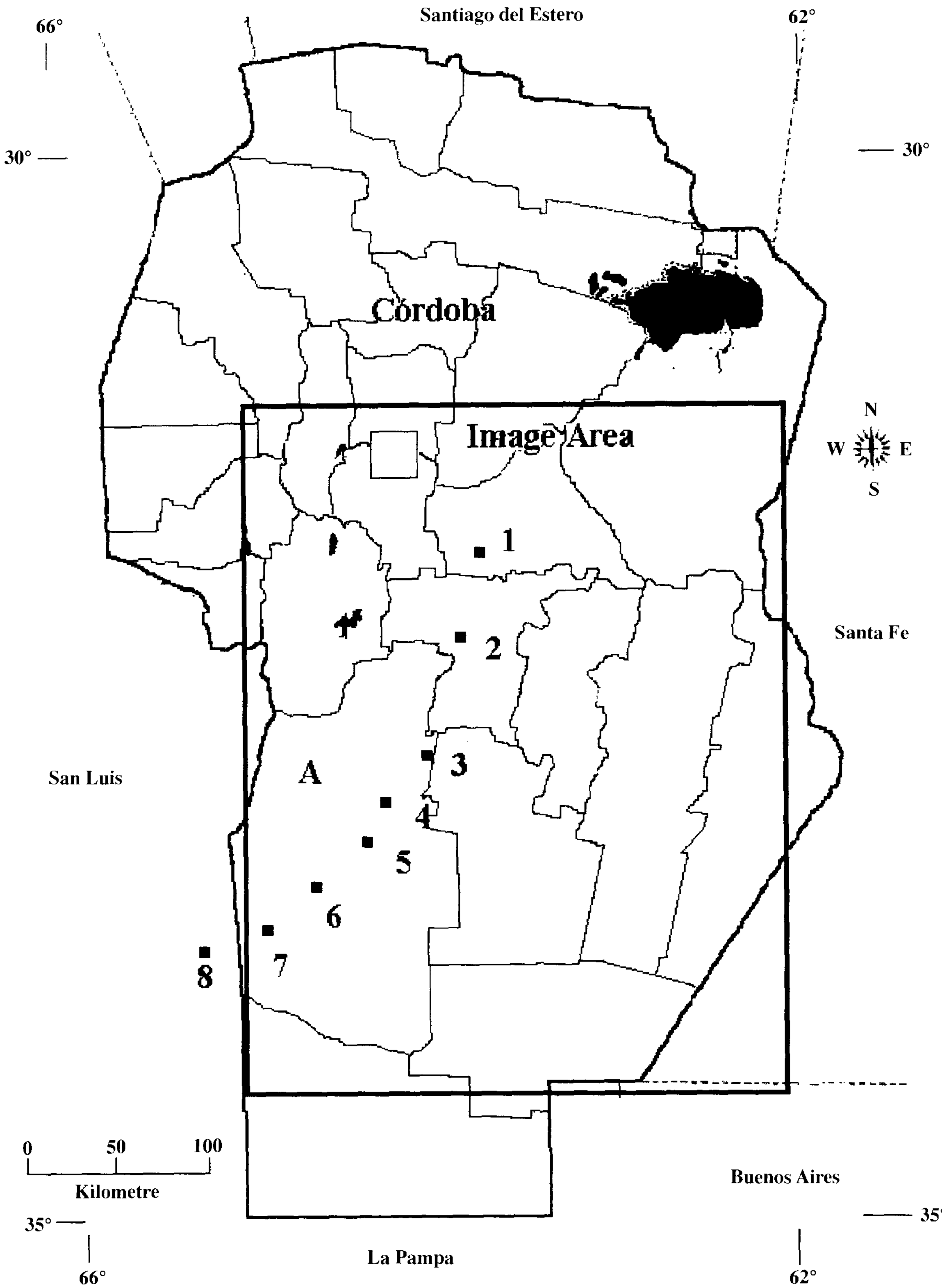

Fig. 1. Study area and location of the insect sampling stations (1. Manfredi, 2. Cabrera, 3. Tancacha, 4. Espinillo, 5. Holmberg, 6. La Sofía, 7. Travaglia, 8. Mercedes). A: Río Cuarto department (highly endemic area); within the Córdoba province, departmental boundaries are shown; lakes are shown in black. The thick bordered rectangle shows the NOAA image area used in this study.

