Remsoft Inc.
332 Brunswick Street,
Fredericton, NB, Canada
E3B 1H1

1-800-792-9468 or
1-506-450-1511

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Simulating process interactions on landscape attributes; fire and spruce budworm in Pukaskwa National Park

Ugo Feunekes, Vice President,
Remsoft Inc.,
332 Brunswick Street
Fredericton, NB Canada E3B 1H1
www.remsoft.com Email: ugo@remsoft.com

I.R, Methven, Professor
Faculty of Forestry
University of New Brunswick
Bag Service #44555
Fredericton, NB Canada E3B 6C3
Email: methven@unb.ca

Summary

Using a model, different amounts of fire were applied to the landscape of Pukaskwa National Park to explore the effect on fire cycle, spruce budworm susceptibility and diversity, Budworm epidemics exerted a positive feedback on the vegetation in terms of susceptibility, but resulted in relatively low levels of diversity. Increasing fire exerted a negative feedback on fuel flammability and rate of increase of the fire cycle. Fire reduced budworm susceptibility below threshold levels, and resulted in an increase in diversity that reached a maximum at an intermediate fire cycle.

1. Introduction

Designating an area of the landscape as a protected area, ecological reserve, or park is an act of management that has ecological consequences. These derive from past human action (1,2), transboundary problems (3), scale incompatibility (4-8), visitor pressures, and protection needs, all of which demand further management action. Such management action, however, needs to flow from explicit goals and objectives related to landscape dynamics. Naturalness *per se* will "not really meet the criterion of a defined management goal" (8).

Landscape dynamics throughout much of the world tend to be a function of exogenous and endogenous processes or disturbances (9,10) which result in a dynamic pattern of communities at different stages of development (11) that Bormann and Likens (12) have termed "the shifting mosaic steady-state". However, this concept implies an equilibrium state while many landscapes tend to be in a state of continual flux and non-equilibrium as a result of fluctuating disturbance regimes and scale effects between disturbances and landscapes (13, 14). Thompson (15) and Pickett and Thompson (16) have coined the phrase "patch dynamics" to capture the concept of non-equilibrium dynamics.

Unfortunately, our knowledge of patch dynamics will always be incomplete, and our ability to express management goals and objectives in terms of patch dynamics is limited. Yet management decisions must continue to be made (no-decision has consequences). While research will improve our understanding, it is often conducted at space and time scales that are irrelevant to management decision-making (17). The only viable approach to this problem, therefore, is the adoption of adaptive management (18-20), an integral component of which is the exploration of management and policy options using computer simulation and modeling approaches. The objective of this study was to simulate the interaction of one exogenous disturbance (fire) and one endogenous disturbance (spruce budworm *Choristomeura fumiferana* predation) on the landscape attributes of Pukaskwa National park in Ontario, Canada.

2. Vegetation and processes of Pukaskwa National Park

Pukaskwa National Park, established as a representative example of the Central Boreal Uplands, is located near the southern edge of the Canadian Shield along the northeast coast of Lake Superior and covers and area of 1,878 km^2

2.1 Forest Vegetation

The vegetation of the park is dominated by upland types composed of black spruce (*Picca mariana)*, jack pine (*Pinus banksiana)*, and white birch (*Betula papyrifera)*. Other species that become important because of site differences or disturbance history are balsam fir (*Abies balsamea)*, trembling aspen (*Populus tremuloides)*, white spruce (*Picea glauca)*, and mountain ash (*Sorbus americana).*

2.2 Dynamics

The dynamics of Pukaskwa National Park are dominated by two major processes; fire as an exogenous physical process, and spruce budworm predation as an endogenous biological process.

2.2.1 Fire

Fire acts as a forcing function on the system one that plays a very important ecological role in the boreal forest in general (21-27), and in the park in particular. Evidence includes charcoal horizons, fire-scarred trees, historical records, and the dominance of fire adapted species such as black spruce, jack pine, white birch, and trembling aspen. Yet the landscape of the park has been under a fire exclusion policy for many decades, first under the jurisdiction of the province of Ontario, and since 1978 under the jurisdiction of the Canadian Park Service. Fire has been recognized as an integral process in the park, and management plans are being developed to incorporated the use of prescribed fire.

