

Spatial stochastic modeling of resin yield from pine stands

Nikos Nanos, Wubalem Tadesse, Gregorio Montero, Luis Gil, and Ricardo Alia

Abstract: The spatial structure of resin-yield in maritime pine stands in central Spain was studied on two different scales and with data from two tapping periods (1998 and 1999). For the fine scale, Moran's I and the K function were used to study within-stand spatial variation. We found that in one plot, trees separated by distances of less than 5 m had similar production. The K function results showed that the distribution of trees did not depart significantly from complete spatial randomness. For a much larger scale, data was available from 37 and 59 ten-tree plots for years 1998 and 1999, respectively. Partial (monthly) yields were also measured. The experimental variograms for the mean plot production showed that a large percentage of the total variance was spatially structured. Furthermore, the experimental variograms for the partial yields revealed changes in the spatial structure of this phenomenon within the same year. Spatial stochastic modeling was shown to be an effective and economic modeling strategy. Temporal variation should be included in future work, with the use of geostatistical space-time models.

Résumé : La structure spatiale de la production de résine dans les peuplements de pin maritime du centre de l'Espagne a été étudiée à deux échelles différentes avec les données de deux périodes d'entaillage (1998 et 1999). À petite échelle, la fonction I de Moran et la fonction K ont été utilisées pour étudier la variation spatiale à l'intérieur du peuplement. Dans une parcelle, nous avons observé que les arbres distants de moins de 5 m avaient une production similaire. Les résultats de la fonction K montrent que la distribution des arbres ne s'écarte pas significativement d'une distribution spatiale entièrement aléatoire. À une échelle beaucoup plus grande, les données provenant de 37 et 59 parcelles composées de 10 arbres étaient respectivement disponibles pour les années 1998 et 1999. La production mensuelle avait aussi été mesurée. Les variogrammes expérimentaux de la production moyenne par parcelle montrent qu'une forte proportion de la variance totale possède une structure spatiale. De plus, les variogrammes expérimentaux de la production mensuelle révèlent qu'il y a des variations dans la structure spatiale du phénomène au cours d'une même année. La modélisation spatiale stochastique s'est avérée une stratégie économique et efficace. La variation temporelle devrait être prise en compte dans les travaux futurs en utilisant des modèles géostatistiques spatio-temporels.

[Traduit par la Rédaction]

Introduction

Resin extraction from pine stands constituted a basic income source in the past for many rural populations all over the world. Species such as maritime pine (*Pinus pinaster* Ait.) and Aleppo pine (*Pinus halepensis* Mill.) have been systematically tapped in the Mediterranean basin since the beginning of the 20th century. In 1965 the international crisis in natural-resin prices rendered its extraction unprofitable, and tapping was practically abandoned; the decline was mainly attributed to increased production costs and intense international competition in the sector.

Our knowledge about the nature of resin production is limited, despite long-standing scientific interest, with research traditionally been focused on genetic improvement (Sehgal and Chauhan 1995; Tadesse et al. 2001) and tapping methods (Hodges and Johnson 1997). Factors that have been reported as controlling the annual resin yield include face orientation (Sheikh 1984), diameter at breast height (Chaudhari et al. 1992), total height (Brito et al. 1982), tapping season, summer temperatures, and evapotranspiration (Deshmukh 1966). Elevated summer temperatures facilitate flux from resin ducts and increase the production, while the occurrence of rainfall immediately after streaking diminishes the production. The combination of environmental factors in space and time and their interaction with stand dynamics and face treatment are the main causes of variability in yield.

Deterministic modeling of the annual or monthly yield of a pine stand can prove to be a laborious task as various environmental factors have to be controlled. A stochastic model, on the other hand, is a more appealing approach to complex environmental phenomena such as the one we are dealing with. While stochastic models do not offer any type of cause-effect relationships, they can be advantageous at the first stages of modeling. Stochastic models should be considered as alternative approaches until more elaborate ones become available (Kyriakidis and Journel 1999).

