Cuad. Soc. Esp. Cienc. For. 37: 43-48 (2013) «Actas de la VIII Reunión sobre Ordenación de Montes»

DYNAMIC TREATMENT UNITS: FLEXIBLE AND ADAPTIVE FOREST MANAGEMENT PLANNING BY COMBINING SPATIAL OPTIMIZATION METHODS AND LiDAR

Rodales dinámicos: combinando métodos de optimización espacial y LiDAR en la planificación forestal para una gestión forestal adaptativa y flexible

Sergio de Miguel Magaña [1], Timo Pukkala [1] y Javier Pasalodos Tato [2]

[1] Faculty of Science and Forestry, University of Eastern Finland. P.O. Box 111. 80101-JOENSUU (Finland). E-mail: sergio.demiguel@uef.fi
[2] Universidad de Santiago de Compostela. Departamento de Ingeniería Agroforestal. Escuela Politécnica Superior. c/Benigno Ledo s/n. Campus universitario. 27002-LUGO (España)

Summary

Modern forest planning needs to take into account several management objectives and to be capable to adapt to new situations. As the forest management objectives vary spatially and temporally, analytical tools are required in order to obtain optimal prescriptions according to the objectives and production potential of a given forest system. Combining optimization methods and new remote sensing technologies (LiDAR) allows one to tackle in a flexible and accurate way the abovementioned challenges. This article summarizes a case study for *Pinus radiata* plantations. A metaheuristic optimization method was used in spatial optimization by utilizing information generated by means of LiDAR in order to produce dynamic treatment units (DTU). This approach considers that forest stand compartments are not fixed and predefined. Forest compartments are created by means of spatial optimization techniques. The basic computation units are raster cells. Previous research has shown that this approach can provide logical and suitable forest management units, and can increase the efficiency of the use of forest resources.

Keywords: *Simulated annealing, Forest-level optimization, Laser scanning, Remote sensing, Sustainable forest management, Pinus radiata*

Resumen

En la planificación forestal moderna es necesario considerar múltiples objetivos de gestión y la capacidad de adaptarse ágilmente a escenarios cambiantes. Los objetivos de gestión forestal varían espacial y temporalmente. Es, por tanto, necesario el uso de herramientas analíticas para obtener prescripciones óptimas acordes con los objetivos de gestión y el potencial productivo del bosque. El uso de técnicas de optimización numérica en combinación con las nuevas tecnologías de teledetección (LiDAR) permite abordar de manera flexible y precisa los desafíos previamente mencionados. Este artículo resume un caso de estudio para plantaciones de *Pinus radiata*. Se utiliza un método

ISSN: 1575-2410

metaheurístico de optimización espacial a partir de información generada mediante LiDAR para producir unidades dinámicas de tratamiento silvícola a las que denominamos “rodales dinámicos”. Los fundamentos de este enfoque son: 1) no existen unos rodales fijos y predefinidos, 2) los rodales se crean mediante optimización espacial, 3) las unidades básicas de cálculo son píxeles raster. La aplicación de este enfoque en estudios anteriores ha generado unidades lógicas y adecuadas de gestión forestal, y ha incrementado la eficiencia en el uso de los recursos forestales.

Palabras clave (en español): *Plantación forestal, Ordenación de montes, Optimización a escala de monte, Teledetección, Gestión forestal sostenible, Pinus radiata*

