ENVIRONMENTAL ENGINEERING

The 8th International Conference
May 19–20, 2011, Vilnius, Lithuania
Selected papers

ISSN 2029-7106 print / ISSN 2029-7092 online
ISBN 978-9955-28-826-8 (1 Volume)
ISBN 978-9955-28-827-5 (3 Volumes)
http://enviro.vgtu.lt

SPATIAL VARIATION OF ASH TOTAL CARBON AND TOTAL NITROGEN AFTER A WILDFIRE

Paulo Pereira[1], Xavier Ubeda[2], Deborah Martin[3]

[1]*Vilnius Gediminas technical university, Saulėtekio ave. 11, LT-10223 Vilnius, Lithuania.*
E-mail: pereiraub@gmail.com
[2]*GRAM (Mediterranean Environmental Research Group), Dept of Physical Geography and Regional Geographic Analysis, University of Barcelona, Montalegre, 6. 08001 Barcelona, Spain. E-mail: xubeda@gmail.com*
[3]*U.S. Geological Survey, 3215 Marine Street (E146), Boulder, CO 80303-1066. E-mail: damartin@usgs.gov*

Abstract. The present work aims to study the spatial variability of ash Total Carbon (TC%) and Total Nitrogen (TN%) after a wildfire occurred in Portugal. Ash TC% a mean of 26.72 % (±8.76 %) and ash TN% of 1.20 % (±0.32 %). We observed that the area recover very fast to wildfire and two years the great part of soil was cover by vegetation. The fire severity (assessed with ash color and $CaCO_3$ content) was more related with ash TC%, than ash TN% due the different vulnerability and response of these two elements to fire temperature and as consequence severity. Previous to model data we tested their normality that only was achieved in the case of TC% after a neperian logarithmic transformation (ln). TN% respected gaussian distribution, however showed a high skewness, thus this variable was also ln transformed. Ash TC%(ln) presented an excellent spatial structure and the experimental model fits better with the rational quadratic model and ash TN%(ln) with the lineal model. Among all interpolation methods tested, the most accurate to interpolate ash TC%(ln) was IDW2 and the less suitable LP3. In relation to ash TN%(ln) the best interpolation technique was SPT and the less precise LP3. This allow us to observe differences that the spatial distribution of both variables is different, that is due the small scale variability observed in ash TC%(ln). In general the models were well performed because the residuals mean were closed to 0 and no differences between average of predicted and estimated values were identified. Ash TC%(ln) spatial distribution was in higher amounts in western, northern part and southeast and northeast corner of the plot and lower in the centre and south of the interested area and ash TN%(ln) was observed in higher amounts in the southwest and southeast part of the plot and lesser in the central part.

Keywords: Total Carbon, Total Nitrogen, Wildfire, Fire Severity, Interpolation Methods, Spatial Distribution.

1. Introduction

Forest fires are a worldwide threat with important impacts on society, economy and ecosystems, as reported in many parts of the globe. Presently with the rapid and unprecedented climate change and changes in land use, they assume a fundamental importance (Lavorel *et al.* 2006; Bonan 2008; Crochane and Laurence 2008; Wotton *et al.* 2010). However, fire is a common disturbance and it is considered as a natural element of the ecosystem. In addition, fire is widely recognized to be for some ecosystems, an essential disturbance for their maintenance (Naveh 1975; Agee 1993; Lloret and Zedler 2009). Among all nutrients, Carbon (C) and Nitrogen (N) are the most affected by fire, which induces important changes in their quantity and quality. Both nutrients start to volatilize at low temperatures (±200 ºC). In the case of C, 85 % is destroyed between 200–300ºC and at 450 ºC for 2 hours or 500 ºC for ½ hour of exposition, 99 % of C is destroyed. Within 200 and 300 ºC between 25–50 % of N is lost and above 500 ºC all N is lost (Neary *et al.* 2005; Knicker *et al.* 2005; Mataix-Solera and Guerrero 2007; Mataix-Solera *et al.* 2009). Thus, it is very likely that after high severity wildfires, important amounts of these nutrients are exported from the burned ecosystem (Johnson 1992).

Ash is the most visible thing after the fire and previous studies already recognized that great part of nutrients for landscape recuperation remains on ash (Mataix-Solera *et al.* 2009; Pereira *et al.* 2010a). Ash also provide the major soil protection in the immediate period after the fire as mentioned elsewhere (Cerdà and Doerr 2008; Pereira *et al.* 2010a). Ash properties depends on fire severity (understood as the impact of fire on the ecosystems (Keeley 2009), that could vary importantly even in small distances as already was identified in some studies (Pereira and Úbeda 2010; Pereira *et al.* 2010b).

Predict with accuracy ash nutrients content in burned areas is of major importance because will allow us to understand if these areas need an intervention or not. This can be achieved testing several interpolating methods as several studies recommend (Triantafilis *et al.* 2001; Robinson and Metternicht 2006; Yilmaz 2007; Miller *et al.* 2008; Pereira and Úbeda 2010; Pereira *et al.* 2010c). Considering that C and N are important nutrients for ecosystem sustainability and fire can affect them coercively, it is of major importance map their distributions with precision. The aim of this study is map ash Total Carbon (TC%) and ash Total Nitrogen (TN%) testing several interpolation methods.

2. Material and Methods

2.1. Study site, sample collection and laboratory analysis

The wildfire occurred near Lisbon area (latitude 38º33'N, longitude 09º03'W, and 55 m a.s.l), Portugal, at July 30, 2007 and consumed ±40 ha of forest composed by *Pinus pinaster* and *Quercus suber* (Figure 1a). According the fireman's in the studied area the fire-line evoluted from west to east. Inside the burned area we designed an experimental plot with 9x27 m (Figure 1b) in a west faced slope (18 %) where the fire effect was more homogenous, and we collected carefully 40 ash samples in soil surface 4 days after the fire. Point coordinates were taken with GPS.