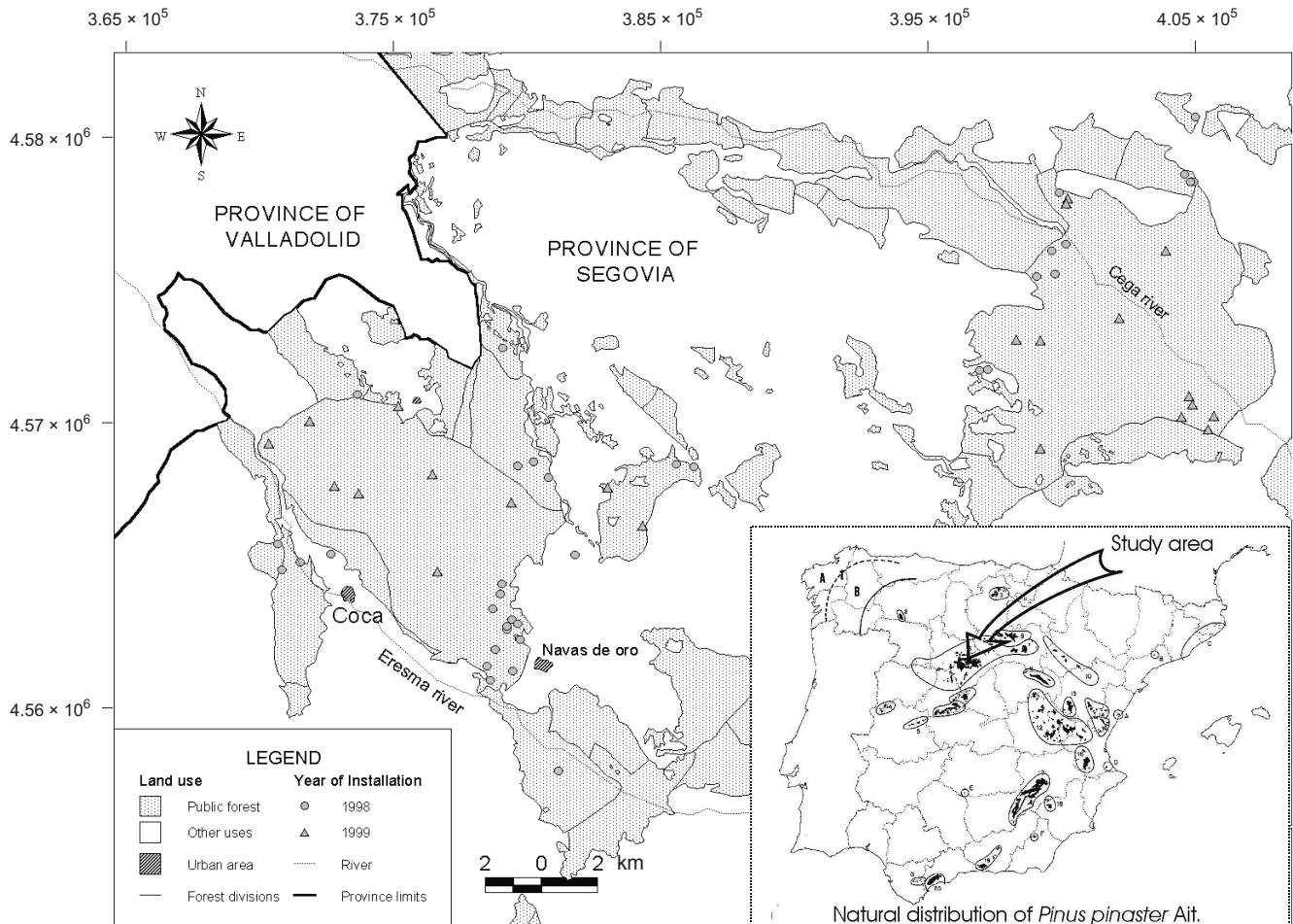
Received July 19, 2000. Accepted February 16, 2001.
Published on the NRC Research Press Web site at
<http://cjfr.nrc.ca> on June 19, 2001.

N. Nanos¹ and G. Montero. Department of Silviculture, Centro de Investigación Forestal – Instituto Nacional de Investigaciones Agrarias, Apdo 8111, 28080 Madrid, Spain.

W. Tadesse and R. Alia. Department of Breeding and Biotechnology, Centro de Investigación Forestal – Instituto Nacional de Investigaciones Agrarias, Apdo 8111, 28080 Madrid, Spain.

L. Gil. Unit of Physiology and Genetics, Escuela Técnica Superior de Ingenieros de Montes, 28040, Madrid, Spain.

¹Corresponding author (e-mail: nanos@inia.es).

Fig. 1. Location of experimental plots. Coordinates (x and y) are UTM (zone 30).

An important aspect of a spatial model is the scale of study. In the case of resin yield, we consider of interest both the within-stand variability of the individual yield, and the among-stand variability of the mean stand production.

Intuitively, within-stand variability can be a result of both genetic and environmental factors. It has been observed that the resin-yield distribution is usually skewed to the high yield classes deviating from normality (Peters 1971; Nanos et al. 2000), but no work has been reported on the spatial arrangement of variability. Within-stand spatial variation for other variables of interest has been explored with spatial autocorrelation indices and the analysis of spatial point pattern. The former have mainly been employed in the study of spatial association in tree growth (Czaplewski et al. 1994; Liu and Burkhart 1994) and the latter in the study of variation in tree size (Moeur 1997), competition (Szwagrzyk and Czerwczak 1993), natural regeneration (Szwagrzyk 1990), fire-induced changes (Rebertus et al. 1989), and sex expression in silver maple (*Acer saccharinum* L.) (Sakai and Oden 1983).

A second and larger scale of spatial variability can be considered among plots of either different or the same stands, which stems largely from variations in environmental conditions. On this scale the average production is of interest rather than the individual yield. The mean stand resin

yield considered as a regionalized variable can be studied and modeled using geostatistics (Matheron 1963). Compared with classical statistical prediction, geostatistical estimations are generally much cheaper to obtain, since no additional covariates need to be measured. This property makes geostatistics an interesting tool for modeling a low-value natural resource such as resin.

A classical deterministic model for the average resin production would have to include climatic parameters as explanatory variables and would be able to resolve many questions about the influence of the environment on the resin yield. Nevertheless, predictions with such a model would require a network of meteorological monitoring stations that is not available (at least not for the desired resolution) in the study area.