Fire cycles across the whole range of the boreal forest range from 50 to 150 years (21) with the higher cycles tending to be associated with lowlands or more humid eastern forests. Van Wagner (28) analyzed data from two sources in Minnesota and Alberta and found a 50 year fire cycle for both. An analysis of the age class distributions of Pukaskwa established an average disturbance cycle of 67 years as of 1990. The age class distribution reflects the effect of both fire and the spruce budworm. However, when the cycle was recalculated as of 1940 (after a series of large fires) the value fell to 37 years, emphasizing the sensitivity of disturbance cycle calculations to time of establishment relative to disturbance events.

2.2.2 Spruce Budworm

Epidemic predation by the spruce budworm is a biological process triggered by a combination of climatic conditions and high proportions of mature fir and spruce in the overstory. Over a period of five to six years the trees are killed and advance regeneration in the understory is released. Both fire and budworm, therefore, recycle the forest and reset the successional clock for those species that are adapted to the respective processes.

There is no direct evidence to link budworm outbreaks with fire occurrence, but since both processes operate on the same landscape concurrently, and since both processes have similar cycles, it is reasonable to hypothesize that there should be both synergistic (14) and feedback effects between the two processes, and that exclusion of one or the other will result in significant landscape effects.

2.3 Landscape Effects

The importance of landscape attributes such as age class distributions, disturbance cycles, and diversity have received increasing attention as important ecological indicators and as management objectives (14, 29-36). These measures tend to be dynamic and subject to continual change, particularly in non-equilibrating landscapes subject to periodic disturbance (13). The objective of this simulation study was to explore the effect of fire and budworm on three landscape attributes: budworm susceptibility, landscape flammability, and landscape diversity.

3. Methodology

The cover types and digital terrain data of Pukaskwa National Park were entered into the SPANS Geographic Information System and a series of time-dependent transition rules developed to control succession with and without disturbance. To simulate fire behavior, the cover types were reclassified into the fuel types of the Canadian Forest Fire Behavior Prediction (FBP) System, and fire was applied randomly to the landscape using a fire growth model.

Five scenarios were run controlled by the number of fires per year: 1, 2, 3, 5 or 10 fires running for 8 hours under an Initial Spread Index (FBP System) of 10. Each fire had a 50:50 probability of being a spring or summer fire and was assigned one of four wind directions based the prevailing winds: 220°, 245°, 270°, or 295°. Weather and the probability of ignition based on risk or hazard were excluded from the simulations. Thus, the only variable controlling the amount of fire under each scenario was the state of the fuels (vegetation) as influenced by fire history and the spruce budworm. The probability of a spruce budworm epidemic was set equal to the proportion of the landscape covered by pure spruce/fir over 50 years of age, with the threshold value set at 30%. Each scenario was run for 200 years into the future and the following landscape attributes were tracked at ten year intervals; i) age class distribution, ii) community type distributions, iii) fire cycles, iv) diversity measures (richness, evenness, and the Shannon Index), and v) budworm susceptibility. The results represent the average of ten iterations of each scenario.

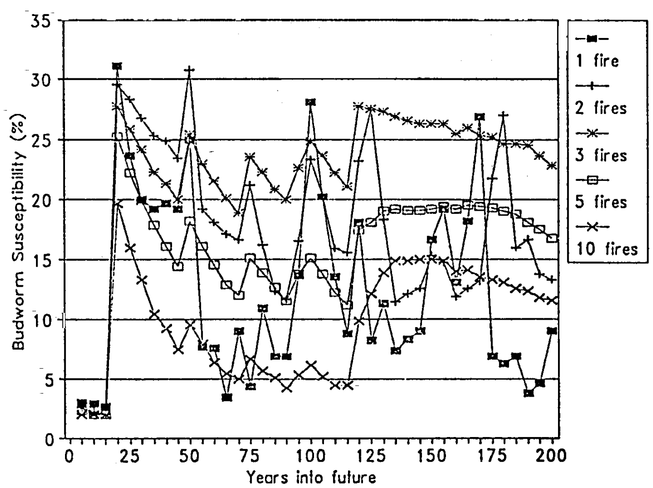

Fig. 1. Variation in budworm susceptibility, based on proportion of mature (50) years spruce/fir, with application of 1,2,3,5, and 10 fires per year representing cycles of 287, 156, 115, 88, and 69 years