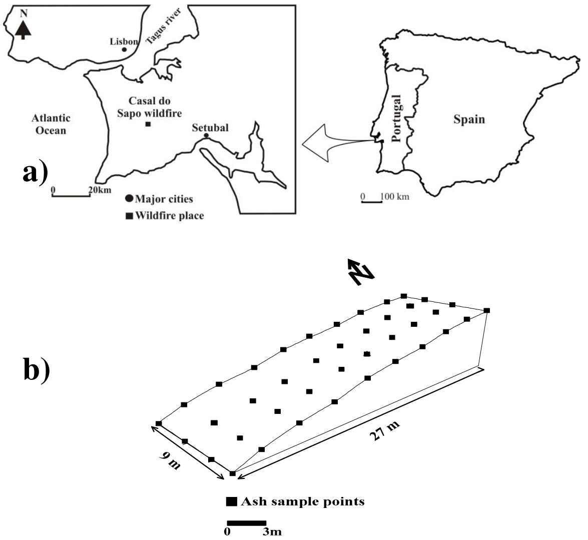

Fig 1. a) Studied area, b) Plot topography and sample points

Samples were stored in plastic bags and taken to laboratory. 1 gr of ash was pulverized at during 2 minutes on the Fritch pulverisette 23 and the ash TC% and ash TN% were analysed with the process of combustion-reduction with gases chromatography with the detector of thermic conductivity EA Flash Series 112 (Thermo-Fisher Scientific, Milan). The data acquisition and the respective calculus were effectuated with the software Eafer 300 (Thermo-Fisher Scientific, Milan). The value of each point is a mean of two replicates. Data is presented in % per dry/height. With the pulverized samples, ash colour was assessed with the Munsell color chart, and for each color, the chroma value was retained. Ash $CaCO_3$ was measured with a Bernard's calcimeter calibrated with 0.2 of pure $CaCO_3$ using a 1:2 hydrochloric acid solution (50 % concentrated HCl and 50 % deionized water). Subsamples of ash weighing 0.2 g were mixed with the 1:2 solution. The $CaCO_3$ was estimated by calculating the difference between the volume of CO_2 before and after introducing each sample (Úbeda *et al.* 2009).

2.2. Statistical analysis, variography, interpolation methods analysis and assessment criteria

Some descriptive statistics analysis were carried out of ash TC% and ash TN%, mean (m), standard deviation (SD), coefficient of variation (CV%), minimum (min), quartil 1 (Q1), median (M), quartile 3 (Q3), maximum (max), skewness (Sk) and kurtosis (Kur). Previous to modelling, data normality was tested with the Shapiro-wilk test (Shapiro and Wilk 1965). Data was considered normal distributed at a $p>0.05$. If original data did not respect Gaussian distribution, a neperian logarithmic (ln) transformation was applied in order to normalize data distribution (Figure 2). Correlation between variables was carried out with a non parametric spearman correlation coefficient, significant at a $p<0.05$.

Variogram and/or semivariogram measure the average dissimilarity between data along the distance. It is calculated by averaging one/half the difference squared of the variable values (Z) over all pairs of observation with the specified separation distance and direction. Variogram modelling allows us to understand the spatial continuity of the variability (Goovaerts 1999; Gringarten and Deutsch 2001). The experimental variogram modelling was carried out in order to observe the variable spatial structure and their correlation with the distance, based on the following mathematical equation:

$$\gamma(\Delta x, \Delta y) = \frac{1}{2}\varepsilon\left[(Z(x+\Delta x+\Delta y) - Z(x,y))^2\right] \qquad (1)$$

where Z(x,y) is the value of the variable in study at the point (x,y), and ε the statistical operator. The variogram, γ is a function of the separation between points (Δx, Δy).

In this study due the lower amount of samples, the experimental variograms performed are isotropic, that consider the variability of the variable equal in all distances. For identify anisotropy in the space are needed at least 150 data points (Webster and Oliver 2007). Spatial dependence of the variables was evaluated with the nug/sill*100 ratio. If the ratio was lower than 25 %, the variable has a strong spatial dependence between 25 % and 75 % the variable had a moderate spatial dependence and greater than 75 % the variable shown a weak spatial dependence (Chien *et al.* 1994).

In order to obtain an accurate interpolation of ash TC% and ash TN%, we tested several interpolation methods. The interpolation methods vary in their assumption, from local to global dimensions and deterministic and stochastic nature (Luo *et al.* 2009). For more detailed information, the interest readers can consult Isaak and Srivastva (1989) and Webster and Oliver (2007).

