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FULL RESEARCH PAPER

Assessment of the spread of chestnut ink disease using remote sensing and geostatistical methods

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Abstract Chestnut ink disease, caused by *Phytophthora cinnamomi* and *P. cambivora*, is responsible for important economic losses and limits the establishment of new chestnut (*Castanea sativa*) groves in Portugal. Although the differences in soil properties and in cropping practices affect ink severity, the regional spread of disease is not known. Data for monitoring *C. sativa* decline were obtained by using field surveys and Small Format Aerial Photography (SFAP), a reliable tool which provides large-scale imagery obtained at low altitude. Visible colour and near-infrared images were obtained with different cameras with an average ground resolution of 22, 14 and 39 cm. The spatial distribution of ink disease in northern Portugal for the years 1995–2004 was estimated through a geostatistical method, and the estimation of precision was determined. From 1995–2002, the chestnut population in the study area increased by 18.5% due to new orchard plantations. After 2002 the population decreased because the new plantations were not sufficient to recover the number of dead chestnut trees, killed mostly by ink disease. The directional semivariograms indicated anisotropy with a greater disease spread in the NE–SW direction. This direction corresponds to site areas at the same altitude, where soil tillage and human mobility are higher.

Keywords Aerial photography · *Castanea sativa* · Kriging interpolation · *Phytophthora cinnamomi*

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Introduction

The rising demand for sweet chestnuts (*Castanea sativa*), in Portugal and elsewhere in Europe, has led to more intensive management practices in order to increase nut production. These include heavier mineral fertilization and increasing the use of pruning, which have progressively replaced traditional farmyard manure (Portela et al. 1998). However, in Portugal, the current widespread incidence of ink disease caused by *Phytophthora cinnamomi* (occasionally by *P. cambivora*) leads to important losses in chestnut production and limits the establishment of new planted areas (Abreu 1992; Martins et al. 1999).

Some chestnut groves affected by ink disease can be found located near healthy trees and also grouped in clusters. This suggests that bad soil conditions and the interaction between site factors and cropping practices can contribute to disease incidence (Portela et al. 1998). Soil compaction associated with these practices also stimulates *P. cinnamomi* development

(Fonseca et al. 2004). The unregulated search for wild mushrooms can also reduce chestnut tree resistance due to the ectomycorrhizal fungi reduction (Bärtschi et al. 1981; Branzanti et al. 1994; Brasier et al. 1993; Martins et al. 1999). However, factors that affect widespread disease and spread incidence, are still not known.

Monitoring chestnut health requires simple methods of damage evaluation because, under favourable conditions, the disease spreads rapidly by zoospores and chlamydospores through water and movement of soil particles (Zentmyer 1980). Control of ink disease is based on preventive measures that should be applied at a regional scale in order to be effective. As a consequence, an efficient monitoring system capable of providing information of the number and size of infected foci is necessary (Vannini et al. 2005). Remote sensing is a good way of detecting the symptoms of infection by soil-borne *P. cinnamomi*: yellowish and sparse foliage, dieback of branches and a gradual decline of infected trees (Zentmyer 1980). These symptoms can be assessed by Small Format Aerial Photography (SFAP), a reliable tool of remote sensing, using aerial platforms carrying small-format cameras for acquiring large-scale imagery ($\geq$1: 5000) at low height ($\leq$2000 m). SFAP can be used for detailed applications, including discrimination of vegetation types, environmental monitoring and assessing vegetative health conditions (Martins et al. 2001).

Previous studies (Ambrosini et al. 1997; Martins et al. 2001) have shown that the evaluation of damage caused by soil-borne *P. cinnamomi* using SFAP did not present significantly different results from those obtained by field observations. Colour near-infrared images (CIR) or visible normal colour images (NC) obtained with 35 mm or 70 mm cameras have also been used in similar forestry pathology studies for many years (Meyer 1982; Bissegger and Heiniger 1994; Warner et al. 1996).

