How to test the significance of the relation between spatially autocorrelated data at the landscape scale: A case study using fire and forest maps[1]

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Abstract: To better understand the relationship between wildfire and forest regeneration in the boreal forest, we quantify their degree of relationship by means of correlation. Given that wildfires in the boreal forest can cover large areas, such correlation needs also to be computed for large areas (*i.e.,* 33,000 km^2 in northern Québec). At this landscape scale, both variables (fire and forest) show strong and significant positive spatial autocorrelation. The presence of spatial autocorrelation in the two variables, however, can affect the statistical significance and the interpretation of their degree of correlation. In this paper, we compare different approaches that have been proposed to solve this problem: a parametric test that corrects for the presence of autocorrelation by adjusting the effective sample size (Dutilleul's modified *t* test); a complete randomization test; a restricted randomization test based on a toroidal shift; the Mantel test that controls for the relative spatial locations among sampling; and the partial Mantel test that controls for the spatial distances among sampling sites. A positive correlation between the two variables was found significant by the parametric test and complete randomization test, but not significant when the restricted randomization test, Dutilleul's modified *t* test, and the Mantel test were used. Conversely, a negative correlation was found by the partial Mantel test. Hence, to control for the presence of spatial autocorrelation, either a restricted randomization test or the Dutilleul method is recommended, while to control for the spatial relative position of the data, the Mantel and partial Mantel tests should be used. A firm understanding of these statistical tests and their respective assumptions regarding the spatial structure of the data is crucial to any valid ecological understanding and interpretation.
Keywords: spatial autocorrelation, spurious correlation, Dutilleul's modified *t* test, Mantel and partial Mantel tests, restricted randomization.

Résumé : Afin de mieux comprendre la relation qui existe entre les feux et la régénération de la forêt boréale, on peut évaluer son importance grâce à des corrélations. Étant donné que les incendies couvrent de vastes étendues en forêt boréale, ces corrélations se doivent aussi d'être calculée à partir de données récoltées sur de grandes superficies (33 000 km^2 dans le Nord du Québec). À cette échelle, les deux variables, soit le feu et la forêt, ont une forte autocorrélation spatiale positive et significative. La présence d'autocorrélation spatiale entre les deux variables peut toutefois affecter la signification statistique et l'interprétation de leur degré de corrélation. Dans cet article, nous comparons différentes approches qui ont été proposées pour résoudre ce problème : un test paramétrique qui tient compte de l'autocorrélation et qui ajuste en conséquence l'effectif de l'échantillon (test *t* modifié de Dutilleul), un test par permutation, un test par permutation avec contraintes fondé sur un décalage toroïdal, un test de Mantel qui prend en considération les localisations au sein d'un échantillonnage et un test de Mantel partiel qui tient compte de la distance entre les sites d'échantillonnage. Nous avons trouvé une corrélation positive et significative entre les deux variables en utilisant le test paramétrique et le test par permutation; la corrélation n'était toutefois pas significative avec le test par permutation avec contraintes, le test *t* modifié de Dutilleul et le test de Mantel. D'autre part, une corrélation négative a été trouvée avec le test de Mantel partiel. En conséquence, si l'on veut tenir compte de l'autocorrélation spatiale, il est préférable d'utiliser un test de permutation avec contraintes ou la méthode de Dutilleul. Si l'on désire prendre en considération la position spatiale relative des données, les tests de Mantel devraient être utilisés. Une connaissance approfondie des tests statistiques et de leurs suppositions respectives à l'égard de la structure spatiale des données est cruciale pour bien comprendre et interpréter les phénomènes écologiques.
Mots-clés : autocorrélation spatiale, fausse corrélation, test *t* modifié de Dutilleul, test de Mantel, test de Mantel partiel, randomisation avec contraintes.