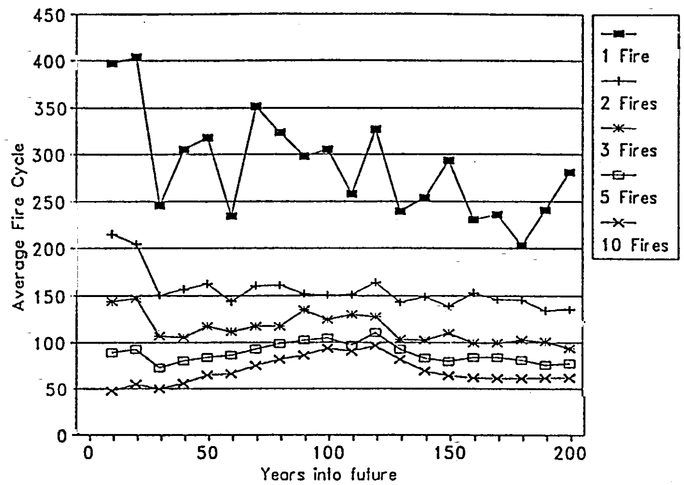

Fig. 2. Variation in average fire cycles with application of 1,2,3,5, and 10 fires per year over a 200 year period.

4. Results

Budworm susceptibility was influenced strongly by the degree of fire, with wide fluctuations in susceptibility being dampened by increasing fire incidence. Under the one and two fires per year regime, budworm susceptibility fluctuated in a series of peaks corresponding to successional dominance by fir and spruce (Figure 1). Thus under low fire conditions, spruce budworm maintained a continual supply of food at recurring intervals. As fire incidence increased, the proportion of later successional stages was reduced, and budworm susceptibility was lowered below the threshold level for initiation of an epidemic. At five and ten fires per year, susceptibility fell to very low levels, rose abruptly at 115 years in the future and then declined slowly. The low fire period was explained by a high proportion of hardwood dominated communities caused by frequent fire, a subsequent reduction in overall fire area caused by reduced flammability of the hardwood, followed by succession to mixes wood and fir-spruce dominated types. These in turn were associated with greater flammability, more burned area, and a reduction in susceptible conifer dominated communities.

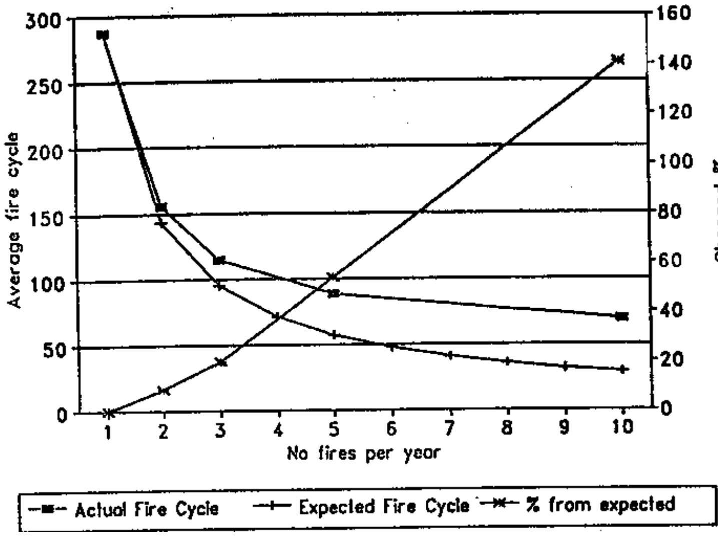

Fig. 3. Change in average fire cycle with increasing number of fires.

The average fire cycle under the one fire per year regime showed wide fluctuations, as opposed to the other treatments where the fluctuations were considerably dampened (Figure 2). With one fire, the pattern was dominated by periods of high flammability associated with regular budworm epidemics and the effects of randomness associated with just one fire per year. Under two fires the effects of randomness were significantly reduced, while with three or more fires budworm epidemics were eliminated. The reduction in the average fire cycle was not proportional to the number of fires, being 287, 156, 115, 88, and 69 years. The decrease followed a negative exponential form that deviated from the expected form (Figure 3), indicating a negative feedback on fire with increasing fire. In other words, increasing fire resulted in a shift to less flammable, hardwood-dominated fuel (vegetation) types, and inhibition of fire spread.

Landscape diversity, as measured by Shannon's Index, was found to be very sensitive to the type of process. Starting diversities were relatively low since the landscape of Pukaskwa, as represented in the database, was dominated by mixedwoods and had not been subjected to any major disturbance since the major fires of the 1930's. Diversity continued to increase in the near future as later successional stands evolved, but with low fire incidence, budworm domination maintained diversity at relatively low, but fluctuating levels (Figure 4). Diversity increased with increasing fire or a reduction in the fire cycle up to a fire cycle of 115 years. With further reductions in the fire cycle, diversity was also reduced.