The spread of ink disease can be estimated by spatial interpolation methods, due to its relation with geographical variables such as soil and climatic characteristics (Martins et al. 2005). The Krige interpolation method, originally developed for gold prospecting in South African mines (Krige 1951), can be used. This method interpolates spatial data and allows for great flexibility in defining the interpolation model, according to field information. It is based in a semivariogram, i.e., a mathematical model for describing the spatial variability of the geographical data. The semivariogram is represented as a graph with x-axis showing the separation distances between observed trees (lags). The y-axis showing the average variability of sample data pairs for each lag distance (Cressie 1986; Eastman 2001). The spread of ink disease can also be estimated on pairs of sample data points ($x-x'$). Every data point (health data) is paired with every other data point. Each pair is characterized by its separation distance (lag) and direction (Goovaerts 1999).

In the present study, SFAP was used to monitor chestnut decline since 1995. The distribution of ink disease was mapped using the geostatistical method known as ordinary kriging (Cressie 1986). The purpose of this paper is to describe and discuss the results obtained using these two methods.

Materials and methods

A study site in the Padrela Region of northern Portugal was selected for its high incidence of the chestnut ink disease, with a mean level of damage of 1.90 when evaluated by remote sensing, or 1.93 when evaluated by ground surveys (0 = healthy tree; 4 = dead or dying tree) (Martins et al. 2001). The site area (12,162 ha) has a Mediterranean climate and chestnut orchards of different ages, from newly-planted trees to trees 30–40 years old (adult trees). The study area is located in a mountain region at altitudes between 400 and 900 m and at international UTM kilometre coordinates (WGS84 datum), up left: 623, 4614; down right: 636, 4593.

Conventional CIR aerial photography (23 × 23 cm format) obtained in 1995 by the Instituto Geográfico Português, was added to a Geographical Information System (GIS) as well as the chestnut area cartography. A 100 × 100 m grid was considered to randomly select 268 circular permanent sampling plots, with an area of 1250 m^2 each. A total of 2892 chestnut trees in the sampling plots were visually evaluated on computer screen, according to the structural and chromatic characteristics of the chestnut canopies (Table 1). Five damage levels were considered, using the European and standardized criteria (Cadahia et al. 1991): 0 = healthy tree (0–10% canopy defoliation); 1 = slightly damaged (11–25% canopy defoliation);

Table 1 Health condition of chestnut trees evaluated 1995–2004 and accuracy coefficients obtained by cross-validation

Year	Sampling plots	Chestnut trees			Average damage	MAE	MAE %	RMSE
		Evaluated	Mortality (%)	New plantations (%)				
1995	268	2892	5.8	3.8	1.40 ± 0.09a	0.002	14.8	1.005
1995–2001	93		19.9	31.8				
2002	93	1068	5.6	14.2	1.30 ± 0.19a	0.001	11.1	0.965
2003	97	1023	14.7	10.4	1.34 ± 0.16a	0.002	13.1	1.018
2004	87	912	12.6	7.3	1.37 ± 0.20a	0.003	14.3	1.045

The average damage with same letter is equal according to Duncan's Multiple Range Test

2 = moderately damaged (26–60% canopy defoliation); 3 = heavily damaged (61–90% canopy defoliation); 4 = dead tree.

In 2002, 2003 and 2004, CIR and NC were obtained from the study area, at an average height of 520 m. A retractile platform developed by Martins et al. (2001) for aerial photography was adapted to a Cessna 172 aircraft, and carried a 35 mm camera, a medium format camera (70 mm), and a digital camera. These cameras were equipped with normal focal distance lenses (50, 80, and 28 mm, respectively), and controlled with the system proposed by Castro et al. (2004). The aerial photos were digitised at 70 ppm (pixels per millimetre), i.e., the same resolution as the digital camera, and orthorectified using *PCI Geomatics*® software. The average ground cell resolution was 22 cm on the CIR (35 mm camera), 14 cm on the NC (70 mm camera), and 39 cm on the digital images.

The chestnut trees were quantified according to the damage scale described above. The trees cut down due to mortality, or the new planted chestnut trees, were also quantified in each year by sampling permanent plots (Fig. 1). The accuracy of image interpretation was improved by field assessments (Martins et al. 2001, 2005).