INTRODUCTION

Modern forest inventory and planning is based on the division of a target forest area into homogeneous stand compartments according to multiple criteria (e.g., stand age, species composition, site quality). Stand compartments constitute the basic management and planning units and they are often considered as fixed (Packalén et *al.*, 2011). Although this has been the traditional planning approach (see Judeich, 1887; Speidel, 1893) in many countries, it has been more recently integrated to the current planning methods in Spain. The main reason for the adoption of this approach is flexibility of the forest planning process (Garitacelaya, 2008). However, is this flexible enough to organize silvicultural and harvesting operations in a more efficient way? Possibly not. Fixed and predefined stand limits may make it difficult to cope with the within-forest and within-stand complexity to maximize the management objectives considered in a forest plan. For example, stand compartments may have within-stand variation in terms of fire risk, scenic beauty, site quality or growing stock volume. Accordingly, Holmgren & Thuresson (1997) questioned the current stand concept arguing that, in real life, forest and stand attributes are described by continuous functions defined on a continuum, and planning parameters may change over time. In consequence, it may be more efficient to allow for different treatments in different areas of a given stand according to the management objectives and stand development stage. One possibility is to consider micro-segments or raster cells which divide a forest and its stands into smaller units which constitute the basic calculation items. These units can be aggregated or dispersed in a flexible way aiming at a specific spatial pattern of treatments or forest features. Depending on the evolution of the forest at every calculation unit, these items can be reorganized into different stand compartments of varying size and shape in successive silvicultural operations. Therefore, these stand compartments are not fixed and predefined anymore, and this is why they can be called dynamic treatment units (DTU). The basic calculations units can be related and rearranged into DTU on a scientific basis by means of spatial optimization techniques. Heinonen et *al.* (2007) and Packalén et *al.* (2011) have shown that using DTU instead of the traditional fixed and predefined forest stand compartments resulted in a more efficient management and a better achievement of the forest management objectives.

This change of paradigm concerning the conception of forest management and planning units (from fixed and predefined to flexible and dynamic) gains additional interest when combined with modern remote sensing techniques. Light Detection And Ranging (LiDAR) technology, often also referred to as Airborne Laser Scanning (ALS), provides planners with forest inventory data for any spatial units, also for raster cells or micro segments. The operational aspects of LiDAR-based inventory and its high accuracy to obtain reliable estimates of forest attributes (e.g., stand basal area, stand volume, mean height) as well as in stand delimitation has already been reported in previous research (see Packalén et *al.*, 2011).

The above-mentioned previous studies on DTU have been carried out in Northern Europe and America. By way of example, in this article we present some preliminary results of the first case study carried out in Spain, which represents an application of the DTU concept to a *Pinus radiata* plantation system in Galicia.

MATERIAL & METHODS

Study Area

Approximately 1.800 hectares located in the municipality of Baamonde, Galicia, north-western Spain, were selected for the study. Moost of the area was covered by *P. radiata* plantations. The study site was defined as a 3,650x11,125 km^2 rectangle according to the following UTM coordinates for the north-western and south-eastern corners, respectively: (596532;4789198) and (600393;4777636).

Optimization methods

A wide range of optimization methods could be used for this purpose, but not so many studies have tackled this topic so far. For aggregating small information units into stand compartments, Holmgren & Thuresson (1997) used a “greedy algorithm”, Lind (2000) utilized simulated annealing, Lu & Eriksson (2000) used genetic algorithm, Öhman (2001) used mixed integer programming, Heinonen et *al.* (2007) tested threshold accepting, Heinonen & Pukkala (2007) applied cellular automaton, and Packalén et *al.* (2011) tried the reduced cost method, all of them on a raster-cell basis. Among the existing optimization approaches, metaheuristics (see Reeves, 1993) have been tested to solve spatial and non-spatial problems in forest planning. Among the metaheuristics methods for combinatorial optimization, simulated annealing (SA) has been proved to perform rather well in previous forest research (e.g., Tarp & Helles, 1997; Bettinger et *al*., 2002; Heinonen, 2007).

Simulated annealing (SA) requires a series of parameters which control the mechanism of the optimization algorithm (Dowsland, 1993). The basic ones are: starting and stopping temperature, cooling schedule, number of iterations (moves) at every temperature. In every iteration, a candidate move, consisting of a random selection of one stand (1-stand neighbourhood) or two stands (2-stand neighbourhood) and a randomly selected treatment schedule for the stand. If the candidate solution improves the value of a given objective function (which represents the forest management objectives), the candidate solution is accepted and it replaces the current solution. In the case that the candidate move does not improve the objective function, it may be still accepted with a probability of $p=\exp((U_{\text{Candidate}} - U_{\text{Current}}) / T_{\text{i}})$, where T_{i} is the current temperature, and U is the value of the objective function. The probability of accepting a candidate solution which is worse than the current one (p) decreases as the optimization process makes progress and as the temperature decreases towards the stopping criterion.