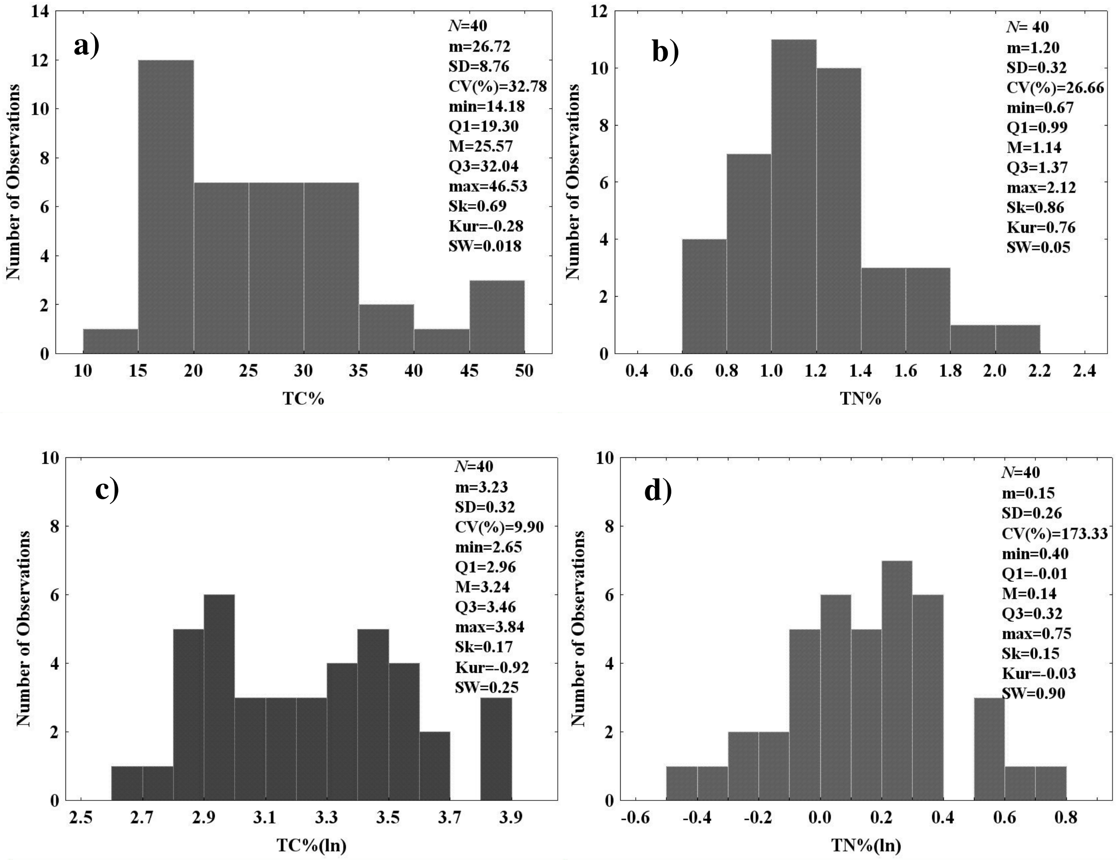

Fig 2. Histograms and some descriptive statistics of a) TC%, b) TN%, c) TC%(ln) and d) TN%(ln)

In this study we tested interpolation precision with 9 interpolation methods, the deterministic methods Inverse Distance to a Power (IDP), with the power of 1, 2, 3, 4 and 5, Local Polynomial (LP) with the power of 1 and 2, Spline with tension (SPT), Completely Regularized Spline (CRS), Multiquadratic (MTQ), Inverse Multiquadratic (IMQ) and Thin Plate Spline (TPS). We considered also some geostatistical methods, Ordinary Kriging (OK) and Simple Kriging (SK). In each interpolation method we include a total of 15 neighbours and we applied a smooth factor of 0.5. Interpolation techniques were assessed based on the errors produced by each method (Observed-Predicted) calculated with the cross-validation technique. Cross validation is obtained by taking each observation in turn out of the sample and estimating from the remaining ones. The differences/errors generated in each interpolation method are used to calculate the interpolation performance of each method. With the errors produced we calculated the mean error (ME) and Root mean squared error (RMSE).

ME was calculated according the equation:

$$ME = \frac{1}{N}\sum_{i=N}^{N}\left[z(x_i) - \hat{z}(x_i)\right] \qquad (2)$$

and RMSE according to the formula:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=N}^{N}\left[z(x_i) - \hat{z}(x_i)\right]^2} \qquad (3)$$

where $z(x_i)$ is the observed value and $\hat{z}(x_i)$ the predicted (Robinson and Metternicht 2006).

The most precise method is the one that presents the lower RMSE. We also compared the mean of the observed and predicted values and relate them with a Pearson correlation coefficient. In order to compare the performance of the interpolation methods in ash TC% and ash TN%, we compare their RMSE's mean with the non-parametric test Mann-Whitney U Test (because both distributions did not respect normality assumptions, even after ln and Box-Cox data transformation), Differences between means, medians and correlations were considered significant at a $p<0.05$. Statistical analyses were carried out with Statistica 7.0 (Statsoft. inc), variograms with Surfer 9.0 (Golden Software) and interpolation tests with ArcGis 9.3 (ESRI), for windows.

3. Results and discussion

3.1. Descriptive parameters and dataset distribution

The summary of the descriptive statistics of ash TC% are shown in the figure 2a. Ash TC% presented a mean of 26.72 % (±8.76 %), and ranged from a maximum of 46.53 % and a minimum of 14.18 %. The CV% is 32.78 % which means that the ash TC% is highly variable in the studied area. In relation to ash TN%, the mean value of all samples is 1.20 % (±0.32 %), with the minimum, maximum of 0.67 % and 2.12 % respectively (Figure 2b). The CV% of ash

TN% (26.66 %) was lower than the observed in ash TC%, however, according to the dimensions of the plot in study, the variability of this element was high also. Overall, we considered that the fire did not had substantial impacts on TC% and TN% content in ash and was sufficient to aid ecosystem recuperation. Two years after the fire the soil cover was almost 70 % (Pereira 2010).

To illustrate the spatial distribution of ash TC% and ash TN% a symbol map was performed (Figure 3). We identified ash with higher amounts of ash TC% in the west and north part of the plot and in less quantity in the centre and south of the plot (Figure 3a). Ash TN% showed also very similar spatial patterns and as expected we identified a positive and significant correlation between variables (Figure 4).