The spatial interpolation of the chestnut health data was determined by a theoretical spherical model (Eq. 1), adjusted to an empirical semivariogram (Eq. 2). In Eqs. 1 and 2, $n(h)$ represents the number of pairs of trees with lag distance h, $Z(\mathbf{x_i})$ represents the health condition for each location $\mathbf{x_i}$ and a represents the range, i.e., the greater lag distance in the model (Cressie 1988).

$$\gamma(h) = \begin{cases} C\left[\frac{3}{2}\cdot\frac{h}{a} - \frac{1}{2}\left(\frac{h}{a}\right)^3\right]; & \text{when } h \le a \\ C; & \text{when } h > a \end{cases} \quad (1)$$

$$y(h) = \frac{1}{2n(h)}\sum_{i=1}^{n(h)}\left[Z(\mathbf{x_i}+h) - Z(\mathbf{x_i})\right]^2 \quad (2)$$

The theoretical semivariogram $\gamma(h)$ was estimated from the empirical values $y(h)$ considering 10 classes of lags h, by using a linear regression method. The existence of anisotropy in the random field was tested relatively in four directions (N–S, E–W, NE–SW, NW–SE), each one defined by an angular sector of ±22.5°. The ordinary kriging interpolation in these directions (100 × 100 m grid) was visually compared to representative maps of altitude, aspect and slope,

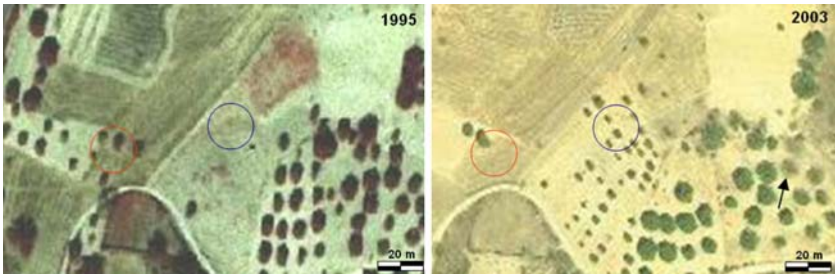

Fig. 1 Examples of permanent sampling plots with chestnut trees felled after 1995 (CIR aerial photography) and new chestnut plantations (FAPF obtained in 2003). The arrow in NC is an example of level 3 damage

given by the Digital Elevation Model (DEM) of the study area.

In order to evaluate the quality of the interpolator, a cross-validation was applied, leaving aside 100 uncorrelated data values not used in the estimation of $\gamma(h)$ or in the estimation of the ordinary kriging coefficients. Accuracy coefficients described by Goovaerts (1999), were used for validation, namely the mean absolute error (MAE), the mean absolute percentage error (MAE%) and the root mean-square error (RMSE).

Results

As expected, the medium format system (70 mm) better distinguished the damage levels, compared to the digital or the 35 mm cameras, due to its larger scale, small ground pixel dimension and its low distortion on the periphery images. In this study no differences were found between the interpretation of the NC and the CIR.

The average damage levels for several years (1995, 2002–2004), were not significantly different according to Duncan's Multiple Range Test. However, the number of chestnut trees removed from the study area, mostly as a result of mortality through ink disease, increased since 1995 (Table 1). In the 1995–2002 period the chestnut population increased, since new plantations (49.8%) supplanted the tree mortality in the same period (31.3%). After 2002, the population reduced because the new chestnut plantations (17.7%) were not sufficient to substitute for the dead trees (27.3%).