The objective function can be defined by means of a utility function (U), taking values from 0 to 1, which is maximized:

$$\text{Max}\ U = \sum_{k=1}^{K} w_k u_k(q_k)$$

There is a sub-utility function u_k for each objective variable, which removes the units of the original objective variable and scales it to range between 0 and 1. The weight of each objective variable is defined by w_k and all the weights contained in the utility function (U) are usually given is such a way that they sum up to 1.

Settings of the simulated annealing algorithm for the *Pinus radiata* case study

The case study presented in this article for a *Pinus radiata* plantation system aims at maximizing the aggregation of cut cells over a forest management plan period of 10 years with even annual harvests. Accordingly, the utility function (U) was defined by twenty one sub-utility functions, namely, ten sub-utility functions for the annual harvested volumes (18,000 m^3·yr^{-1}), ten sub-utility functions accounting for the spatial objective variable (proportion of cut-uncut border) and one sub-utility function for the ending volume at the end of the 10-year management plan. The basic calculation units were 25x25 m^2 raster cells. The simulation of *P. radiata* stand dynamics was based on the stand-level growth and yield models published by Castedo-Dorado et *al*. (2007) for this species in Galicia, Spain. The required input variables for simulation (dominant height, stand basal area and number of trees per hectare) were estimated at the raster cell level from the LiDAR-based information provided by the National Plan for Aerial Orthophotography (PNOA) with a nominal sampling density of approximately 0,5 measurements$\cdot$m^{-2}. A model for predicting stand age was developed using both stand variables and topographic variables as predictors in order to enable the computations of site index for every cell.

RESULTS & DISCUSSION

An example of the optimal arrangement of treatment units (forest stand compartments) is displayed in Figure 1, the black and the grey areas representing the stand compartments with cuttings in the first year and second year, respectively. It can be seen that the level of aggregation of silvicultural operations in high. However, some treatment units have not been aggregated to larger forest compartments and still remained small and isolated, which is partly due to the fact that the optimization algorithm stopped prematurely due to too high freezing temperature. It can be seen from Figure 2 that the annual proportion of cut-uncut area along the 10-year forest plan did not yet reach a minimum, which means that running the optimization for a longer time may still increase the aggregation of the treatment units. On the other hand, the SA algorithm may perform worse than some alternative methods which are capable of executing more complicated moves and, possibly, be more efficient when dealing with spatial problems (Pukkala & Kurttila, 2004; Pukkala et *al.*, 2009). The optimization method successfully converged to the target annual harvested volume of 18.000 m^3 (Fig. 3). These results show that, based on LiDAR data, it is possible to produce optimal forest plans according to one or multiple management objectives. As Heinonen et *al.* (2007) and Packalén et *al.* (2011) already showed, this approach would also increase the efficiency of forest management and the achievement of the management objectives would increase compared to the traditional forest planning procedures. The above-mentioned higher flexibility and versatility of this approach is also an extra positive feature when aiming at adaptive forest management and planning. In addition, coupled with low-cost LiDAR-based forest inventory methods (when compared to traditional forest inventory), this planning approach may increase the efficiency of the whole planning process. Of course, using optimization techniques and LiDAR in forest management increases to some extent the computational complexity and, therefore, skilled and well trained staff would be needed to properly apply such science-based tools in modern forest planning.