Introduction

In the last decade, concerns about wildfire impacts on forest regeneration have increased. This is primarily due to the occurrence of large wildfires near human settlements, Yellowstone's 1988 fire being the most obvious example (Christensen *et al.,* 1989; Elfring, 1989; Romme & Despain, 1989; Turner *et al.,* 1994). The occurrence of huge wildfires is frequent in the boreal forest of northern Québec (Payette *et al.,* 1989). But little is known about the impacts of these wildfires on forest regeneration and potential deforestation on a landscape scale (Payette, Fortin & Gamache, 2001). Although wildfires in boreal forest are needed to ensure regeneration of fire-adapted species such as black spruce (*Picea mariana* [Mill.] BSP.) and jack pine (*Pinus banksiana* Lamb), changes to the fire regime due to climate change may result either in species composition shift (Johnson, 1978; Arseneault & Payette, 1992; Torn & Fried, 1992; De Grandpré, Gagnon & Bergeron, 1993; Bergeron & Flannigan, 1995) or deforestation (Payette & Gagnon, 1985; Balling, Meyer & Wells, 1992).

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To quantify the impacts of wildfires on boreal forest, data covering large areas are needed to detect significant patterns. To obtain data at the landscape scale, both aerial photographs and remotely sensed imagery can be used to map fires and forest stands. Such maps need to be validated by fieldwork to obtain fire event dates and remnant forest ages (Payette *et al.,* 1989). Then, to quantify the degree of relationship, a Pearson correlation between the two maps, fire and forest, can be computed. Here, a positive correlation could indicate either that large fires leave a larger number of forest stands intact or that fires positively affect the forest regeneration process. Conversely, negative correlation could be related to the negative impact of fires on forest regeneration (deforestation). Although the computation of such correlation seems straightforward, at least three methodological problems need to be addressed.

CORRELATION BETWEEN MAP DATA

First, fire and forest maps obtained by either photo-interpretation (polygon, vector data) or classified remotely sensed data (pixel, grid cell) are categorical, attribute, data. Unfortunately, correlation between polygon maps cannot be performed directly because the location of the polygons and their respective centroids are not the same in the two maps and correlation between two variables is usually computed on variables measured on the same object or at the same location. Thus, to perform a correlation between two polygon maps, we must first convert the vector data (polygons) into raster data (grid cells), such that each grid cell has data for both variables. This conversion procedure raises an important issue: which grid cell spatial resolution (grain) should be used? In the present case, although the majority of fires are of small size (< 200 ha), some are quite large (100,000 ha); use of too large a grid cell size would cause small fire polygons to be lost in the conversion. A balance is therefore needed between a not too small and a not too large grid cell size: too fine a resolution does not add any new information, while too large a grid cell implies that small fires or forest data are lost (Bregt *et al.,* 1991; van der Knaap, 1992). Furthermore, the conversion from vector to raster data implies that the attribute of a polygon (*i.e.,* categorical variable) will be assigned to grid cells. Such qualitative data cannot be used directly to compute Pearson correlation, which requires quantitative data, so this categorical information needs to be transformed into quantitative data first. The solution used here was to convert the vector data into small grid cells to retain most of the information and then to re-sample this raster map using larger sampling units, counting the number of grid cells where a fire occurred or where a forest was found. Such "re-sampling" results in two quantitative variables that can then be used to compute the correlation between them.

PRESENCE OF SPATIAL AUTOCORRELATION

Second, most ecological data exhibit some degree of spatial autocorrelation, depending on the scale at which the data were recorded and then analyzed (Fortin, 1999). Spatial autocorrelation refers to the pattern in which observations from near-by locations are more likely to have similar magnitude. Here, both variables are likely to be spatially autocorrelated: forest spreads by seed dispersal and fire spreads from an ignition source. Specifically, in the presence of positive autocorrelation, parametric statistics, such as a Pearson correlation coefficient, tend to be declared significant when they should not be, *i.e.,* a type I error occurs (Legendre & Legendre, 1998). In other words, the presence of spatial autocorrelation implies that the data are not independent and do not correspond to a full degree of freedom, so the statistical testing is too liberal. Tests that take into account and correct for the presence of spatial autocorrelation need therefore to be used. Several procedures have been proposed to address this issue and are reviewed by Dale and Fortin (2002). Here, we use different procedures for parametric tests: a complete randomization test, a restricted randomization test, and Dutilleul's (1993) modified *t* test. We also use the Mantel test (Mantel, 1967) and partial Mantel test (Smouse, Long & Sokal, 1986).

SPURIOUS CORRELATION

And third, there is always the possibility that the relationship between two variables is spurious, *i.e.,* due to one or more other variables that were not collected (Legendre, 1993). In our case, it is possible that both fire events and forest remnants are affected by some environmental factors that were not measured. To investigate this possibility, the partial Mantel test is used, utilizing the spatial location of the sampling units as a surrogate for unmeasured factors with a spatial pattern (Fortin & Gurevitch, 2001). In this paper, we show how these three problems can be taken into account while studying the correlation between spatially autocorrelated data at the landscape scale.