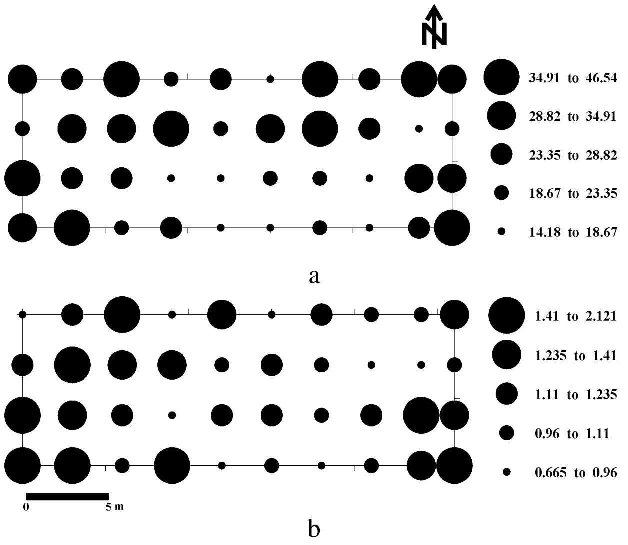

Fig 3. Symbol map of ash a) TC% and b) TN%

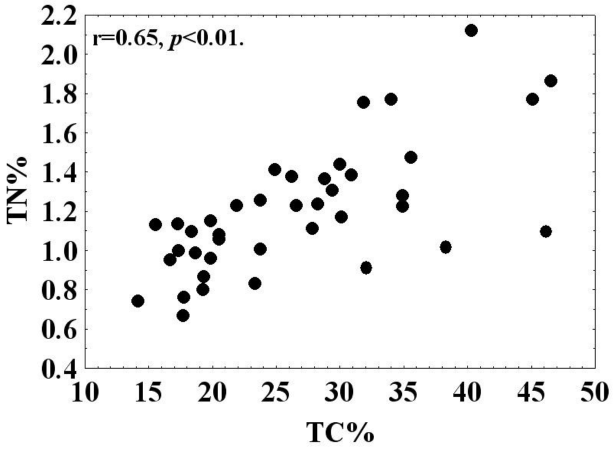

Fig 4. Correlation between TC% and TN%

The ash TC% histogram showed a positive skewness and a negative kurtosis which means that the distribution is influenced by the lower values, but very much distributed across the dataset. Thus, SW *p* value was lower than 0.05, and the distribution did not respect the normality. The distribution of ash TN% shown skewness slightly higher than ash TC% (0.86), however the kurtosis was much more positive, which means that the values were not so distributed across the dataset. In this case the SW *p* value was slightly higher than 0.05 and respected the normal distribution. Both distributions were positively skewed and as referred in several studies skewed distributions could lead to biased analysis and conclusions in statistical and spatial interpolation analysis (McGrath *et al.* 2004; Zhang and McGrath 2004). Thus, we applied a neperian logarithm (ln), for the data respect the normality in ash TC% and ash TN% data. With this transformation, the skewness decrease and both distributions and respected the normality, as observed in SW test (Figure 2c and d). The ln data was used in interpolation data modelling.

3.2. Correlation between TC% and TN% with fire severity

Ash TC% and ash TN% content in ash depend on the fire severity (Pereira 2010). One of the most applied methods to identify fire severity is the ash colour and ash $CaCO_3$ content (Goforth *et al.* 2005; Úbeda *et al.* 2009). We observed a non significant negative correlation between ash TC% and fire severity (ash colour and $CaCO_3$) that is even lower in the case of the ash TN% (Table 1). This shows that both nutrients decrease with fire severity, especially ash TC%. The lower correlation observed in the ash TN% case is very likely due the increase of the element until 400 °C as Pereira *et al.* (2008) observed in laboratory burnings. In this fire the temperatures were between 350–400 °C and in some points reached to 500–550 °C (Pereira 2010). Thus, it is very likely that ash produced around 350 °C had lower amount than the ash the ash produced around 400 °C. Due the higher temperatures of exposition the ash produced at higher temperatures (500–550 °C) is very likely to have lower amounts of TN% than the mentioned temperatures. This increase until 400°C and decrease thereafter might have influence on ash TN% correlation with fire severity that increases with temperature of exposition (Úbeda *et al.* 2009).

The fire do not induce an increase of N in ash, however their proportion in relation to other elements can increase, and this gives an idea of an increase of N. According some authors the effects of fire in N remains an enigma (DeBano *et al.* 1998; Neary *et al.* 2005). N pools after fire can increase, decrease or remain equal and this depends on the method used to calculate N. If the TN estimation is based on % for dry weight, as in the present case, N concentration can increase until 500°C (DeBano *et al.* 1998). This explains the increase of %TN until the 400 °C and the lack of correlation.

3.3 Spatial structure of ash TC% and TN%

The spatial structure of ash TC%(ln) and ash TN%(ln) is revealed by the variograms shown in the figure 5. The variogram of ash TC%(ln) presents an excellent structure since the nugget effect is 0 and no measured error was identified (Figure 5a). This means that the sampling density is adequate to identify spatial structures.

The theoretical model that fits better with the experimental is the rational quadratic, shown a range of 2.08 m and a nug/sill ratio of 100 % which means that the variable has a high spatial dependence. In relation to ash TN%(ln) (Figure 5b) the theoretical model that fits more with the experimental is the lineal, which means that the variability of the variable increases in all the area of interest and do not reach the sill, the point beyond that the variability of the variable is residual. These results shown that, beside the statistical correlation observed between the two variables, their spatial structure is slightly different. The mentioned is very likely to be due the different effects of fire in both nutrients. We already saw that there are different correlations with fire severity (Table 1) and these different responses are revealed in the variogram structure.