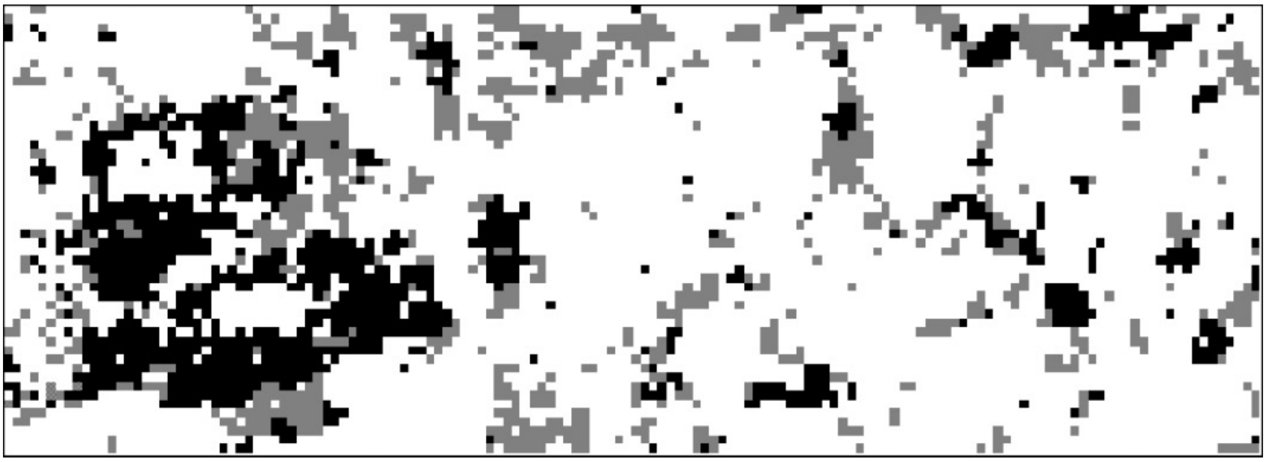

Figure 1*. Example of dynamic treatment units (DTU) for the first and second year of the 10-year forest management plan. Black areas have a cutting proposal in the first year, grey areas in the second year*

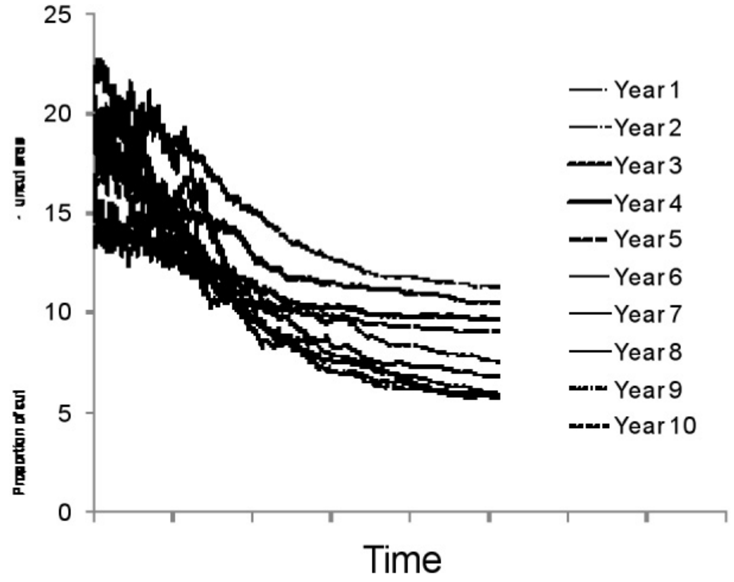

***Figure 2**. Evolution of the proportion of cut-uncut area border during the optimization process for the different years considered in the forest plan. Lower proportion of cut-uncut area implies higher degree of aggregation of cuttings*