Methods

DATA

The fire data used are from a 33,000-km^2 area in northern Québec (56° to 58° 30' N and 74° to 76° W). Fire events occurred between 1920 and 1959 (Figure 1a) and encompass two biomes: the forest-tundra and the shrub-tundra. Fire events were mapped using aerial photographs (scale of 1:40,000) taken between 1954 and 1957 and then validated by survey (see Payette *et al.,* 1989 for details). In the southern part of the forest-tundra, forest is extensive, while the northern shrub-tundra is mostly treeless and is dominated by lichen-heath and shrubs. Remnant forests were mapped using the same aerial photographs for a total of 20,300 forest stands (Figure 1b). Fire events and remnant forests were digitized at 1:250,000 scale. Then, the polygons were converted into a raster format using 100 m × 100 m grid cell resolution.

To compute the correlation between fire events and remnant forests, the study area was re-sampled using sampling units of 20 km × 20 km, for a total of 105 units (*i.e.,* 7 × 15). In each of these new sampling units, the number of grid cells that were burned or that were identified as forest were counted. Based on these new quantitative variables, we first computed the degree of spatial autocorrelation in each map using Moran's *I* coefficient (Legendre & Fortin, 1989). As illustrated in Figure 2, both variables are strongly autocorrelated, and the spatial correlograms are both globally significant after a Bonferroni correction ($\propto' = 0.05/10 = 0.005$). The shape of both spatial correlo-