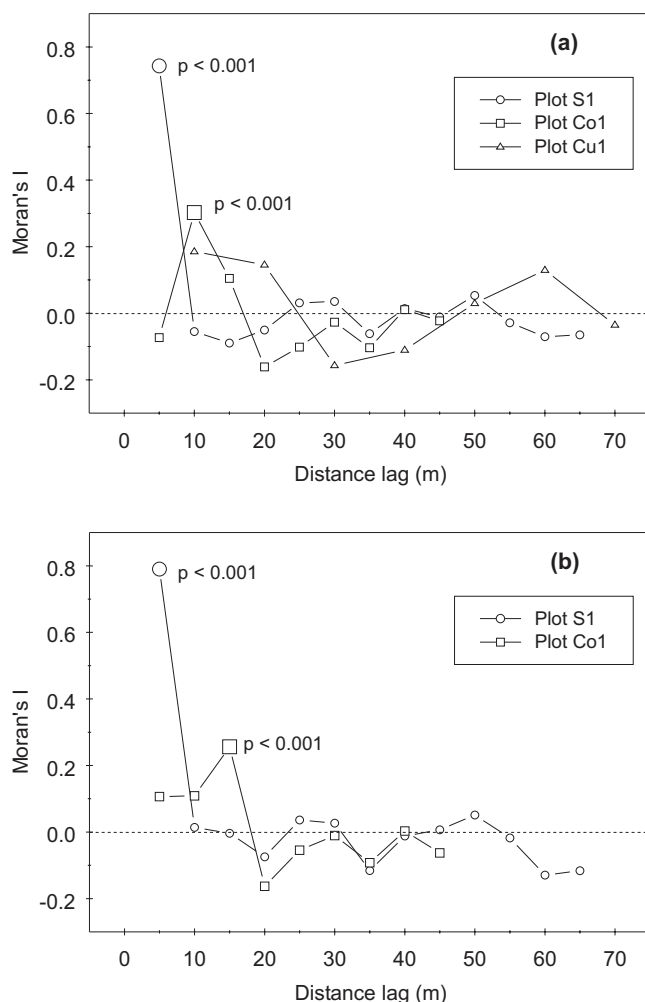
This paper is mainly concerned with the study of the spatial variability and modeling of resin yield, while some temporal aspects are also discussed. The objectives are (i) to explore the within-stand spatial structure and (ii) to study and predict the mean stand production.

Materials and methods

Study area

All study sites were located in pure, natural maritime pine

Fig. 2. Moran's I index for the three studied plots as a function of lag-distance between trees for (a) 1998 and (b) 1999. Data for plot Cu1 in 1999 could not be collected because of technical problems. The broken line indicates the expectation of Moran's I under no spatial association.



stands of the "Tierra de Pinares" of Segovia (central Spain); these are the only stands that are still tapped in Spain. The maritime pine formations of the area are very homogeneous, both genetically (Salvador et al. 2000) and ecologically (Alía et al. 1996). The terrain is flat, providing ideal conditions for resin tapping but the soil is very poor and consists mainly of dunes.

Data

Data was collected over two tapping periods (May to October of 1998 and 1999). Within-stand variation was studied in three rectangular plots (S1, Co1, and Cu1) of varying size; the first consisted of 100 trees while the rest had 50 trees each. Data for the third plot (Cu1) could not be collected in 1999 because of technical problems. Locations of all trees in each of the plots were determined with a compass and an electronic distance-measuring device. No slope corrections were necessary.

Among-stand variation was studied using a separate data set. The total number of available plots during the first tapping period was 37, while this set increased to 59 for the 1999 data. Each plot consisted of 10 trees. The exact plot locations were determined with the global positioning system (GPS) (Fig. 1). The spatial distribution of plots was not ideal for a geostatistical analysis, because

it was mandatory to consider plots only in compartments with trees of large diameter at breast height (more than 35 cm). This was due to the fact that resin tapping begins only when the tree reaches this diameter. In Fig. 1, two groups of plots can be distinguished. The group on the lower left, which has the most plots, corresponds to the "Coca" forest unit, whilst the other group is from the "Cuellar" unit.

Bark chipping with application of acid paste was used for extraction, following the same protocol for all trees. Annual resin production was weighed in the field during the five field trips carried out each year (every 30–40 days). By the end of the tapping period data was available from five partial productions, corresponding to the following time periods: (i) May–June; (ii) July; (iii) August; (iv) September; and (v) October.

Statistical analysis

Within-stand spatial variation

Moran's I is a scalar statistic that measures the degree of spatial dependence of an attribute y , which has been measured at discrete locations (i, j) in space:

$$[1] \quad I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (y_i - \bar{y})(y_j - \bar{y})}{\left(\sum_{i=1}^n (y_i - \bar{y})^2 \right) \left(\sum_{i \neq j} w_{ij} \right)}$$

where w_{ij} is a weight equal to the inverse of the distance between points i and j , n is the number of data points, and $\bar{y}$ is the mean value of y .

Moran's I was computed within distance lags (5-m lags were used for plots S1 and Co1 and 10-m lags for plot Cu1). This index usually lies inside the $[-1, 1]$ interval, and under the null hypothesis of no spatial association, its expectation is zero. Significant departures from the expected value were checked using the results from 500 random permutations of the sampled values. The Bonferroni's adjustment was used since the realized tests are not independent.

For the point pattern analysis, trees in each plot were divided into two production groups (i.e., low and high production). Individuals that yielded less than the median of the plot were classified as low yielders, while the rest were considered as high-yielding trees. The square-root transformation $L(t)$ of Ripley's original function (Ripley 1977) was then computed for each production group:

$$[2] \quad L(t) = \sqrt{\frac{\hat{K}(t)}{\pi}} - t$$

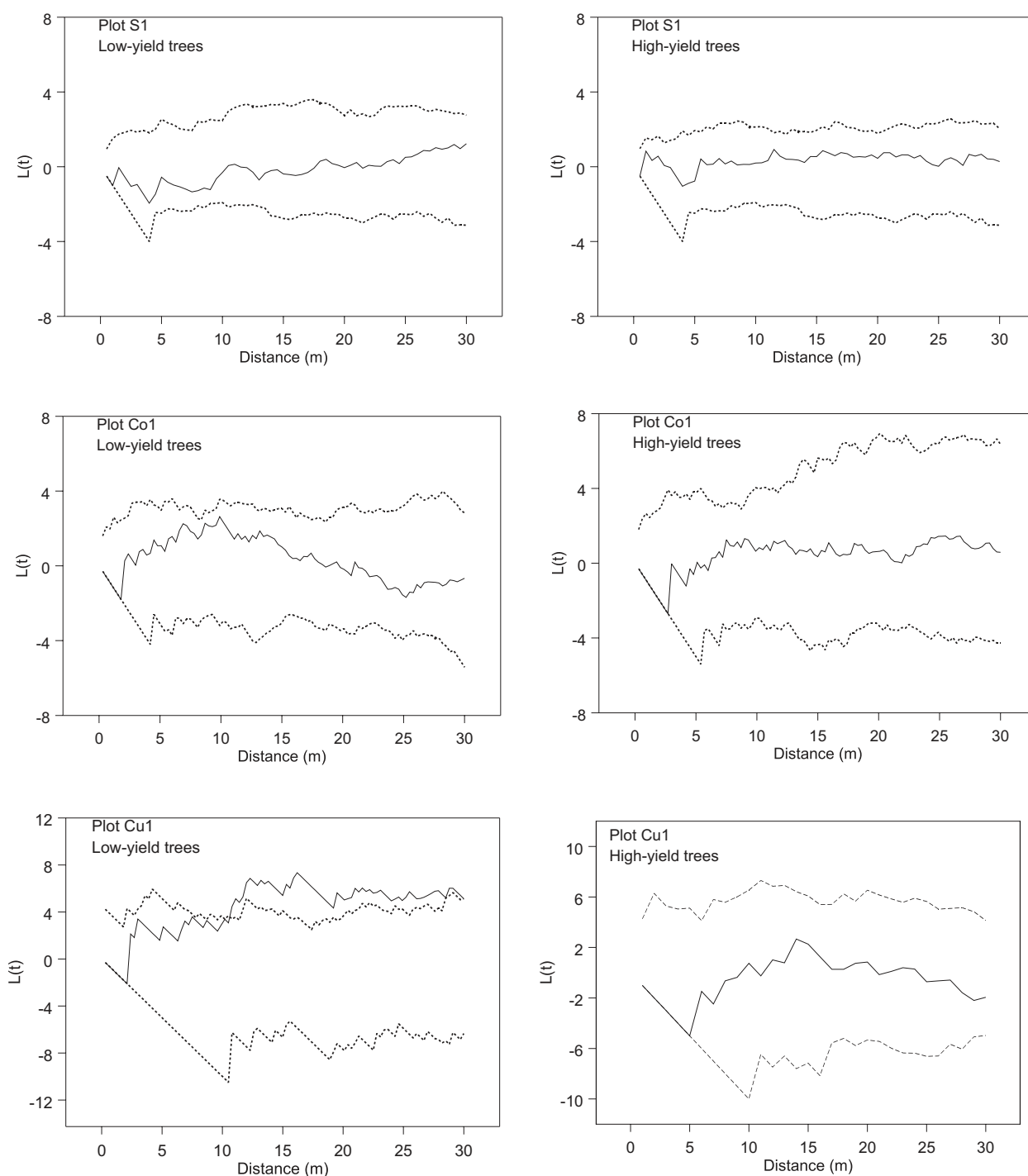
where $\hat{K}$ is the edge-corrected K function for distance t . The expectation of $L(t)$ is zero under the null hypothesis of complete spatial randomness (for details see Besag in the discussion of Ripley (1977)). The significance of deviations of $L(t)$ from complete spatial randomness was checked with 99 realizations of a homogeneous Poisson process. Final graphs of $L(t)$ versus the distance t were produced for each plot and year of study. When the observed $L(t)$ was higher than the upper (or smaller than the lower) confidence envelope, we rejected the null hypothesis in favor of the alternative of clumping (regularity) in the observed spatial pattern.

Among-stand spatial variation

The experimental variograms of mean annual plot production were initially computed using the formula:

$$[3] \quad \hat{\gamma}(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{a=1}^{N(\mathbf{h})} [z(u_a) - z(u_a + \mathbf{h})]^2$$

Fig. 3. $L(t)$ as a function of distance t for high and low yields for each plot. The broken lines indicate the higher and lower Monte Carlo envelopes. Significant clumping was observed only in one plot for low yielders. Only results for 1998 are presented.

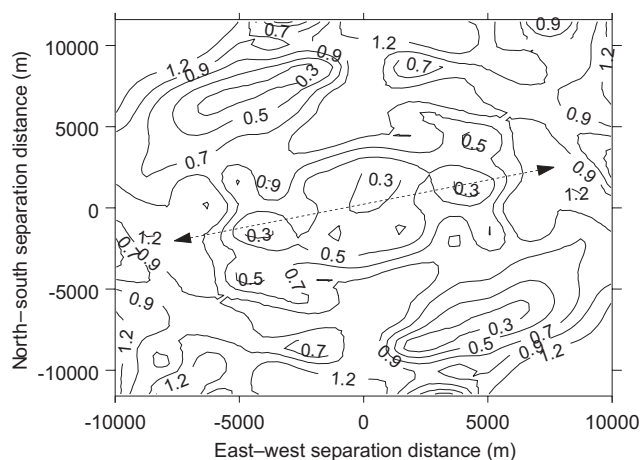


where $N(\mathbf{h})$ is the number of pairs of data locations a vector $\mathbf{h}$ apart, while $z(u_a)$ and $z(u_a + \mathbf{h})$ are measurements at locations u_a and $u_a + \mathbf{h}$, respectively. Variograms were constructed for both years of study, but because of the insufficient number of plots for the first year, the analysis was focused on measurements from the second year.

Anisotropy was detected by variogram maps (Isaaks and Srivastava 1989), which were constructed from directional variograms computed with 40° angular tolerance and 4000 m band-

width. A gridding algorithm was then applied to the resulting variogram values and the directions of maximum and minimum continuity were judged visually. Anisotropy was corrected by rotating clockwise the coordinate system so as to identify the main axes of anisotropy and linearly transforming the rotated coordinates according to the anisotropic variogram model (Isaaks and Srivastava 1989; Goovaerts 1997). Kriging was finally performed in the transformed coordinate system using a global search neighborhood.

Fig. 4. Variogram map of the average annual resin yield. The arrow indicates the direction of maximum continuity.