Table 1. Correlation between ash TC% and TN% with ash colour and $CaCO_3$.n.s (not significant at a $p<0.05$)

	Ash colour	$CaCO_3$
TC%	$-0.27^{n.s}$	$-0.29^{n.s}$
TN%	$-0.05^{n.s}$	$-0.12^{n.s}$

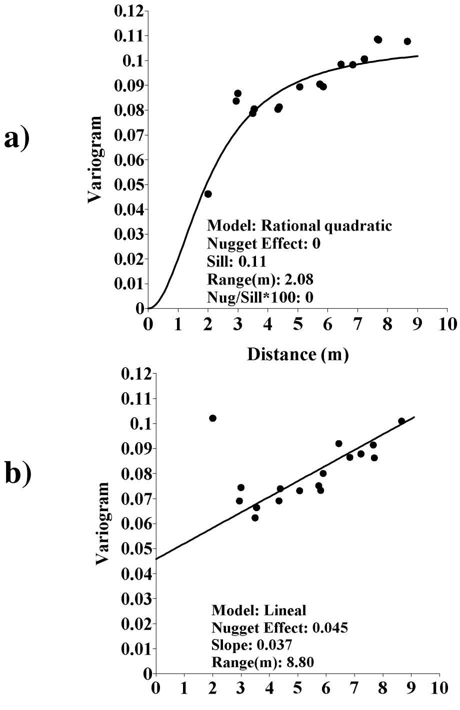

Fig. 5. Isotropic variograms calculated for a) ash TC%(ln) and b) TN%(ln)

3.4. Spatial distribution of ash TC% and ash TN%

Previously to data modelling we tested several interpolation methods in order to identify the most accurate. The interpolations accuracy for ash TC%(ln) and ash TN%(ln) are exposed in the table 2 and we can observed that among all tested methods the most accurate to interpolate ash TC%(ln) was IDW2 (RMSE: 0.2400) and the less precise was LP3 (RMSE: 0.5567). IDW methods are better interpolators if local characteristics of the variable are more important than regional (Smith *et al.* 2009). This means that some local characteristics of the vegetation (e.g. fuel type, structure, disposition on soil surface, moisture and micro-topographical characteristics) had influence fire temperatures on the combustible and as consequence in fire severity and ash TC%(ln). This small distance variation characteristics agree with the high CV% of ash TC%(ln) (Figure 2a) and we observed that fire could have important variations in ash properties as observed elsewhere (Pereira *et al.* 2010b).

All methods were considered unbiased (ME close to 0) and no significant differences were identified between observed and predicted methods, which means that all methods were predicted with confident degree of accuracy. The coefficient of correlation between observed and predicted is high in the most accurate methods (e.g IDW2 and SPT). In relation to ash TN%(ln) the most precise method to interpolate was SK (RMSE: 0.2949) and the less accurate was once again LP3 (RMSE: 0.8308). Contrary to ash TC%(ln) this variable shows a regionalized pattern of distribution because SPT assumptions and other radial basis functions are very similar to geostatistical methods (Webster and Oliver 2007; Smith *et al.* 2009). The low CV% also reflects this situation (Figure 2b).

In general, all methods were unbiased and we did not identify significant differences between observed and estimated which mean that the models were carried out with reliability. The correlations between the observed and predicted points, as in the case of TC%(ln) are higher in the most accurate methods (Table 2b). The TN%(ln) RMSE's mean is significantly higher at a $p<0.001$ and this shown that on average that the interpolations where significantly more accurate in TC%(ln) than in TN%(ln) (Figure 5).

The interpolated maps with the most precise method are exposed in the Figure 6. Ash TC%(ln) distribution shows a greater heterogeneity and small scale variability with high values contiguous to lower values and as mentioned this can be due the combustible characteristics previous to fire and the impacts of the temperature. Nevertheless it can be identified a pattern. In general, higher content of ash TC% are identified in western, northern part and southeast and northeast corner of the plot and lower in the centre and south of the interested area where the majority of the ash were from *Pinus pinaster* (Pereira 2010), recognized as a extreme flammable specie (Núñez-Regueira *et al.* 1996), thus more vulnerable to fire temperatures (Pereira 2010).

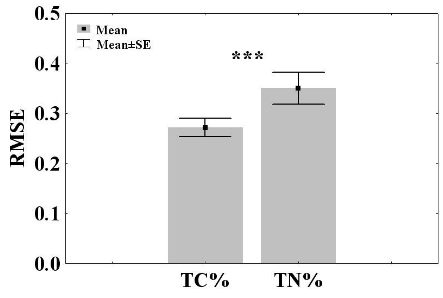

Fig. 5. Comparison between TC% and TN% RMSE's means. ***, difference significant at a $p<0.001$

Table 2. Summary statistics of the interpolation methods accuracy for a) TC%(ln) and b) TN%(ln). Accuracy is assessed throughout cross validation method. Minimum error (Min) and Maximum error (Max) in each interpolation method. In bold the most accurate method and underlined the less precise. Differences between Obs vs Est., significant at a $p < 0.05$. Significant correlations at a $p < 0.01$** and $p < 0.001$***. n.s, not significant at a $p<0.05$.

a)