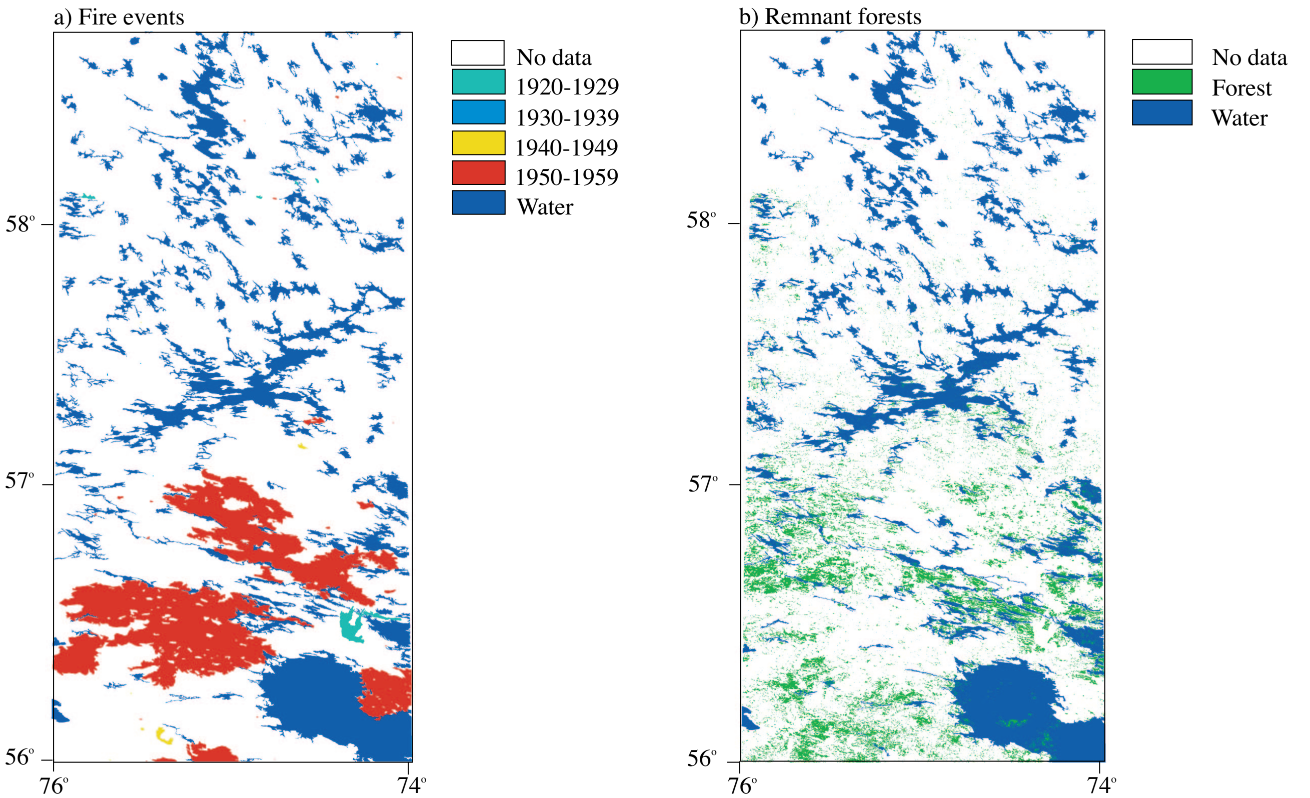

FIGURE 1. a) Fire events between 1920 and 1959; b) remnant forests in northern Québec (56° to 58° 30' N and 74° to 76° W). Grid cell resolution is 100 m × 100 m.

grams indicates a strong spatial trend (Legendre & Fortin, 1989).

PARAMETRIC TESTS

The implication of the presence of positive spatial autocorrelation is that adjacent sampling locations are more likely to have comparable values than expected by random chance. This lack of independence means that each sampling location does not bring a full degree of freedom. Consequently, while the estimation of the Pearson correlation is correct between two spatially autocorrelated variables, its significance cannot be tested using the parametric n-2 degrees of freedom; rather, an adjusted degree of freedom should be used to account for the intensity of spatial autocorrelation of each variable. Here, we use one of these methods, Dutilleul's adjustment method (1993) (but see Dale & Fortin, 2002 for a more comprehensive review).

The estimated effective sample size will be less than the actual sample size, n, as a function of the degree of spatial autocorrelation (Cliff & Ord, 1981). One of these approaches, proposed by Clifford, Richardson and Hémon (1989) and then modified by Dutilleul (1993), consists of first estimating the magnitude of spatial autocorrelation in the data and then reducing the degrees of freedom proportionally to the amount of spatial autocorrelation estimated (Haining, 1991). In brief, the significance of the correlation coefficient is based on an estimated effective sample size, $\hat{M}$. It is assumed that all pairs of points (i, j) can be divided into k strata, with the covariances within strata for the variables x and y considered constant. Such strata can be defined in terms of the k distance classes of a spatial correlogram. Given these k distance classes, $\hat{M}$ takes into account the degree of spatial autocorrelation in each variable, x and y, in estimating the variance, $\hat{\sigma}_r^2$, of the coefficient of correlation, r_{xy} (see Dutilleul, 1993 for mathematical details). The estimated effective sample size is defined as

$$\hat{M} = 1 + \hat{\sigma}_r^2 \qquad [1]$$

The significance of the correlation coefficient is then given by a t-test with $\hat{M}$-2 degrees of freedom. As Fortin (1992) showed, the reliability of this correction is directly related to the estimated degree of spatial autocorrelation, and in turn the estimated degree of spatial autocorrelation varies according to the number of distance classes. Fewer distance classes result in larger distance class intervals and a lower value of spatial autocorrelation, while more distance classes imply smaller distance class intervals with higher values of spatial autocorrelation (Fortin, 1999). Here, we investigate how the number of distance classes influences the value of estimated effective sample size using three sets of classes: 15, 10, and 5.

RANDOMIZATION TESTS

The spatial dependence of the data also has implications for randomization procedures (Fortin & Jacquez, 2000). Indeed, randomization tests assume that the data are exchangeable, *i.e.*, that the shuffling of the sampled values is equally likely over that entire sampled region. Randomization tests require, as do parametric tests, the assumption that the sampled observations are independent. It is therefore inappropriate to use randomization tests with spatially autocorrelated data. In fact, with spatially autocor-