7 and 22 of each month as the period limits. By contrast, we grouped the satellite image data at 15 day intervals, with days 1 and 15 as the period limits. Thereafter, two paired data per month will be considered in the analysis relating insect abundance and satellite images. Using the MVC method we obtained two NDVI images per month (one at the beginning and the other in the middle of each month). A correlation analysis between NDVIs and insect density estimates was carried out with different time lags, to find a function that would predict future insect abundance from past images. The first lag between NDVI and density was 6 days (e.g. NDVI on day 1 and insect abundance on day 7). The second lag was 21 days (e.g. NDVI on day 1 and insects on day 22), the third 36, etc. Image analysis was carried out using Idrisi 4.1 (Eastman, 1994) and ad hoc programs written in MS QuickBasic 4.5.

Data analysis

Delphacodes kuscheli density was calculated as the log number of macropterous individuals collected per cm^2 of trap surface divided by the number of days that the plastic film was exposed to field conditions. The pattern of change in abundance was analysed through temporal correlation and mean absolute difference of density estimates between sampling station pairs separated by different distance intervals. The analysis was carried out via the following steps: 1) calculate the distance between all pairs of sampling stations; 2) classify sampling station pairs according to the distance that separates them (this resulted in eight groups of data pairs that represent observed densities at eight increasing distances; 3) pool the data of the sampling stations pairs according to 2); 4) calculate the mean absolute difference of the data pairs and its correlation coefficient; 5) analyse the relationship between the mean absolute difference and correlation of densities with distance between sampling stations.

If the density were the same on each sampling date at all the sampling stations, and changed in the same way during the study period in all the studied areas, the mean absolute difference should be zero and the correlation high and constant over distance. If density varied randomly in time and space, the correlation should be low and the mean absolute difference should not show a relationship with distance. If density was mostly influenced by local factors, distance should be positively related with the mean absolute difference and negatively correlated with the density correlation between sampling stations separated by different distance intervals (i.e. population density changes in nearby stations should be more similar than density changes in distant ones).

From each composite image, the mean NDVI of a 3 × 3 pixel area centred on the insect sampling stations was calculated. The southernmost sampling station (Mercedes) was not included in the NDVI calculations because it was outside the limits of the available images. The relationship between crop data for each provincial county reported on the National Agriculture Census (Indec, 1988), insect abundance from the sampling stations and NDVI values from the composite images were analysed through regression and correlation analysis. The average NDVI per county was calculated overlaying the county limits to the NDVI image and asking the EXTRACT module of IDRISI to calculate the average within each polygon (= county).

