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The use of heuristic optimization in risk management of wind damage in forest planning

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Abstract

In this work heuristic techniques were used with a forest growth model (SIMA), mechanistic wind damage model (HWIND) and GIS software (ArcGIS) in order to manage the risk of wind damage in forest planning. The study optimized clear-cut regimes taking into account the risk of wind damage and timber harvest over a 30-year simulation (planning) period in a forest located in central Finland. To demonstrate the effect of management goals related to wind damage, the amount of stand edges at risk was either minimized or maximized with or without even-flow targets of harvested timber. The three heuristic techniques included in the preliminary tests (simulated annealing, tabu search, and genetic algorithms) produced rather similar results for the planning problems. Tabu search performed slightly better than simulated annealing and genetic algorithms, and was therefore used in the subsequent analyses. The optimizations showed that the risk of wind damage could be decreased by aggregating clear-cuts and avoiding clear-cuts at the edge of stands with a high possibility of being damaged. The even-flow timber harvesting objective limited the possibilities of minimizing the risk of wind damage. In addition, the optimization of clear-cut regimes was sensitive to the criterion of critical wind speed that bisected the stands into risky and non-risky ones.

Keywords: Clear-cut; Genetic algorithms; GIS; Integrated approach; Simulated annealing; Tabu search

1. Introduction

Wind-induced damage is a continuous cause of economic loss in forests. For example, in Europe about 180 million m^3 of timber was levelled by wind during storms in December 1999 (UNECE/FAO, 2000). Recently in southern Sweden about 70 million m^3 of timber was lost in a winter storm in 2004 (Nordström, 2005). Also in Finland, over 7 million m^3 of timber was lost in November 2001 (Pellikka and Järvenpää, 2003). The economic impact of wind damage is particularly severe in managed forests due to the reduction in the yield of recoverable timber, increased costs of unscheduled thinning and clear-cutting, and the necessity to deviate from the optimal cutting schedule.

In principle, the susceptibility of a forest stand to wind damage is controlled by tree and stand characteristics, such as tree species, diameter, height and stand density (Coutts, 1986; Gardiner, 1995; Peltola et al., 1999). Since, these characteristics change dynamically along with forest growth, the risk of wind damage will also change (Slodicak, 1995; Zeng et al., 2006). Wind damage is most likely to be found where there are sudden changes in wind loading to which the trees are not acclimatized; such as in stands adjacent to newly clear-cut areas or in stands that have recently been heavily thinned (Neustein, 1965; Lohmander and Helles, 1987; Peltola, 1996a,b; Gardiner et al., 1997; Peltola et al., 1999).

When planning the spatial patterns of clear-cuts and the management of forest edges, the fundamental issue is how clear-cuts affect the local wind speed and direction of airflow at the downwind edges of the clearings, and consequently the level of risk in these conditions (Peltola, 1996a; Venäläinen et al., 2004). The risk of wind damage can be reduced at a regional scale, for example, by avoiding new edges especially in old stands and by cutting the most vulnerable stands (usually old ones, see Zeng et al., 2004). On the other hand, after the closure of regenerated gaps over time (as seedling stands grow), the risk of wind damage at the edges will decrease again (Zeng et al., 2006). Timber production objectives affect the temporal and spatial patterns of clear-cuts, which consequently affect the risk of wind damage.

In recent years, statistical and process-based growth and yield models have been developed to simulate forest growth under

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certain environmental and management conditions (e.g. Kellomäki et al., 1992; Kellomäki and Väisänen, 1997; Matala et al., 2003). Mechanistic wind damage models based on tree and stand characteristics and environmental factors have been developed to predict the wind speeds needed for uprooting or breaking the stems of trees (e.g. Peltola et al., 1999; Gardiner et al., 2000; Ancelin et al., 2004). Recently, Zeng et al. (in press) embedded a forest growth model (SIMA, see Kellomäki et al., 1992) and a mechanistic wind damage model (HWIND, see Peltola et al., 1999) into GIS software ArcGIS to build a decision support system (DSS). The DSS can assess the influence of certain forest management regimes (e.g. clear-cut) on the risk of wind damage at the stand and regional levels. However, it is not yet capable of optimizing the management regimes (timber harvesting) so as to minimize the risk of wind damage.