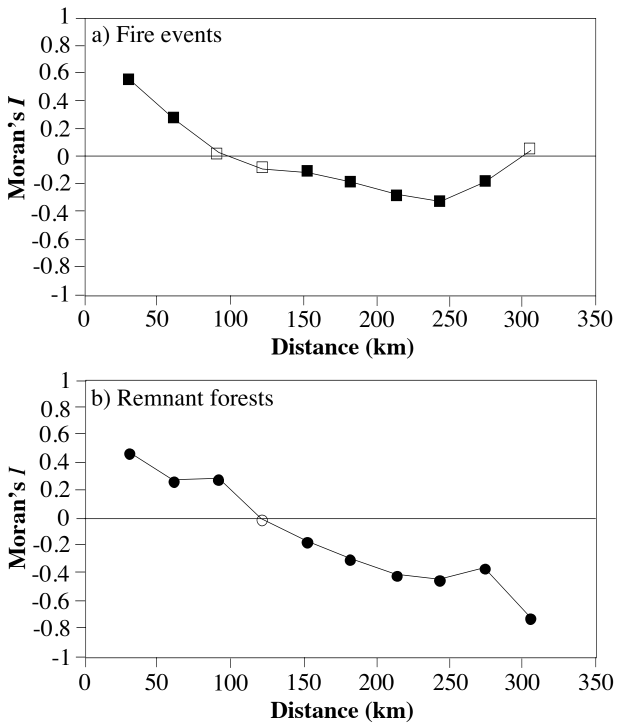

FIGURE 2. Moran's *I* spatial correlograms using 10 equidistance classes of the a) fire events and b) remnant forests. Significant coefficients ($\alpha = 0.05$) are indicated by filled symbols (not significant coefficients are indicated by open symbols). Each spatial correlogram is globally significant after a Bonferroni correction ($\alpha' = 0.05/10 = 0.005$).

related data, only restricted randomization tests should be used, where the randomization procedure is restricted to take into consideration the spatial dependence of the data (Manly, 1997; Fortin & Jacquez, 2000). One way to restrict the randomization is to use the torus randomization procedure (Upton & Fingleton, 1985). The restricted part is achieved by keeping the original spatial, or temporal, structure of both variables fixed, and the randomization distribution part is carried out (in the case of maps) by shifting one map over the other by a given spatial lag and recomputing the correlation several times. This is achieved using a two-dimensional torus constructed by connecting the edges of the map such that points near one side find close neighbours on the opposite side, creating a donut-shaped distance between sampled locations. This restricted randomization procedure maintains the inherent spatial structure of each variable. Because the number of restricted randomizations performed depends on the shape and size of the study area, this test can be too liberal (Fortin, Drapeau & Jacquez, 1996). Another way to perform restricted randomization is to estimate the degree of spatial autocorrelation in the data and then to restrict the randomization by simulating data that have the same degree of spatial autocorrelation (Fortin & Jacquez, 2000).

One randomization method that often is used by ecologists is the Mantel test (Manly, 1997). In 1967, Mantel proposed to compute the degree of relationship between distance matrices based on data obtained at the same sampling locations. The Mantel statistic is the product of corresponding elements of the distance matrices that are summed as follows:

$$Z = \sum_{i=1}^{n}\sum_{j=1}^{n} A_{ij}B_{ij}, \text{ for } i \neq j \qquad [2]$$

where the variable distance matrix A might contain some measure that represents the differences in the value of the variable, or set of variables, among all n sampling units, and the distance matrix B might contain differences of another variable, or set of variables, among the same n sampling units. The Mantel statistic Z can be normalized such that it behaves like a product moment correlation coefficient, r, by varying from -1 to 1. Significance is assessed by using a randomization test where the reference distribution is computed by randomly reassigning the rows and columns of one matrix, each time computing a new Mantel statistic. This type of randomization by rows and columns is a weak form of restricted randomization procedure that preserves the relative position and structure among pairs of sampling locations.

The other test that is often used to control for the effect of spatial structure is the partial Mantel test (Smouse, Long & Sokal, 1986). This statistic computes the degree of relationship between two distance matrices while controlling for the effect of a third one. This is achieved by regressing each matrix by the third one and then computing a Mantel test with the residuals of the regressions. Often, the third matrix is the Euclidean distances among the sampling locations. In this way, spatial distances among the sampling locations are controlled for. Significance testing is achieved with randomization tests, as in the Mantel test. Hence, by construction, the Mantel and the partial Mantel tests do not control for the degree of spatial autocorrelation in the data: they only correct for the relative positions (Mantel test) or spatial distances (partial Mantel) among the sampling locations.

Here, we will use a complete randomization test, a restricted randomization test based on toroidal shift, the Mantel test, and the partial Mantel test to examine the differences between these various randomization procedures.