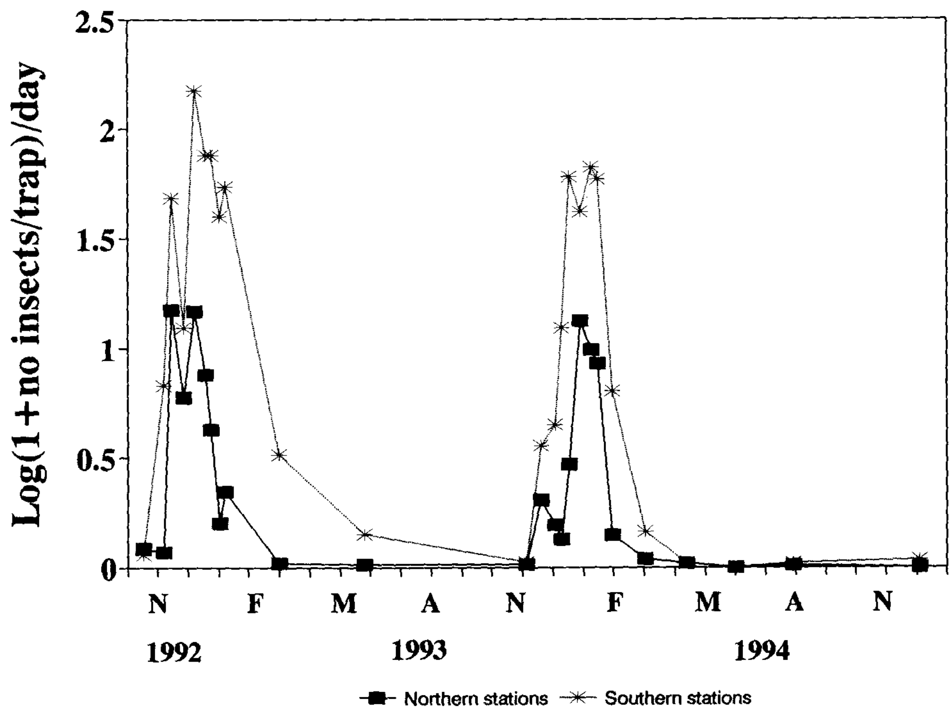

Fig. 2. Density of *Delphacodes kuscheli* during the study period in the northern sampling stations outside the endemic area (average of three sampling stations) and in the central and southwestern sampling stations, within the endemic area (average of five sampling stations).

Results

In general, the population density of *D. kuscheli* showed a clear seasonal pattern in the study area, increasing from October until the second half of December, decreasing abruptly afterwards to almost disappear in May of each year (fig. 2). The maximum peak density occurred during the second half of December, when a maximum density of two insects/trap/day was recorded (high traps data). Density estimates (as the log[number of insects/cm^2]) from low and high sticky traps were highly correlated according to a linear function (r = 0.85, P<0.001, n = 139), although high traps captured 1.55 times the number of insects captured in the lower ones. Based on these results, the following analysis of insect abundance will refer only to the data recorded from high traps. As all high traps were the same size, density estimation of *D. kuscheli* will be expressed as number of insects per trap per day.

The temporal changes of population density during the two studied years were very similar at all the sample sites in terms of density values through time (increasing-decreasing phases and peak density dates). During 1992, peak density occurred earlier (on 14 December $\pm$6 days [mean$\pm$s.d.]) than during 1993 (on 29 December$\pm$15 days) (P<0.01, t-test). During 1992, peak density occurred earlier in the northern than in the southern sampling stations (with a difference of 10 days and a significant linear increase of peak density date from north to south); in 1993 peak densities occurred approximately at the same time (spread over 15 days), with no detectable latitudinal trend of peak density dates.

Density was lower in the three northeastern sampling stations (outside the endemic region) than in the southwestern stations (within the endemic region). An UPGMA (unweighted pair-group method, arithmetic average) cluster analysis (over the study period and the eight sampling stations) of the euclidean distances calculated from standardized values of density estimates showed that the most different sampling stations were the ones located in the northeastern part of the study transect: Manfredi, Tancacha and Cabrera stations (fig. 2).

Considering the density estimates of the spring and summer months for the whole study period, the highest average density occurred at La Sofia, and decreased towards Mercedes (to the south) and Manfredi (to the north), where the lowest average density was observed (fig. 2).

A plot with the log mean (x axis) and log variance (y axis) of *D. kuscheli* abundance at each sampling station during a particular season (i.e. 1992 or 1993) shows the spatial and temporal features of changes in abundance. In this plot, the spread of the data along the x axis is an indication of the spatial variation of abundance among sampling stations, whereas the spread of the data along the y axis indicates the temporal variation of abundance within a season in a particular sampling station. The abundance in the 1992 season was less variable either spatially or temporally (less variation of the data on both the mean and variance axis). The relation between the spatial and temporal variation was similar in 1992 and 1993, as shown by the good linear fit of the data to a common function (intercept =−0.30, slope = 1.80; R^2 = 0.94) (fig. 3).