Intra-annual variation was explored by constructing variograms for each partial yield. Data had previously been standardized to zero mean and unit variance, to facilitate comparisons between partial yields. The main variogram features (i.e., nugget, sill, and range) were judged visually without fitting variogram models.

Results

Within-stand spatial variation

The estimated autocorrelation indices for the three studied plots are shown in Fig. 2. Spatial association was evident in plot S1 for the first lag where Moran's I was equal to 0.74 and 0.79 for years 1998 and 1999, respectively. The 500 random permutations demonstrated the low probability of such values being observed by chance for both years of study ($p < 0.001$). Regarding the plot Co1, similar spatial patterns were not detected, although there was some evidence of slight spatial association at 10 and 15 m distance lag for 1998 and 1999, respectively. In the third plot (Cu1), Moran's I equaled 0.19 ($p > 0.05$) for the 10 m distance lag. The spatial pattern did not change from one year to another.

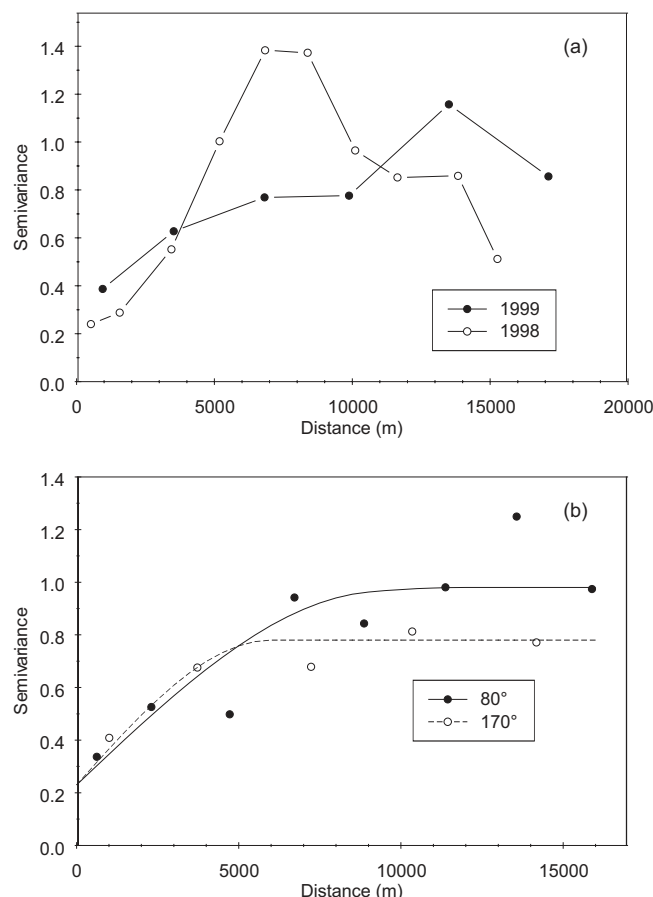
The second-order analysis of spatial point pattern showed that trees in two plots (S1 and Co1) were distributed randomly. Nevertheless, we found significant clumping of low-yield individuals in the third plot at distances larger than 10 m (Fig. 3). It should be noted that this plot was more heterogeneous (large variation in tree age and density) as compared with the other two plots.

Among-stand spatial variation

The omnidirectional experimental variograms for mean plot production are shown in Fig. 5a. The 1998 variogram showed a parabolic behavior near the origin and a hole effect for distances larger than 8 km that could be due to insufficient number of pairs of observations. On the other hand, the 1999 variogram was linear near the origin. The range of spatial correlation was approximately 7 km and the nugget variance 0.25 for both variograms. In the subsequent analysis only measurements from the second year are considered.

Resin yield for 1999 exhibited anisotropy, with the axis of maximum continuity lying approximately in the 80° direction (Fig. 4). The directional variograms computed at 80°

Fig. 5. Variograms of the annual resin yield: (a) omnidirectional variograms for years 1998 and 1999 and (b) directional experimental variograms and models (year 1999).



and 170° , as well as the directional variogram models are presented in Fig. 5b. Their models are the following:

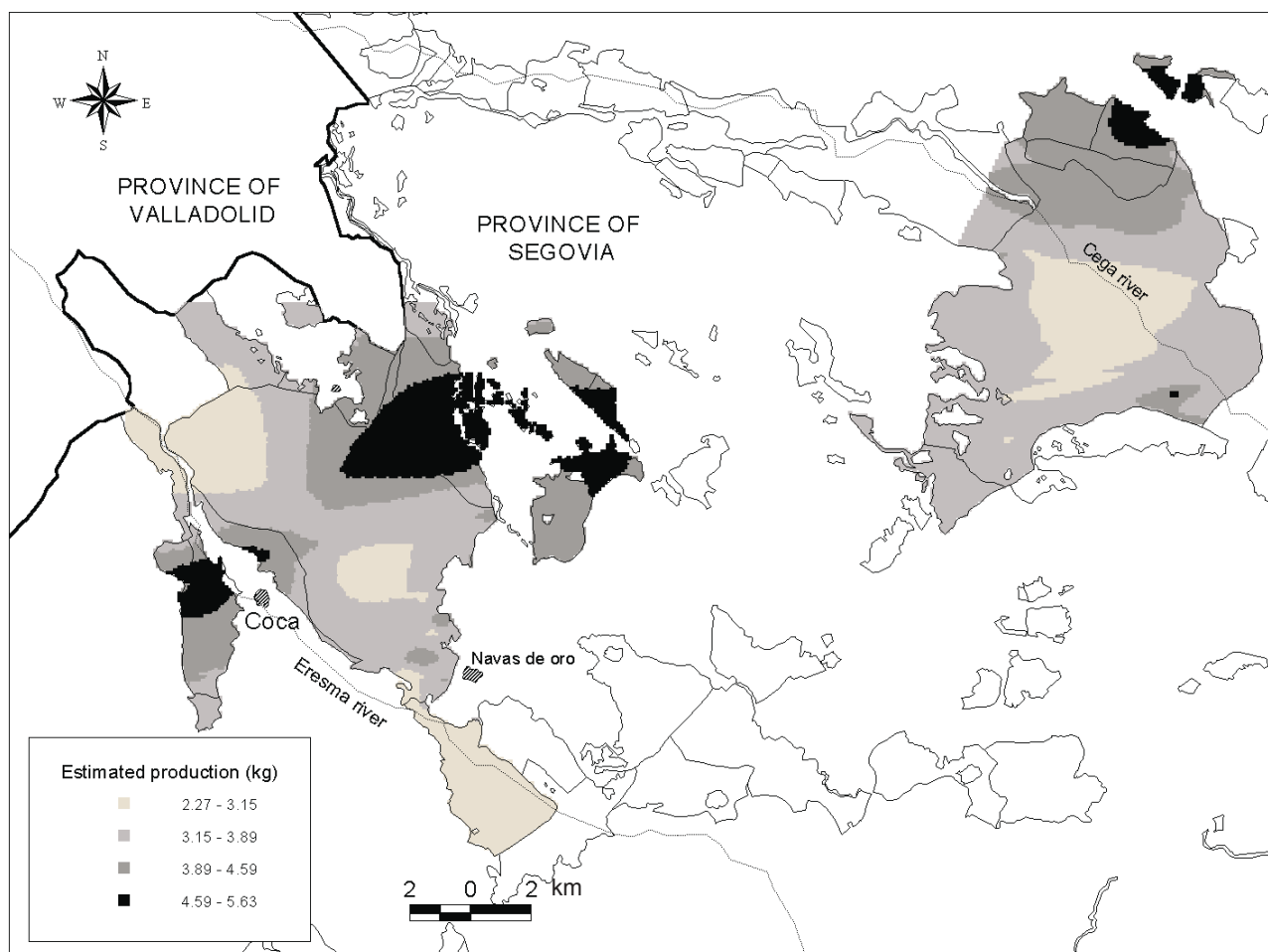
$$[4] \quad \gamma(h_{80}) = 0.23 + 0.55 \times \text{SPHER}_{9000}(h_{80}) + 0.2 \times \text{SPHER}_{12\,000}(h_{80})$$

$$[5] \quad \gamma(h_{170}) = 0.23 + 0.55 \times \text{SPHER}_{6000}(h_{170})$$

where h_{80} and h_{170} are the x and y separation distance in the rotated coordinate system. The variogram model of eq. 4 is composed of a nugget component equal to 0.23, a spherical model (SPHER) with a contribution of 0.55 and a range of 9000 m, and a zonal (spherical) component with a range of 12 000 m and a contribution of 0.2 only in the 80° direction. The variogram model of eq. 5 is composed of a nugget equal to 0.23 and a spherical component with a contribution of 0.55 and a range of 6000 m.

The anisotropic variogram model was finally reduced to an isotropic one of the form

$$[6] \quad \gamma(h') = 0.23 + 0.55 \times \text{SPHER}_{6000}(h_1) + 0.2 \times \text{SPHER}_{12\,000}(h_2)$$

Fig. 6. Kriged map of mean annual resin production for 1999.

by linear transformation of the rotated coordinates. In the transformed coordinate system the distances h_1 and h_2 are computed using the formulas

$$h_1 = \sqrt{(0.66h_{80})^2 + (h_{170})^2}$$

(0.66 is the anisotropy ratio) and $h_2 = h_{80}$.

Finally, a kriged map of the mean resin yield for 1999 was constructed (Fig. 6). An area of high production can be distinguished in the northeastern part of the forest in "Coca." The kriged surface is actually a very smooth one because of the relatively large nugget effect and variogram range.

The variograms for each of the five partial productions indicated some changes in spatial continuity during the 1-year tapping period (Fig. 7). In July the production was higher in "Coca" than in "Cuellar" (400-g difference). This difference can be seen in the experimental variogram of July as a rapid increase in the semivariance when moving from 10 000 to 15 000 m distance. In this case, therefore, it is difficult to infer the spatial covariance and, hence, reach meaningful conclusions as to the spatial continuity of the July partial yield. The smallest range of spatial correlation was observed in May–June (approximately 5000 m), while the largest in August (10 000 m). The relative nugget effect varied too and

was found to be smaller in August (approximately 20%) and larger in September and October (approximately 55%).

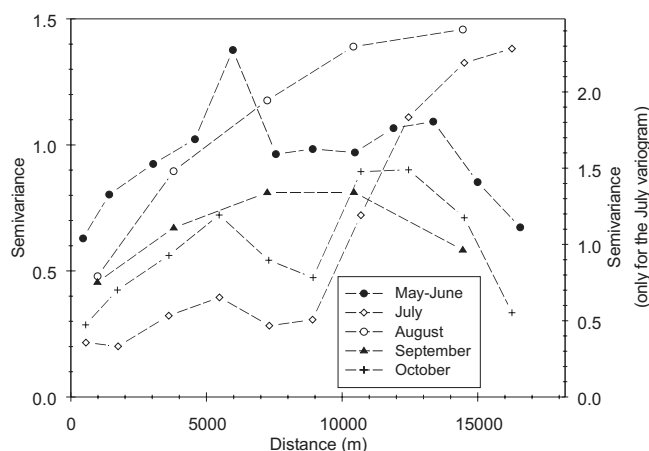
Discussion

Within-stand spatial variation

Within-stand variation does not appear to be spatially structured, at least not for the studied plots. At later stages of the stand development in plot S1, trees that have one or more neighbors at distances from 5 to 7 m will be felled according to the traditional silvicultural practice, and this plot is likely to present a spatial structure similar to that of the other two plots, which are indeed much older and less dense. In any case, the spatial association found at such small spacing can be considered as a random spatial pattern for it has no practical implications.