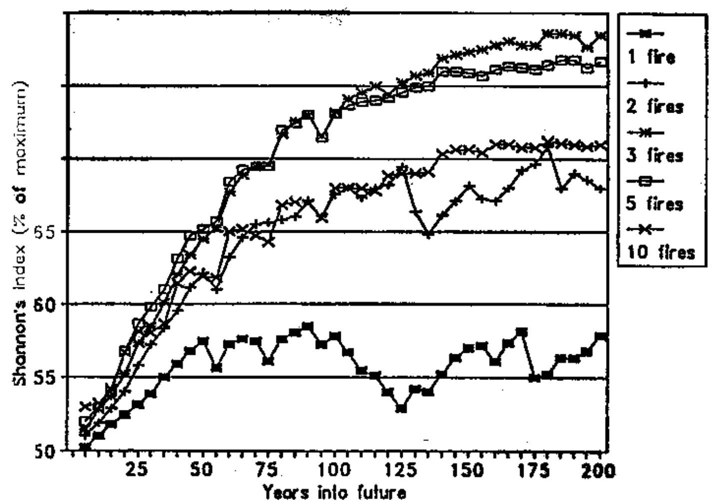

Fig. 4. Change in the Shannon Diversity Index (H'), expressed as a percent of the maximum, with application of 1,2,3,5, and 10 fires per year corresponding to fire cycles of 287, 156, 115, 88, and 69 years.

5. Discussion

Due to the stochasticity associated with budworm epidemics, the random assignment of fires to the landscape, and the climination of budworm susceptibility with increased fire it was not possible to detect any synergism between fire and budworm. Budworm exerted a positive feedback on the system and maintained the forest in a state suitable to its perpetuation. While variations in the fire cycle have often been attributed to variations and periodicitimies in fire climate, this simulation has shown that such variations can originate from disturbance and fuel feedback on landscape flammability alone. Thus budworm epidemics caused periodic increase in flammability and periodic decreases in the fire cycle, while increasing fire incidence had a negative feedback on the system relative to fire, and caused a periodic reduction in flammability.

Low diversity associated with the spruce budworm could be explained by the fact that epidemic predation by this species is a large scale, landscape-wide phenomenon that promoted domination by fir and spruce, and creates large areas of the same age class. Fire, as simulated here, was a relatively small scale phenomenon that promoted a variety of age classes and developmental stages and thus an increase in diversity. However, as fire incidence increased and the fire cycle was reduced this effect was reversed as a result of domination by hardwoods and a reduction in the variety of age classes. The relatively smooth changes in diversity associated with fire were a function of the regular, annual occurrence of fire. In most fire regulated systems, fire occurs as a periodic phenomenon (37) which results in a fluctuation in diversity (31). The maximization of diversity at an intermediate fire cycle of 115 years agrees with other studies on the effect of disturbance on diversity (35, 36). Grime (38) has postulated that species density is maximized at intermediate levels of stress, since at low levels a few highly competitive species dominate, while at high levels a few stress-adapted species dominate. Spruce budworm promotes the tolerant competitive species such as fir and spruce, while high fire incidence promotes stress-adapted, vegetatively reproducing species such as trembling aspen. The results of the simulation also support Huston's (39) hypothesis that diversity is increased in conditions where competitive equilibrium is prevented or disrupted by periodic population reductions and environmental fluctuations.

The above represents but a small subset of the scenarios that need to be run to establish management strategies for a landscape such as that of Pukaskwa National Park. Given this proviso, the simulation indicates that fire exclusion leads to a budworm controlled system with positive feedback and a relatively low landscape diversity. Reintroduction of fire reduces budworm susceptibility and maximizes diversity at intermediate fire cycles. Since the boreal landscape of the park is fire adapted and fire dependent, with a natural fire cycle in the 100 year range, it could be hypothesized that epidemic budworm predation is a human artifact emanating from fire exclusion. A prescribed fire strategy employing regular fire on a 100 year cycle, therefore, would simulate the natural boreal cycle, minimize or exclude future budworm epidemics, create a negative exponential age class distribution, and maximize landscape diversity. Further simulations would be required to address fire periodicity and fire size, and to determine the interaction of these variables on budworm susceptibility and landscape diversity.

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