The average absolute difference of density between sampling station pairs increased with the distance between the sampling stations, according to a multiplicative model (R^2 = 0.84, fig. 4). The correlation of density changes

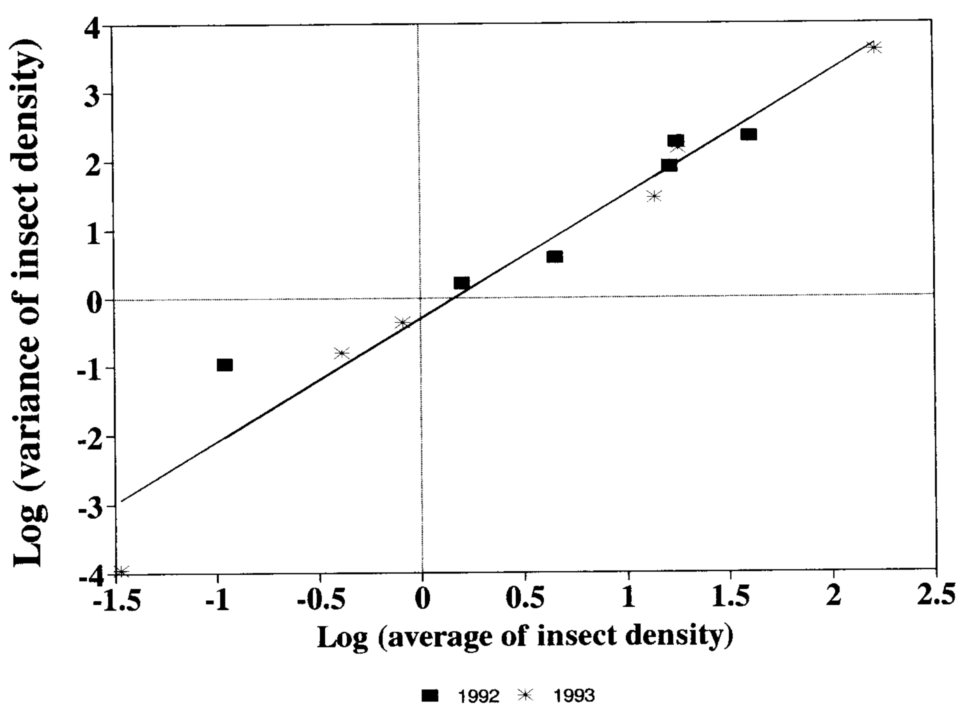

Fig. 3. Relationship between log mean and log variance abundance of *Delphacodes kuscheli* for each season (1992 and 1993) and each sampling station.

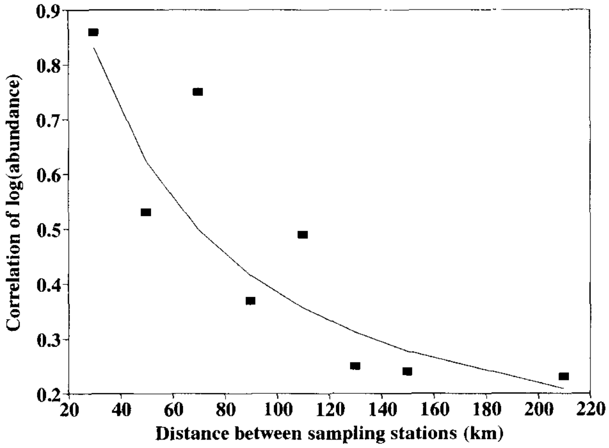

Fig. 4. Relationship between the mean absolute difference between *Delphacodes kuscheli* density of sampling station pairs and distance between sampling stations.

decreased with the distance between the sampling stations according to a reciprocal model ($R^2 = 0.78$, fig. 5).

November is the month when the main green ground cover is oats. A linear multiple regression model between the mean NDVI of each county for the second half of November 1992 against the proportion of the ground covered with natural grasses, annual cultivated grasses (except oats), oats and perennial grasses for the 27 counties belonging to the departments where the insect sampling stations were placed was highly significant ($R^2 = 0.84$). In this regression the partial correlation for oats was $r = 0.76$ ($P<0.001$, $n = 27$) (table 1). The same regression, but using NDVI data for January 1993, gave a poorer fit ($R^2 = 0.34$) (table 2). On the other hand, the temporal variation of *D. kuscheli* abundance (log transformed data) and mean NDVI (for 3×3 pixel cells over the insect sampling stations) with a time delay of 36 days (i.e. insects at time t against NDVI at t–36 days) were highly correlated according to a linear model ($r = 0.90$, $P<0.001$, $n = 42$), from August until the second half of November.