The significant spatial association in the first lag of plot S1, may be attributed to genetic similarity or microenvironmental factors, since the K function for the same plot, showed no deviations from complete spatial randomness. The alternative hypothesis that similarity is due to competition, is not supported by the results, because should that have been the case, we would have expected clustering for

Fig. 7. Experimental variograms of the five partial yields (data was standardized prior to the variogram computation).



low yielders. The detected clumping for low yielders in plot Cu1, seems to be a local phenomenon. Generally our results indicate that the spatial distribution of trees with respect to their resin yield does not deviate from complete spatial randomness. For other stand variables such as tree size, it has been found that, in some cases, large-sized trees are regularly distributed in space, while small ones tend to be clustered as a result of competition (Moeur 1997).

Among-stand spatial variation

Presently, the only information regarding the production capacity of those stands is given by Allué and Allué (1994) who reported an average production of 3.6 kg/tree. The kriged map in Fig. 6 showed that some stands produce as much as 5.5 kg/tree, while others hardly reach 2.5 kg/tree. The most productive stands can be identified and tapping could be restricted there in an attempt to make extraction more profitable for tappers. Furthermore, since resin and timber are incompatible forest products (resin tapping diminishes the timber quality), kriged maps of resin production combined with stand prediction systems could prove to be useful tools in a spatially optimized and multipurpose forest management plan.

The structural analysis provided some useful insights into the issue and nature of resin yield. The existence of a sill, for example, in the raw variogram indicates that resin production is a transition phenomenon (Chilés and Delfiner 1999). It is usually observed when discontinuities delimit compartments of low and high productivity. The average length of those compartments can be inferred from the range of the raw variogram, which in our case was equal to 12 and 6 km for directions of 170 and 80°, respectively. It is most likely that discontinuities were caused by climatic factors (mainly rainfall and temperature) since the range of spatial correlation was found to vary within the same year using the partial yield variograms. The influence of climatic agents on the resin yield has also been reported in previous studies (Deshmukh 1966).

The annual resin yield presented a large nugget component (approximately 25% of the total sill). According to Chilés and Delfiner (1999), nugget variance can be due to microstructures, variability at distances smaller than the

sampling interval or measurement errors. Very often their relative contribution to the nugget variance cannot be distinguished. This proportion of variation is of great interest to tappers: with the currently applied method (bark chipping) a professional tapper can work with 5000 trees per year, occupying an area of approximately 25–35 ha (density 150–200 trees/ha). The kriged estimates obtained by our sampling scheme will not capture the variability at such a small scale, and for this reason, samples taken from a finer grid will be necessary.

Interannual variability in the resin production has been previously reported (Hodges and Johnson 1997). Intuitively, large-scale variation should be time-dependent when factors that govern the production are mainly climatic. On the contrary, if the main source of variation is due to edaphic agents, it seems logical to assume a constant spatial structure over a period of time. Interannual variability cannot be captured in the kriged map of Fig. 6, since only 1 year of data was available; therefore, data taken over larger time periods will be required for the construction of a definite resin production map. Temporal variation complicates the modeling process but should be considered in future work using the extension of geostatistics to include time as an additional dimension (Houllier and Pierrat 1992; Stein et al. 1998; Kyriakidis and Journel 1999).

On the other hand, the main features of the spatial structure varied within the year. With the exception of the July variogram, where a trend was identified, the rest of the partial-yield variograms are useful for drawing conclusions on the way the production varied in space and time. The production was more continuous in space during August, since the relative nugget effect was smaller. All the short-range factors that control production were probably rendered insignificant by the elevated temperatures experienced in August. The smallest variogram range during May and June combined with the large relative nugget imply that the production was less continuous (small-scale oscillations in the production were large). The production during these months is usually less compared with the rest of the year and may be greatly influenced by short-range environmental factors such as water availability and local frosts.

In forestry there has been relatively little research into geostatistical prediction of stand attributes. Other variables that have been successfully predicted with geostatistics are the site index (Hock et al. 1993) of *Pinus radiata* Donn. ex D. Don, total tree height (Samra et al. 1989), timber volume (Holmgren and Thuresson 1997), tree stem size and increment (Biondi et al. 1994), stand density (Mandallaz 2000), and parameters of diameter distribution models (Nanos and Montero 2002). To our knowledge, this is the first attempt to spatially model a nontimber forest product. Geostatistics could be used in the future for modeling other similar products (cork, stone pine kernels, or other gum extractives), which, being affected by climatic and soil conditions, are expected to exhibit autocorrelation in space.

Acknowledgments

The authors thank the Junta de Castilla y León for the technical support. We are also grateful to Prof. Alfred Stein, an anonymous referee, and Marta Pardos for their comments

on the manuscript. Irena T. Farrel and Barbara Vamvoura improved the English version and Francisco Javier Auñón helped in data collection. This work was funded by INIA, project SC97-118 and a grant from Sofia Chlorou foundation and the National Technical University of Athens.