On the other hand, heuristic optimization techniques are increasingly being used in forest planning (Borges et al., 2002). These techniques include simulated annealing (SA) (e.g. Dahlin and Sallnäs, 1993; Lockwood and Moore, 1993; Öhman, 2000), tabu search (TS) (e.g. Bettinger et al., 1997; Boston and Bettinger, 1999), and genetic algorithms (GA) (e.g. Lu and Eriksson, 2000; Falcao and Borges, 2001). Among others, different variations and combinations of these techniques have also been applied in forestry (Bettinger et al., 1999; Boston and Bettinger, 2002; Falcao and Borges, 2002; Heinonen and Pukkala, 2004). Unlike traditional mathematical programming, heuristic techniques have the potential to solve optimization problems with complicated spatial constraints, which are usually formulated as non-linear 0–1 integer programming problems (Boston and Bettinger, 2002). In the above context, geographical information system (GIS) can serve as a common data and analyses framework (Rao et al., 2000). It can be used to store forest data with spatial attributes, and couple models and techniques together. In addition, GIS defines the topology between polygons (e.g. forest stands) and polylines (e.g. forest edges) so that spatial calculation can be done within the software.

We use, in this work, optimization methods to include the risk management of wind damage into forest planning, in addition to the objectives concerning timber harvest. For this purpose, heuristic optimization techniques were employed together with a forest growth model (SIMA), mechanistic wind damage model (HWIND) and GIS software (ArcGIS). The integrated approach was used to optimize the temporal and spatial patterns of clear-cuts in relation to objectives concerning the risk of wind damage and timber harvest over a 30-year simulation (planning) period in a forest located in central Finland. The risk of wind damage was either minimized or maximized with or without an even-flow target of harvested timber. These problems correspond to maximum and minimum impact of harvests on the risk of wind damage at forest edges.

2. Material and methods

2.1. Study site and forest database

The forest area employed in this study represents a typical boreal forest in central Finland (63°01′N; 27°48′E). It was mostly dominated by Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) stands, but some birch (*Betula* spp.) and other broad-leaved stands were also present. The site was surveyed in 2001 and included 395 ha of forests and 46 ha of open terrain (i.e. lakes, fields and clear-cut areas). The 395 ha of forest consisted of 142 ha Scots pine (76 stands), 225 ha Norway spruce (158 stands), 26 ha of birch (27 stands) and 2.5 ha other broad-leaved species (5 stands). The area has an undulating terrain with some small hills and altitudes ranging between 90 and 170 m above sea level.

In this work, GIS software ArcGIS 9 was used to store forest stands including their boundaries. Since trees located at forest edges were expected to have the highest risk of wind damage in Finnish conditions, only stands adjoining gaps were considered to have risk. The risk of wind damage was represented by the length of vulnerable edges (edges at risk). If a stand adjoined a gap and its critical wind speed was lower than the critical speed criterion (e.g. 20 m s^{-1}), the boundary between the stand and the gap was considered as a vulnerable edge. The relationship between forest stands and their boundaries were based on topology and created in ArcGIS. Each stand boundary segment was appended with its length, and left and right polygon identifiers. They were imported to the optimization algorithm in addition to the forest growth and harvest volume data. The optimal temporal schedule and spatial pattern of the clear-cuts, output by the optimization algorithm, was correspondingly imported to ArcGIS. In this way, all the clear-cut stands and the most vulnerable edges could be visualized on the maps.

2.2. Simulation of treatment alternatives

2.2.1. Simulation of stand dynamics with SIMA

The growth and yield model SIMA (Kellomäki et al., 1992) was used to simulate the growth and yield of treatment alternatives of stands. In the model, the mass growth (including foliage, branches, stem and roots) of each tree in a stand is calculated based on diameter growth, which is limited by temperature conditions and the availability of light, soil moisture and nitrogen (Kellomäki et al., 1992). The mortality of the trees in a stand is controlled both by stand age and minimum allowable growth rate of trees (Kellomäki et al., 1992). After clear-cut the stand was regenerated artificially by giving the initial seedling stand properties regarding tree species, stand density (number of trees per hectare) and diameter of seedlings. The properties of the SIMA model with its parameters and inputs and the validity of its outputs, have been described in detail by Kellomäki et al. (1992), Kolström (1998) and Talkkari et al. (1999).

In this work, we simulated the dynamics (forest growth with or without a clear-cut) of forest stands over a 30-year period. During the 30-year planning period, there may be no clear-cut, or a clear-cut alternatively took place at either the 5th, 15th or 25th year of the simulation. Therefore, each stand might have a maximum of four alternative schedules. The stands, which did not exceed clear-cut criteria at the 5th, 15th or 25th year, had number of alternative schedules less than 4. The criteria, which specified whether a clear-cut was allowed or not, were mean