When the relationship between the NDVI and the original insect data set (not log transformed) between August and

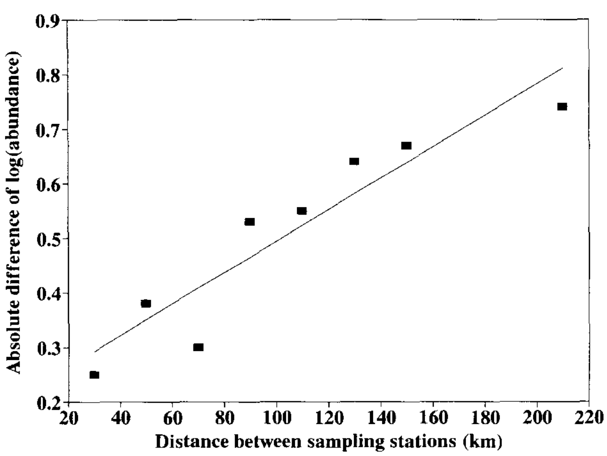

Fig. 5. Relationship between the temporal correlation of *Delphacodes kuscheli* density and distance separating the sampling stations.

Table 1. Multiple linear regression analysis ($y = a + bx_1 + cx_2 + dx_3 + ex_4$) between average NDVI for the first week of November 1992 (y) and density of crop surfaces (x_1 to x_4) within the counties of the study region.

Independent variable	Coefficient	Partial correlation
Constant (a)	0.3120**	
Oats (x_1)	0.0267**	0.76
Perrennial forage crops (x_2)	0.0325**	0.80
Natural grasses (x_3)	0.0279**	0.60
Annual forage crops (except oats) (x_4)	–0.0170**	0.50

$R^2 = 0.81$; n = 27; ***P*<0.01; **P*<0.05.

Table 2. Multiple linear regression analysis ($y = a + bx_1 + cx_2 + dx_3 + ex_4$) between average NDVI for the second week of January 1993 (y) and density of crop surfaces (x_1 to x_4) within the counties of the study region.

Independent variable	Coefficient	Partial correlation
Constant (a)	0.5392**	
Oats (x_1)	–0.0012 ns	–0.43
Perennial forage crops (x_2)	–0.0041 ns	–0.50
Natural grasses (x_3)	–0.0099 ns	–0.53
Annual forage crops (except oats) (x_4)	–0.0090 ns	–0.58

$R^2 = 0.35$; n = 27; ***P*<0.01; ns, not significant.

November was analysed, two data groups were apparent: a first one, with an estimated maximum abundance of less than two insects/day belonging to sampling stations located outside the endemic region, and a second one with an estimated maximum abundance of more than two insects/day belonging to sampling stations within the endemic region (fig. 6). Considering the two groups independently, a linear fit for the first group showed a lower NDVI threshold of 0.085 ($\pm$0.056, 95% confidence interval), below which the model would predict absence of *D. kuscheli*. A linear fit for the second group showed a lower NDVI threshold of 0.21 ($\pm$0.046, 95% confidence interval), over which the model would predict the occurrence of a high *D. kuscheli* density, coincident with the endemic region. Based on these regression models, and using the time series

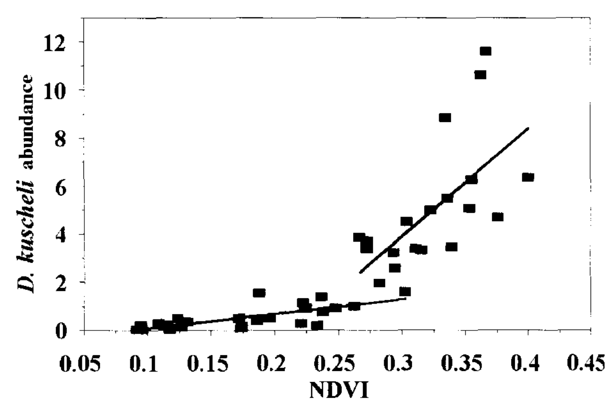

Fig. 6. Relation between *Delphacodes kuscheli* density and NDVI values. Linear functions were independently fitted to insect density below and above two insects/trap/day.