Method	Min	Max	ME	RMSE	Obs *vs* Est	*r*
IDW 1	-0.630	0.535	-0.0138	0.2486	0.730	$0.27^{\text{n.s}}$
IDW 2	**-0.552**	**0.536**	**-0.005901**	**0.2396**	**0.878**	**0.37***
IDW 3	-0.484	0.527	-0.00009853	0.2405	0.997	0.38*
IDW 4	-0.443	0.515	0.003341	0.2497	0.933	0.36*
IDW 5	-0.439	0.505	0.004727	0.2552	0.908	0.35*
LP 1	-0.413	0.561	0.01539	0.2411	0.691	0.44**
LP 2	-0.488	0.671	0.004537	0.265	0.915	0.48**
LP 3	-1.810	2.046	0.003725	0.5567	0.966	0.33*
GP	-0.699	0.572	-0.002861	0.2701	0.947	$0.00^{\text{n.s}}$
SPT	-0.515	0.527	-0.002803	0.2422	9.942	0.35*
CRS	-0.491	0.514	-0.002245	0.2439	0.954	0.35*
MTQ	-0.502	0.502	-0.0003034	0.2613	0.994	0.34*
IMTQ	-0.549	0.547	-0.005175	0.2402	0.893	0.37*
TPS	-0.502	0.502	0.00109	0.3262	0.994	0.34*
OK	-0.544	0.560	-0.003676	0.2407	0.924	0.36*
SK	-0.531	0.558	-0.006206	0.2400	0.827	0.37*
UK	-0.651	0.553	-0.007086	0.2562	0.863	$0.11^{\text{n.s}}$

b)

Method	Min	Max	ME	RMSE	Obs *vs* Est	*r*
IDW 1	-0.621	0.416	-0.0117	0.2969	0.806	0.35*
IDW 2	-0.608	0.459	-0.005941	0.2973	0.901	0.36*
IDW 3	-0.579	0.458	-0.001885	0.2983	0.968	0.35*
IDW 4	-0.539	0.499	0.002849	0.3048	0.953	0.35*
IDW 5	-0.548	0.529	0.005779	0.3122	0.908	0.35*
LP 1	-0.554	0.513	0.03185	0.3019	0.511	0.39*
LP 2	-0.703	1.234	0.01692	0.3984	0.792	$0.27^{\text{n.s}}$
LP 3	-2.088	3.131	0.04722	0.8308	0.724	$0.05^{\text{n.s}}$
GP	-0.716	0.536	-0.00455	0.3328	0.932	$-0.03^{\text{n.s}}$
SPT	**-0.616**	**0.428**	**-0.01256**	**0.2949**	**0.791**	**0.37***
CRS	-0.604	0.507	-0.003012	0.3041	0.950	0.33*
MTQ	-0.621	0.607	0.001484	0.3403	0.978	$0.27^{\text{n.s}}$
IMTQ	-0.613	0.440	-0.008097	0.3012	0.876	$0.31^{\text{n.s}}$
TPS	-0.701	0.870	0.008235	0.4465	0.908	$0.14^{\text{n.s}}$
OK	-0.615	0.449	-0.01087	0.2992	0.821	0.34*
SK	-0.597	0.460	-0.01024	0.2976	0.830	0.35*
UK	-0.590	0.462	-0.0125	0.2989	0.810	0.35*

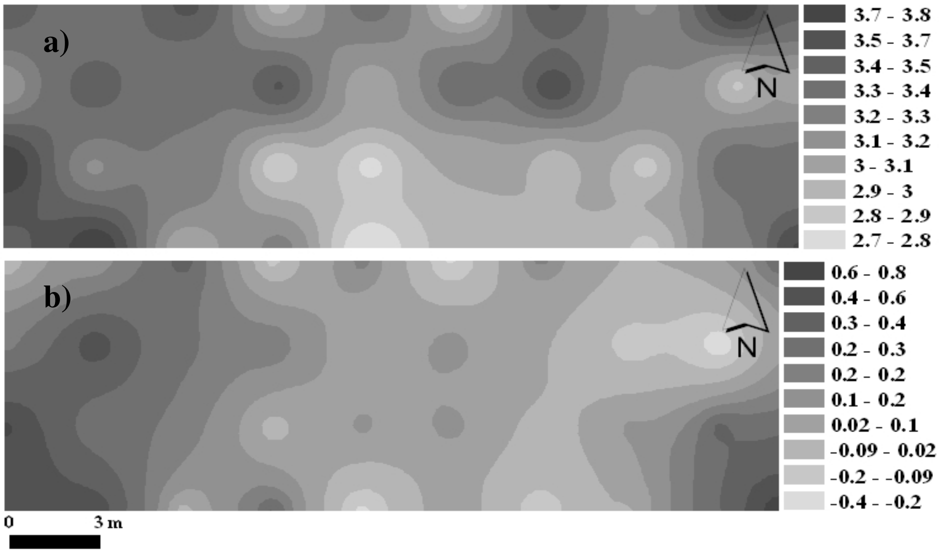

Fig. 6. Interpolated maps of a) TC% and b) TN% with the most accurate methods

In relation to ash TN%(ln) we observed a slight different spatial distribution as consequence of the different effects of temperature in this element. Hence we identified ash, with higher content of ash TN% in the southwest and southeast part of the plot and lesser in the central part of the area of interest. Beside the correlation between the variables (Figure 4) it is observable the different spatial distribution of the variables. In addition, the most suitable methods for interpolate ash TC% and ash TN% are different, thus indicate that the spatial distribution is not similar.