References

- Alía, R., Martín, S., De Miguel, J., Galera, R., Agúndez, D., Gordo, J., Salvador, L., Catalán, G., and Gil, L. 1996. Las regiones de procedencia de *Pinus pinaster* Ait. Dirección General de Conservación de la Naturaleza, Madrid.
- Allué, C., and Allué, M. 1994. Notas sobre la marcha ordenada del monte "Pinar Viejo" (Coca, Segovia) I, Actas de la reunión de Valsain. Sociedad Española de Ciencias Forestales, Madrid. pp. 295–306.
- Biondi, F., Myers, D.E., and Avery, C.C. 1994. Geostatistically modeling stem size and increment in an old-growth forest. *Can. J. For. Res.* **24**: 1354–1368.
- Brito, J.O., Barrichelo, L.E.G., do Couto, H.T.Z., Capitani, L.R., and Neves, M.A. 1982. Método rápido para estimar a produção de resina em árvores de *Pinus*. Instituto de Pesquisas e Estudos Florestais, São Paulo, Brazil, Circ. Tec. 148.
- Chaudhari, D.C., Goel, C.L., Joshi, B.D., Uniyal, D.N., Bist, R.S., and Prasad, A. 1992. Correlation between diameter and resin yield by the rill method of tapping. *Ind. For.* **118**: 456–459.
- Chilés, J.P., and Delfiner, P. 1999. Geostatistics: modeling spatial uncertainty. John Wiley & Sons, New York.
- Czaplewski, R.L., Reich, R.M., and Bechtold, W.A. 1994. Spatial autocorrelation in growth of undisturbed natural pine stands across Georgia. *For. Sci.* **40**: 314–328.
- Deshmukh, D.K. 1966. Characterization of Chir pine (*Pinus roxburghii* Sargent) for resin yielding capacities. *Ind. For.* **92**(June): 368–390.
- Goovaerts, P. 1997. Geostatistics for natural resources evaluation. Oxford University Press, New York.
- Hock, B.K., Payn, T.W., and Shirley, J.W. 1993. Using a geographic information system and geostatistics to estimate site index of *Pinus radiata* for Kaingaroa Forest, New Zealand. *N.Z. J. For. Sci.* **23**: 264–277.
- Hodges, A.W., and Johnson, J.D. 1997. Borehole oleoresin production from slash pine. *South. J. Appl. For.* **21**: 108–115.
- Holmgren, P., and Thuresson, T. 1997. Applying objectively estimated and spatially continuous forest parameters in tactical planning to obtain dynamic treatment units. *For. Sci.* **43**: 317–326.
- Houllier, F., and Pierrat, J.C. 1992. Application des modèles statistiques spatio-temporels aux échantillonnages forestiers successifs. *Can. J. For. Res.* **22**: 1988–1995.
- Isaaks, E.H., and Srivastava, R.M. 1989. An introduction to applied geostatistics. Oxford University Press, New York.
- Kyriakidis, P.C., and Journel, A.G. 1999. Geostatistical space-time models: a review. *Math. Geol.* **31**: 651–684.
- Liu, J., and Burkhart, H.E. 1994. Spatial autocorrelation of diameter and height increment predictions from two stand simulators for loblolly pine. *For. Sci.* **40**: 349–356.
- Mandallaz, D. 2000. Estimation of the spatial covariance in universal kriging: application to forest inventory. *Environ. Ecol. Stat.* **7**: 263–284.
- Matheron, G. 1963. Principles of geostatistics. *Econ. Geol.* **58**: 1246–1266.
- Moeur, M. 1997. Spatial models of competition and gap dynamics in old-growth *Tsuga heterophylla*/*Thuja plicata* forests. *For. Ecol. Manage.* **94**: 175–186.
- Nanos, N., and Montero, G. 2002. Spatial prediction of diameter distribution models. *For. Ecol. Manage.* In press.
- Nanos, N., Tadesse, W., Montero, G., Gil, L., and Alía, R. 2000. Modelling resin production distributions for *Pinus pinaster* Ait using two probability functions. *Ann. For. Sci.* **57**: 369–377.
- Peters, J.W. 1971. Variation in oleoresin yielding potential of selected slash pines. *For. Sci.* **17**: 306–307.
- Rebertus, A.J., Williamson, G.B., and Moser, E.B. 1989. Fire-induced changes in *Quercus laevis* spatial pattern in Florida sandhills. *J. Ecol.* **77**: 638–650.
- Ripley, B.D. 1977. Modelling spatial patterns. *J. R. Stat. Soc. B*, **39**: 172–212.
- Sakai, A.K., and Oden, N.L. 1983. Spatial pattern of sex expression in silver maple. *Am. Nat.* **122**: 489–508.
- Salvador, L., Alía, R., Agúndez, D., and Gil, L. 2000. Genetic variation and migration pathways of maritime pine (*Pinus pinaster* Ait) in the Iberian peninsula. *Theor. Appl. Genet.* **100**: 89–95.
- Samra, J.S., Gill, H.S., and Bhatia, V.K. 1989. Spatial stochastic modeling of growth and forest resource evaluation. *For. Sci.* **35**: 663–676.
- Sehgal, R.N., and Chauhan, S.K. 1995. Genetic improvement research on *Pinus roxburghii* in the last two decades—a review. *Ind. J. For.* **18**: 107–114.
- Sheikh, M.I. 1984. Face positions yield different quantities of resin from *Pinus roxburghii*. *Pak. J. For.* **34**: 97–100.
- Stein, A., Van Groenigen, J.W., Jeger, M.J., and Hoosbeek, M.R. 1998. Space-time statistics for environmental and agricultural related phenomena. *Environ. Ecol. Stat.* **5**: 155–172.
- Szwagrzyk, J. 1990. Natural regeneration of forest related to the spatial structure of trees: a study of two forest communities in the western Carpathians, southern Poland. *Vegetatio*, **89**: 11–22.
- Szwagrzyk, J., and Czerwczak, M. 1993. Spatial patterns of trees in natural forests of east-central Europe. *J. Veg. Sci.* **4**: 469–476.
- Tadesse, W., Nanos, N., Auñón, F.J., Arrabal, C., García, C., Gil, L., Alía, R., and Pardos, J.A. 2001. Genetic improvement of resin yield from maritime pine in Spain. *For. Chem. Rev.* **Jan.–Feb.**: 10–16.