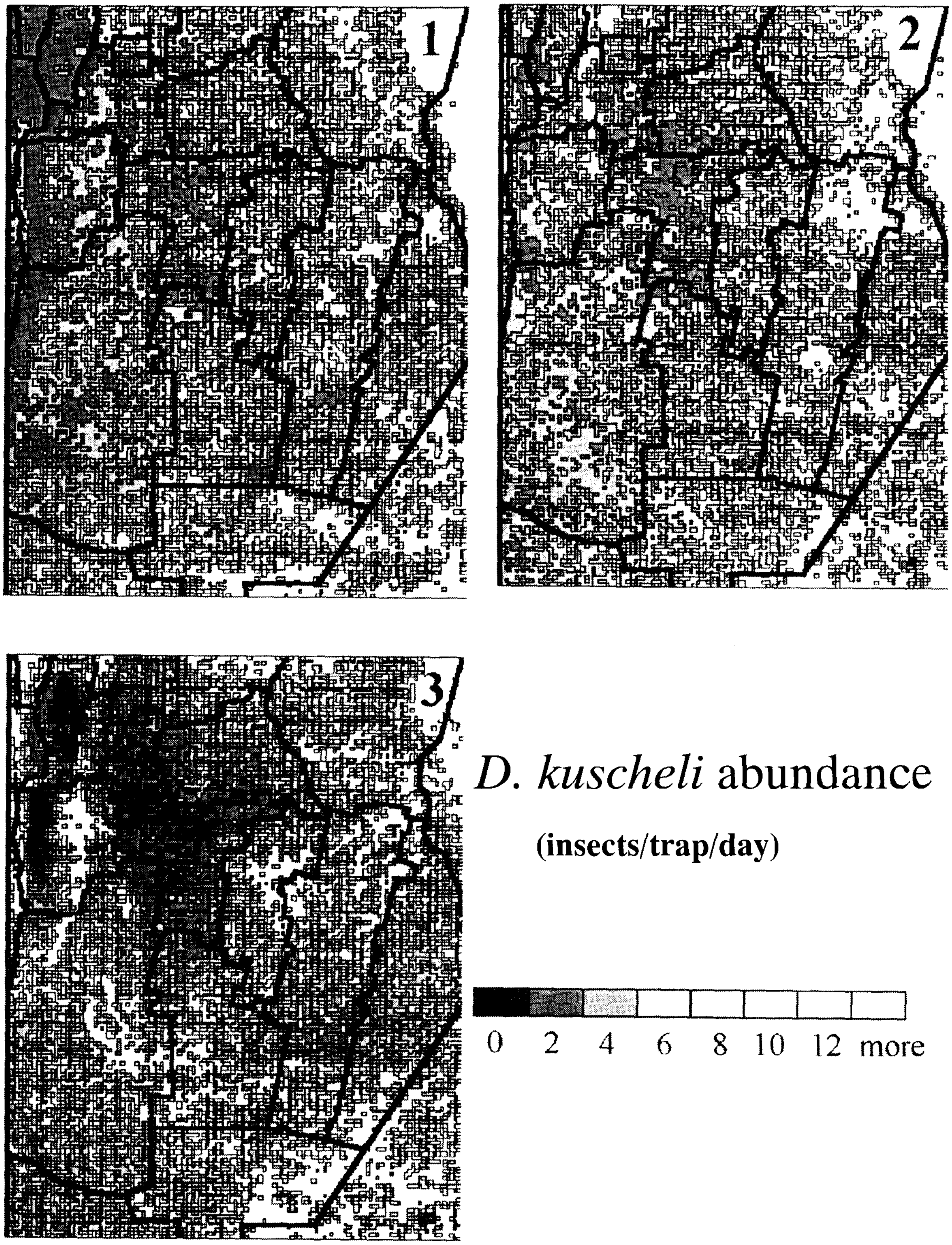

Fig. 7. Examples of insect abundance maps for first half of November 1992 (1), second half of December 1992 (2) and second half of January 1993 (3) based on NDVI maximum value composites of the second half of September 1992, first half of Novemeber 1992 and first half of December 1992, respectively. The thick black lines represent departmental boundaries (see fig. 1).

of the satellite derived NDVI values, maps of the distribution and abundance of *D. kuscheli* within the study area for the spring and summer of 1992, were produced. This estimate shows the likely spatial expansion and temporal increase of the vector species density during the study period, that coincide with the distribution map of Remes Lenicov (1992) (fig. 7).