4. Conclusions

From this study we concluded that:

1. In the studied plot the wildfire did not induce critical losses in ash TC% and ash TC%, and the landscape recover faster. Two years after the wildfire, great part of the soil was covered.
2. The symbol map showed that concentrations of ash TC% and ash TN% in the studied plot were identified in the west and north part and less in centre and south of the plot.
3. Ash TC% is more related with fire severity than ash TN% due the different vulnerability and response of both elements to fire temperature identified previously in laboratory fire simulations.
4. Ash TC%(ln) shown an excellent spatial structure, spatial dependence and the experimental model that fits more with the theoretical model it is the rational quadratic. The lineal theoretical model fits more with the experimental model observed in the ash TN%(ln) data which means that the variability of the variable increases in all area of interest.
5. The interpolation method that predict with more accuracy TC%(ln) distribution is the IDW2 and the less precise was LP3. In relation to TN%(ln) the best most precise method was SPT and the less accurate also LP3. These tests allow us to understand that the variables in study have different spatial patterns and variability.
6. The comparison between all methods shown that the interpolations were more accurate with TC%(ln) data than with TN%(ln) data. This reveals that the predictions were more precise in the first element. In general the methods were well performed because ME is nearby 0 and no significant differences were identified between observed and predicted values
7. The interpolation of the data with the most accurate method gave us a better understanding of data distribution. Ash TC% was identified in higher amount in western, northern part and southeast and northeast corner of the plot and lower in the centre and south of the interested area and ash TN% was identified in higher amounts in the southwest and southeast part of the plot and lesser in the central part. The lower concentrations of both elements are related with the presence of *Pinus pinaster*, specie with high flammability.

Acknowledgments

This study was supported by Spanish Ministry of Science and Technology, project: CGL2006-11107-C02-02/BOS “Evaluation of the quality of Mediterranean soils affected by fire in a middle and large term” and European Regional Development Fund (FEDER) Funds. We are also thankful to Serveis Científico-Tècnics from the University of Barcelona.

References

Agee, J. K. 1993. Fire Ecology of Pacific Northwest Forests. 1st ed. Island Press. 499. ISBN 1-55963-230-5.

Bonan, G. B. 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320: 1444–1449.

Cerdà, A.; Doerr, S. H. 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period, *Catena* 74(3): 256–263.

Chien, Y. L.; Lee, D. Y.; Guo, H. Y.; Houng, K. H. 1997. Geostatistical analysis of soil properties of mid-west Taiwan soils. *Soil Science* 162(5): 291–298.

Crochane, M. A.; Laurence, W. F. 2008. Synergisms among fire, Land use, and climate change in the Amazon. *Ambio*, 37(7-8): 522–527.

DeBano, L. F.; Neary, D. G.; Ffolliott, P. F. 1998. *Fire’s effects on ecosystems*. John Wiley and Sons, Inc.New York, 1st Edition. 352. ISBN-10: 0471163562.

Goforth, B. R.; Graham, R. C.; Hubbert, K. R.; Zanner, W.; Minnich, R. A. 2005. Spatial distribution and properties of ash and thermally altered soils after high-severity forest fire, southern California. *International Journal of Wildland Fire* 14(4): 342–354.

Goovaerts, P. 1999. Geostatistics in soil science: state-of-the-art and perspectives. *Geoderma,* 89(1-2): 1–45.

Gringarten, E.; Deutsch, C. V. 2001. Variogram interpretation and modelling. *Mathematical Geology,* 33(4): 507–534.

Isaaks, E. H.; Srivastava, R. M. 1989. *An Introduction to Applied Geostatistics*, Oxford University Press, 592. ISNB-10:0195050126.

Johnson, D. W. 1992. Effects of forest management on soil carbon storage. *Water, Air, and Soil Pollution*, 64(1–2): 83–120.

Keeley, J. E. 2009. Fire intensity, fire severity and burn severity: a brief and suggested usage. *International Journal of Wildland Fire*, 18(1): 116–126.

Knicker, H.; González-Vila, F. J.; Polvillo, O.; González, J. A.; Almendros, G. 2005. Fire-induced transformation of C- and N- forms in a different organic soil fractions from a Dystric Cambissol under a Mediterranean pine forest (*Pinus pinaster*). *Soil Biology & Biochemistry,* 37(4): 701–718.

Lavorel, S.; Flannigan, M. D.; Lambin, E. F.; Scholes, M. C. 2006. Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies to Global Change*, 12(1): 33–53.

Lloret, F.; Zedler, P. H. 2009. The effect of fire on vegetation. in: Cerdà, A.; Robichaud, P. R. (eds) *Fire effects on soils and restoration strategies*, Science Publishers, New Hampshire, 257–295. ISBN: 978-1-57808-526-2.

Luo, W., Taylor, M. C., Parker, S. R. 2008. A comparision of spatial interpolation methods to estimate continuous wind speed surfaces using irregularity distributed data from England and Wales. *International Journal of Climatology,* 28(7): 947–959.

Mataix-Solera, J.; Guerrero, C. 2007. Efectos de los incendios forestales en las propiedades edaficas [Fire effects on soil properties]. in: Mataix-Solera, A. (ed.) *Incendios forestales, suelos y erosión hídrica* [Forest fires, soils and wáter erosion], Caja Mediterráneo CEMACAM, Alcoi, 7–40. ISBN: 978-84-7599-194-8.