Results and discussion

The relationship between fire events and forest remnants was found, based on Pearson correlation, to be positive but weak ($r = 0.2035$). The significance of this correlation was then estimated using 1) the parametric test with $n - 2$ degrees of freedom ($p = 0.037$), 2) the complete randomization procedure ($p = 0.030$), and 3) the torus restricted randomization procedure ($p = 0.229$) (Table I). These results indicate that while the correlation was significant when based on the parametric test and the complete randomization procedure, it was not significant when based on the torus restricted randomization procedure, which controls for the spatial structure of the variables. This exercise illustrates that false positive findings can be obtained if the assumption of independence of the data is not valid, as in the case of spatially autocorrelated data (Figure 2). These results confirm that an assessment of probability using either the parametric test or the randomization test can be misleading, resulting in an erroneous conclusion that there is a significant correlation between the two variables when actually there is not.

Dutilleul's modified t test, which takes the degree of spatial autocorrelation into account, was used to test the significance of the correlation using three equidistance classes: 1) 15 equidistance classes of 20.308 km each; 2) 10 equidistance classes of 30.463 km each (as illustrated in Figure 2); and 3) 5 equidistance classes of 60.926 km each. In the three cases (Table I), the effective sample size decreases drastically from 105 to about 18 (ranging from 18.030 to 19.882). The three estimated effective sample sizes indicate that the correlation of 0.2035 was not significant. However, when the number of equidistance classes increases from 5 to 15, the estimated effective sample size decreases. Indeed, as the number of equidistance classes increases from 5 to 15, the distance class interval decreases from 60.926 to 20.308 km, which raises the degree of spatial autocorrelation estimated in the first distance class. This is because the existence of more distance classes implies that each distance class interval is smaller, which in turn makes it more likely that sample points in the same distance class have similar values (Fortin, 1999). Given that the estimated effective sample size is inversely proportional to the degree of spatial autocorrelation, its value decreases as the degree of spatial autocorrelation increases and thus as the number of distance classes increases. Furthermore, when both sampling unit size and distance class vary, the estimated degree of spatial autocorrelation can change from significant to nonsignificant (Fortin, 1999). Thus, caution must be used when using Dutilleul's modified t test, since its reliability is directly related to the estimated degree of spatial autocorrelation. To avoid having to use the estimated value of spatial autocorrelation, one could use a different approach and directly compute a spatial regression where local neighbourhood effects are incorporated by using a conditional autoregressive model (see Cressie, 1993; Bailey & Gatrell, 1995; and Ver Hoef *et al.,* 2001 for mathematical details).

The Mantel test confirmed the Pearson correlation result (Table II). The relationship between the two variables is weak (r = 0.1126) and not significant (p = 0.1760). The fact that the Mantel test (0.1126) computes the correlation on distance matrices rather than on the raw data explains why the magnitude of correlation is weaker with the Mantel test than the Pearson correlation (0.2037). Both tests indicate a positive correlation between fire events and forest remnants. A negative relationship was found, however, when the Euclidean distances among sampling locations were controlled for using the partial Mantel test (Table II; r = -0.1116, p = 0.0001). Such a change, from a positive to a negative correlation, is a good indication of a potentially spurious correlation between fire and forest that may be due to one or more unmeasured variables. In the present case, the spatial distance among the sampled locations is a surrogate for these unmeasured variables. Most likely, given the latitudinal extent of the data (*i.e.,* from 56° to 58° 30' N), the spatial distance acts as a surrogate for both weather and biomes. The positive correlation between fire events and forest remnants is probably due to the fact that in the southern part of the region, the forest regenerates more quickly and there are more fires due to the presence of this fuel load, while in the northern part, there are fewer fires and forest remnants. When controlling for this south-north fuel load gradient by using the spatial distances matrix, in the partial Mantel test, the expected negative relation between fire and forest was obtained.