Discussion

Although the data reported here refer to the flying population of *D. kuscheli*, there is evidence that this population is linearly correlated ($r = 0.89$, $P<0.01$, $n = 8$) with the density of the total ground population of *D. kuscheli* (nymphs and adults), estimated using a suction device from October to December within the endemic region (Pérez Harguindeguy *et al.*, unpublished data), suggesting that density estimation based on sticky trap captures is a reliable technique for the study of *D. kuscheli* populations.

The 6 m traps captured almost twice the number of insects captured by the 1.5 m traps. Several factors could be responsible for this difference: flight behaviour, wind speed at different heights and the vegetation type within the patch where each low trap was placed. It is not possible to demonstrate which is the cause of this difference, with the available data.

Within the study area, the population abundance of *D. kuscheli* showed a clear seasonal pattern, increasing from October (roughly coinciding with the senescence of the winter oats crop), peaking in December (coinciding with late maize sowing dates) to disappear in March–April. Considering that the 3 week period after maize emergence exhibits the highest susceptibility to MRDV infection, early sowing dates (September–October) would be a good strategy to break the co-occurrence of young maize plants and high vector densities, hence decreasing the likelihood of MRDV transmission and infection.

Considering the data of the 2-year study period, the average population density of *D. kuscheli* was higher within the endemic region than outside it, and showed the lowest values towards the northeastern extreme of the study transect (Manfredi sampling station, in the centre of Córdoba province).

The temporal correlation of population abundance decreased with the distance between sampling stations, whereas the average absolute difference between abundance in sampling station pairs increased with the distance between sampling stations. These relationships indicate that the local dynamics of planthopper abundance dominate over global-area abundance dynamics and suggest that regional variables play a minor role compared with local variables. This coincides with an independent finding (for the same study area) showing that high landscape heterogeneity (promoted by intensive agriculture exploitation) is associated with low densities of *D. kuscheli* (Grilli & Gorla, unpublished).

This study also showed that NDVI values calculated from the NOAA-11 meteorological satellite are good descriptors of the abundance of *D. kuscheli* almost 40 days ahead, through to November each year (predicting what is going to occur until January). This 40-day period is probably related to the delay caused by the development time of *D. kuscheli* by which insects detected by sticky trap (macropterous adults) respond to changes in the ground vegetation measured in real time by the AVHRR sensor.

After November, the ability of NDVI to describe *D. kuscheli* density is lost, probably because this date coincides with sowing of a number of different crops that are not appropriate to *D. kuscheli* development (i.e. soybeans and peanut). However, it is worth noting that the highest susceptibility of the maize crop to MRDV infection occurs during the first three weeks after plant emergence, by which time NDVI values could be used as good predictors of the critical dates and areas where a high density of *D. kuscheli* (and hence a high incidence of MRDV) can be expected.

The strong relationship shown between the land area cultivated with oats and *D. kuscheli* abundance could be used as an alternative method to estimate the abundance of *D. kuscheli*. However, the use of this approach requires that data on land management over the whole affected area (10.3×10^6 hectares belonging to 30,710 farmers) should be available on a yearly basis. Unfortunately, there is no routine collection of this information, and only every 10 years is there an agronomic census. Although the land cultivated with oats should provide a good indicator of *D. kuscheli* abundance, a reliable prediction would most likely need data on temperature and rainfall to allow for the heterogeneity of oat growth over the whole area. Again, there is a restriction on the use of this approach as only two meteorological stations exist within the area.

The results of this study may be used as the basis for the development of a monitoring and forecasting system of vector abundance, because of its low cost, wide coverage and reliability, provided there is real time availability of the NOAA images. Although satellite information and *D. kuscheli* abundance showed a highly significant relationship, validation will be necessary using independent data for the same study area and, particularly outside it.

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