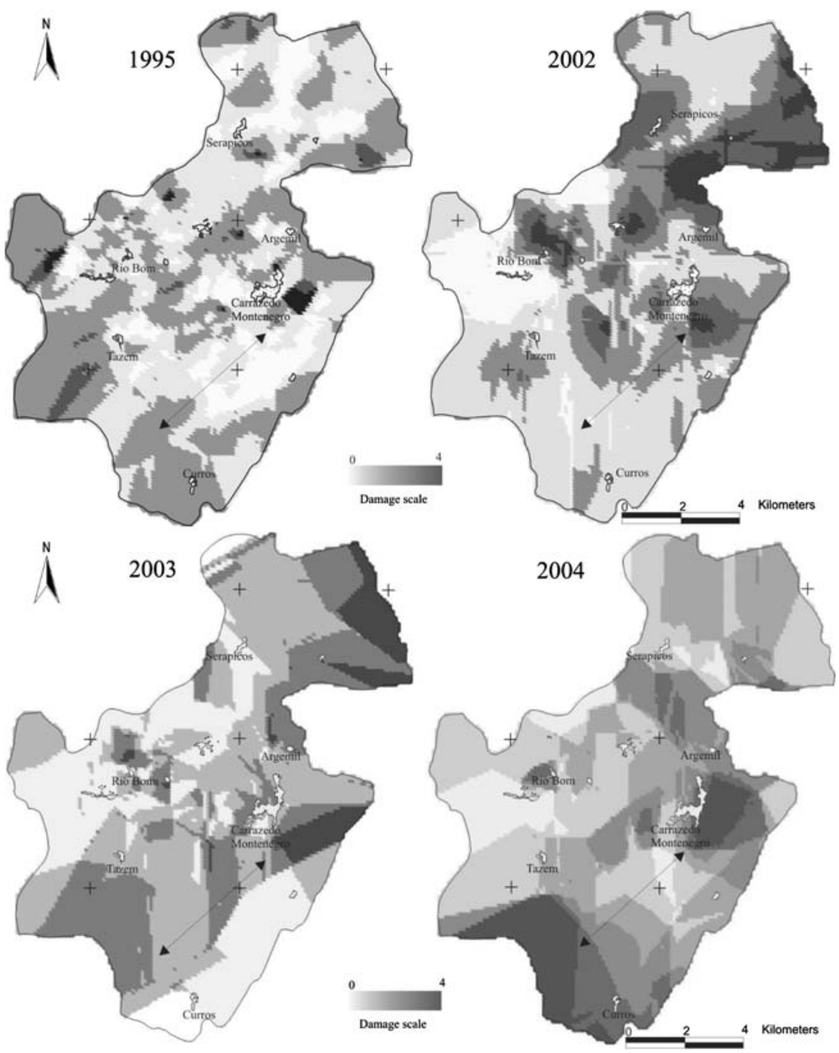

Fig. 2 Ink disease spread of 1995–2004 obtained by ordinary kriging. The arrows show the anisotropy on NE–SW azimuth

The chestnut health data, adjusted on empirical semivariograms and in spherical models, showed several foci of *P. cinnamomi* incidence and areas without ink disease. This can be associated with the variability of the chestnut health condition caused by differences in cropping practices. The kriging interpolation also revealed that the most affected areas in 1995 had worsened in 2003 and 2004 (Fig. 2).

The coefficients obtained by cross-validation, namely the MAE%, which expresses the accuracy as a percentage, showed that the ordinary kriging method gives acceptable results on a first assessment of the ink spatial distribution (Table 1). Compared to 1995, in following years, more clusters with dead trees were detected (Fig. 2). The directional semivariograms also revealed anisotropy in the NE–SW direction, corresponding to areas located at the same altitude, observed on the DEM.

Discussion

The use of SFAP and light aircraft reconnaissance is a good way of monitoring chestnut health conditions due to its accuracy and low cost (Martins et al. 2001, 2005). The research flight described cost about €300 per year (excluding the cameras), which is approximately 15% of the cost a conventional photographic survey for the same study area. NC and CIR provide accurate visual information on chestnut ink disease but this could be improved by digital image processing in future studies. This study proved the advantages of monitoring the same chestnut plots in different years using remote sensing, because tree mortality can be mistaken in previous years for felled trees and new plantations (Fig. 1). Without this photographic data the field measurements would be incomplete.

Until now, precise data on ink disease spread in Portugal was unavailable. The methodology presented in this paper proved to be effective in the diagnosis of the widespread occurrence of the disease, and can certainly be used in other countries.

Under the geostatistical approach, a variogram model needs to be selected, and this often requires rotations and transformations to account for anisotropy (Cressie and Chan 1989). In this study, several foci were detected in the 1995–2004 period but the continuity between affected areas is not clear, because every year many dead trees are replaced by new and healthy chestnuts (Fig. 2). Also, disease spread obtained by ordinary kriging mostly occurs in areas with the same altitude where generally soil tillage and human mobility are easier. As a result, the spread of ink disease may primarily be due to the transport of soil infested with chlamydospores and other inocula of *Phytophthora* species, reported by several authors (Abreu 1992; Martins et al. 1999; Fonseca et al. 2004).

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