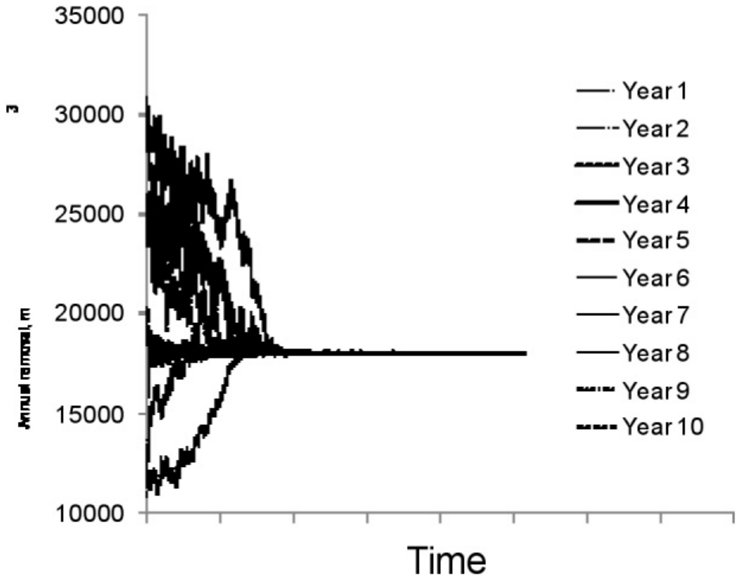

***Figure 3**. Evolution of the annual removal ($m^3\ yr^{-1}$) during the optimization process*

REFERENCES

Bettinger, P.; Graetz, D.; Boston, K.; Sessions, J. & Chung, W.; 2002. Eight heuristic planning techniques applied to three increasingly difficult wildlife planning problems. *Silva Fenn.* 36(2): 561-584.

Castedo-Dorado, F.; Diéguez-Aranda, U. & Álvarez-González, J.G.; 2007. A growth model for Pinus radiata D. Don stands in north-western Spain. *Ann. For. Sci.* 64: 453-465.

Garitacelaya, J.; 2008. La sorprendente historia de cómo se disiparon y desvanecieron los métodos de ordenación de montes. *Cuad. Soc. Esp. Cienc. For.* 27: 95-102.

Heinonen, T.; 2007. Developing spatial optimization in forest planning. University of Joensuu, Faculty of Forestry. *Dissertationes Forestales* 34. 48 p.

Heinonen, T.; Kurttila, M. & Pukkala, T.; 2007. Possibilities to aggregate raster cells through spatial optimization in forest planning. *Silva Fenn.* 41(1): 89-103.

Heinonen, T. & Pukkala, T.; 2007. The use of cellular automaton approach in forest planning. *Can. J. For. Res.* 37(11): 2188-2200.

Holmgren, P. & Thuresson, T.; 1997. Applying objectively estimated and spatially continuous forest parameters in tactical planning to obtain dynamic treatment units. *For. Sci.* 43(3): 317-326.

Judeich, F.; 1918. *La ordenación de montes*. Traducción de la sexta edición alemana (1887) por Eduardo Herbella y Zobel. Madrid.

Lind, T.; 2000. Strategic forestry planning - evaluation of variable spatial aggregations and forest landscapes. Ph.D. thesis. *Acta Universitatis Acriculturae Sueciae Silvestria* 149: 28.

Lu, F. & Eriksson, L.O.; 2000. Formation of harvest units with genetic algorithms. *Forest Ecol. Manage.* 130: 57-67.

Öhman, K.; 2001. Forest planning with consideration to spatial relationships. Doctoral diss. Department. of Forest Resource Management and Geomatics, SLU. *Acta Universitatis agriculturae Sueciae*, *Silvestria* 198: 32.

Packalén, P.; Heinonen, T.; Pukkala, T.; Vauhkonen, J. & Maltamo, M.; 2011. Dynamic Treatment Units in Eucalyptus Plantation. *For. Sci.* 57(5): 416-426.

Pukkala, T. & Kurttila, M.; 2004. Examining the performance of six heuristic optimisation techniques in different forest planning problems. *Silva Fenn.* 39(1): 67-80.

Pukkala, T.; Heinonen, T. & Kurttila, M.; 2009. An application of a reduced cost approach to spatial forest planning. *For. Sci.* 55(1): 13-22.

Dowsland, K.A.; 1993. Simulated annealing. *In*: C.R. Reeves (ed.), *Modern heuristic techniques for combinatorial problems*: 20-63. John Wiley & Sons. Great Britain.

Speidel; 1893. Aus Theorie und praxis der Forstbetriebseinrichtung. *Allgemenie Forst und Jagdzeischrift* 69: 145-181.

Tarp, P. & Helles, F.; 1997. Spatial optimization by simulated annealing and linear programming, *Scand. J. For. Res.* 12(4), 390-402.