Mataix-Solera, J.; Guerrero, C.; Arcenegui, V.; Bárcenas, G.; Zornoza, R.; Perez-Bejarano A.; Bodi, M. B., Mataix-Beneyto, J.; Gómez, I.; Garcia-Orenes, F.; Navarro-Pedreño, J.; Jordán, M.M.; Cerdá, A.; Doerr, S. H.; Úbeda, X.; Outeiro, L.; Pereira, P.; Jordán, A.; Zavala, L. M. 2009. Los incendios forestales y el suelo: un resumen de la investigación realizada por el Grupo de Edafología Ambiental de la UMH en colaboración con otros grupos [Forest fires and the soil. Resume of the reasersch carried out with the Soil Environmental Group of the UMH with other groups]. in: Cerdà, A., Mataix-Solera, J. (Eds), *Efectos de los incendios forestales sobre los suelos en España. El estado de la cuestión visto por los científicos españoles* [Fire effects on soil in Spain. The state of the art saw by the Spanish scientists]. Càtedra de Divulgació de la Ciència. Universitat de Valencia. 185–217. ISBN: 978-84-370-7653-9.

McGrath, D.; Zhang, C.; Carton, O. T. 2004. Geostatistical analyses and hazard assessment on soil lead in silvermines area. *Environmental Pollution,* 127(2): 239–248.

Miller, D. C.; Rivington, M.; Mattews, K. B.; Buchan, K.; Bellochi, G. 2008. Testing the spatial applicability of the Johnson-woodward method for estimating solar radiation from sunshine duration data. *Agricultural and Forest Metereology*, 148(3): 466–480.

Naveh, Z. 1975. The evolutionary significance of fire in the Mediterranean region. *Vegetació*, 29(3): 199–208.

Neary, D. G.; Ryan, K. C.; DeBano, L. F. 2005. *Wildland fire in the ecosystems: effects of fire on soils and water*. Gen. Tech. Rep. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

Núñez-Regueira, L.; Rodríguez Añon, J. A.; Proupín Castiñeras, J. 1996. Calorific values and flammability of forest species in Galicia. Coastal and hillside zones. *Bioresource Technology,* 57(2): 111–119.

Pereira, P. 2010. Efeitos da intensidade de fogo nas caracteristicas fisico-quimicas das cinzas das especies vegetais Mediterraneas e o seu impacto na qualidade da água, PhD thesis, Barcelona University.

Pereira, P.; Oliva, M.; Baltrenaite, E. 2010b. Modelling extreme precipitation in hazardous mountainous areas. Contribution to landscape planning and environmental management. *Journal of Environment Engineering and Landscape Management,* 18(4): 329–342.

Pereira, P.; Bodi, M.; Úbeda, X.; Cerdà, A.; Mataix-Solera, J.; Balfour, V.; Woods, S. 2010a. Las cenizas y el ecosistema suelo [Ash and soil ecosystem]. In: Cerdà, A., Jordan, A. (Eds.). *Actualización en métodos y técnicas de estudio de los suelos afectados por incendios forestales* [Actualization of the study methods and techniques of soils affected by forest fires]. Càtedra de Divulgació de la Ciència. 345–398. ISBN: 978-84-370-7887-8.

Pereira, P.; Úbeda, X. 2010. Spatial variation of heavy metals released from ashes after a wildfire, *Journal of Environmental Engineering and Landscape Management*, 18(1): 13–22.

Pereira, P.; Úbeda, X.; Baltrenaite, E. 2010b. Mapping Total Nitrogen in ash after a Wildfire, a microplot analysis. *Ekologija*, 56 (3–4): 144–152.

Pereira, P.; Úbeda, X.; Martin, D.; Mataix-Solera, J.; Guerrero, C. 2010c. Effects of a low severity prescribed fire on water-soluble elements in ash from a Cork Oak (*Quercus suber*) forest located in the northeast of the Iberian Peninsula. *Environmental Research*, 111(2): 237–247.

Pereira, P.; Úbeda, X.; Outeiro, L.; Martin, D. 2008. Effects of fire intensity on Carbon and Nitrogen of leaf litter of three Mediterranean species (*Quercus suber*, *Quercus robur*, *Pinus Pinea*), *EGU General Assembly 2008*, *Geophysical Research Abstracts, 10,* EGU 2008 -A- 01140, ISSN: 1029-7006.

Robinson, T. P.; Metternicht, G. 2006. Testing the performance of spatial interpolation techniques for mapping soil properties. *Computers and Electronics in Agriculture,* 50(2): 97–108.

Shapiro, S., Wilk, M. 1965. An análisis of variance test for normality. *Biometrika,* 52(3-4): 591–611.

Smith, M. J.; Goodchild,M. F.; Longley, P. A. 2009. *Geospatial Analysis. A comprehensive guide to principles techniques and software tools*. Troubador Publishing. Leicister. 394. ISBN 0-415-31681-2.

Triantafilis, J.; Odeh, I. O. A.; McBratney, A. B. 2001. Five geostatistical models to predict soil salinity from electromagnetic induction data across irrigated cotton. *Soil Science Society American Journal*, 65(3): 869–878.

Úbeda, X.; Pereira, P.; Outeiro, L.; Martin, D. A. 2009. Effects of fire temperature on the physical and chemical characteristics of the ash two plots of cork oak (*Quercus suber*). *Land Degradationa and Development,* 20(6): 589–608.

Webster, R.; Oliver, M. A. 2007. *Geostatistics for environmental scientists.* Wiley Interscience. 2nd ed. London. 330. ISBN*:* 978-0-470-02858-2.

Wotton, B. M.; Nock, C. A.; Flannigan, M. D. 2010. Forest fire occurrence and climate change in Canada. *International Journal of Wildland Fire*, 19(3): 253–271.

Yilmaz, H. M. 2007. The effect of interpolation methods in surface definition: an experimental study. *Earth Surface Processes and Landforms,* 32(9): 1346–1361.

Zhang, C.; McGrath, D. 2004. Geostatistical and GIS analyses on soil organic carbon concentration in grassland of southeastern Ireland from two different periods. *Geoderma,* 119(3-4): 261–275.