Conclusion

The presence of spatial autocorrelation affects the significance level of both parametric and randomization tests (Table III). The different significance tests used here allowed us to identify that although the relationship between fire events and forest remnants was positive, it was weak and not significant when the spatial structure of the data was corrected for using Dutilleul's modified t test and the restricted randomization test. It is therefore recommended that with spatially autocorrelated data, either Dutilleul's modified t test, adjusting for spatial autocorrelation, or restricted randomization tests, controlling for spatial structure, be used. Randomization tests should not be used when the data are spatially autocorrelated; rather, restricted randomization procedures should be used. Furthermore, Dutilleul's method should be used with caution, because the estimated effective sample size is inversely proportional to the estimated degree of spatial autocorrelation in each variable. This issue can be alleviated by using conditional autoregressive models instead (Cressie, 1993; Ver Hoef *et al.,* 2001). Finally, the partial Mantel test was able to identify a spurious relation between fire events and forest remnants while controlling for a third variable, here latitudinal distance, that was affecting both. However, the reader should pay attention to recent publications on the partial Mantel test that investigate its statistical properties (Oden & Sokal, 1992; Legendre, 2000; Raufaste & Rousset, 2001).

TABLE I. Relationships between fire events and remnant forests based on Pearson's correlation coefficient.

Variables	r	Probability
Fire*Forest	0.2035	0.037 (n = 105; $\nu = n - 2 = 103$)
	0.2035	0.030 (complete randomization)
	0.2035	0.229 (restricted randomization using toroidal shift)
	0.2035	0.417 (Dutilleul's $\hat{M}$ = 18.030; $\nu = \hat{M} - 2$ = 16.030; 15 equidistance classes of 20.308 km each)
	0.2035	0.411 (Dutilleul's $\hat{M}$ = 18.444; $\nu = \hat{M} - 2$ = 16.444; 10 equidistance classes of 30.463 km each)
	0.2035	0.391 (Dutilleul's $\hat{M}$ = 19.882; $\nu = \hat{M} - 2$ = 17.882; 5 equidistance classes of 60.926 km each)

TABLE II. Relationships between fire events and remnant forests based on Mantel and Partial Mantel tests.

Variables	r	Probability (based on 999 randomizations plus the observed value)
Fire*Forest (Mantel)	0.1126	0.1760
Fire*Forest.XY (partial Mantel)	-0.116	0.0001

TABLE III. Significance level of parametric and randomization tests, significant (* < 0.05); not significant: ns.

Test	Sign of the correlation	Parametric	Complete Rand.	Rest. Rand.	Dutilleul
Pearson	+	*	*	ns	ns
Mantel	+			ns	
partial Mantel	-			*	

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Literature cited

Arseneault, D. & S. Payette, 1992. A postfire shift from lichen-spruce to lichen-tundra vegetation at tree line. Ecology, 73: 1067-1081.

Bailey, T. C. & A. C. Gatrell, 1995. Interactive Spatial Data Analysis. Longman Scientific & Technical, Essex.

Balling, R.C., Jr., G. A. Meyer & S. G. Wells, 1992. Climate change in Yellowstone National Park: Is the drought-related risk of wildfires increasing? Climatic Change, 22: 35-45.

Bergeron, Y. & M. D. Flannigan, 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air and Soil Pollution, 82: 437-444.

Bregt, A. K., J. Denneboom, H. J. Gesink & Y. Van Randen, 1991. Determination of rasterizing error: A case study with the soil map of The Netherlands. International Journal of Geographical Information Systems, 5: 361-367.

Christensen, N. L., J. K. Agee, P. F. Brussard, J. Hugues, D. H. Knight, G. W. Minshall, J. M. Peek, S. J. Pyne, F. J. Swanson, J. W. Thomas, S. Wells, S. E. Williams & H. A. Wright, 1989. Interpreting the Yellowstone fires of 1988. BioScience, 39: 678-685.

Cliff, A. D. & J. K. Ord, 1981. Spatial Processes: Models and Applications. Pion, London.

Clifford, P., S. Richardson & D. Hémon, 1989. Assessing the significance of the correlation between two spatial processes. Biometrics, 45: 123-134.

Cressie, N. A. C., 1993. Statistics for Spatial Data. J. Wiley & Sons, New York.

Dale, M. R. T. & M.-J. Fortin, 2002. Spatial autocorrelation and statistical tests in ecology. Écoscience, 9: 162-167.

De Grandpré, L., D. Gagnon & Y. Bergeron, 1993. Changes in the understory of Canadian southern boreal forest after fire. Journal of Vegetation Science, 4: 803-810.

Dutilleul, P., 1993. Modifying the *t* test for assessing the correlation between two spatial processes. Biometrics, 49: 305-314.

Elfring, C., 1989. Yellowstone: Fire storm over fire management. BioScience, 39: 667-672.

Fortin, M.-J., 1992. Detection of ecotones: Definition and scaling factors. Ph.D. Thesis. Department of Ecology and Evolution, State University of New York at Stony Brook, New York.

Fortin, M.-J., 1999. Effects of sampling unit resolution on the estimation of spatial autocorrelation. Écoscience, 6: 636-641.

Fortin, M.-J. & J. Gurevitch, 2001. Mantel tests: Spatial structure in field experiments. Pages 308-326 *in* S. M. Scheiner & J. Gurevitch (ed.). Design and Analysis of Ecological Experiments. 2nd edition. Oxford University Press, New York.

Fortin, M.-J. & G. M. Jacquez, 2000. Randomization tests and spatially autocorrelated data. Bulletin of the Ecological Society of America, 81: 201-206.

Fortin, M.-J., P. Drapeau & G. M. Jacquez, 1996. Statistics to assess spatial relationships between ecological boundaries. Oikos, 77: 51-60.

Haining, R., 1991. Bivariate correlation with spatial data. Geographical Analysis, 23: 210-227.

Johnson, E. A., 1978. Fire recurrence in the subarctic and its implications for vegetation composition. Canadian Journal of Botany, 57: 1374-1379.

Legendre, P., 1993. Spatial autocorrelation: Trouble or new paradigm? Ecology, 74: 1659-1673.

Legendre, P., 2000. Comparison of permutation methods for the partial correlation and partial Mantel tests. Journal of Statistical Computation and Simulation, 67: 37-73.

Legendre, P. & M.-J. Fortin, 1989. Spatial pattern and ecological analysis. Vegetatio, 80: 107-138.

Legendre, P. & L. Legendre, 1998. Numerical Ecology. 2nd English edition. Elsevier, Amsterdam.

Manly, B. F. J., 1997. Randomization, Bootstrap and Monte Carlo Methods in Biology. 2nd edition. Chapman & Hall, London.

Mantel, N., 1967. The detection of disease clustering and a generalized regression approach. Cancer Research, 27: 209-220.

Oden, N. L. & R. R. Sokal, 1992. An investigation of three-matrix permutation tests. Journal of Classification, 9: 275-290.

Payette, S. & R. Gagnon, 1985. Late Holocene deforestation and tree regeneration in the forest-tundra of Québec. Nature, 313: 570-572.

Payette, S., M.-J. Fortin & I. Gamache, 2001. The subarctic forest-tundra: The anatomy of a biome in a changing climate. BioScience, 51: 709-719.

Payette, S., C. Moreau, L. Sirois & M. Desponts, 1989. Recent fire history of the northern Québec biomes. Ecology, 70: 656-673.

Raufaste, N. & F. Rousset, 2001. Are partial Mantel tests adequate? Evolution, 55: 1703-1705.

Romme, W. H. & D. G. Despain, 1989. Historical perspective on the Yellowstone fires of 1988. BioScience, 39: 695-699.

Smouse, P. E., J. C. Long & R. R. Sokal, 1986. Multiple regression and correlation extensions of the Mantel test of matrix correspondence. Systematic Zoology, 35: 627-632.

Torn, M. S. & J. S. Fried, 1992. Predicting the impacts of global warming on wildland fire. Climatic Change, 21: 257-274.

Turner, M. G., W. W. Hargrove, R. H. Gardner & W. H. Romme, 1994. Effects of fire on landscape heterogeneity in Yellowstone National Park, Wyoming. Journal of Vegetation Science, 5: 731-742.

Upton, G. J. G. & B. Fingleton, 1985. Spatial Data Analysis by Example. Volume 1: Point Pattern and Quantitative Data. J. Wiley & Sons, New York.

van der Knaap, W. G. M., 1992. The vector to raster conversion: (Mis)use in geographical information systems. International Journal of Geographical Information Systems, 6: 159-170.

Ver Hoef, J., N. Cressie, R. N. Fisher & T. J. Case, 2001. Uncertainty and spatial linear models for ecological data. Pages 214-237 *in* C. Hunsaker, M. Goodchild, M. Friedl & T. Case (ed.). Spatial Uncertainty in Ecology: Implications for Remote Sensing and GIS Applications. Springer-Verlag, New York.