

THE DYNAMIC LANDSCAPE

Considering all the environmental and socioeconomic influences that affect forest growth, it is remarkable that, over millennia, plantation foresters have an exceptionally good batting average in establishing plantations that turned out pretty much as they had perceived they would - often long after they had passed on. The strength of successful plantation foresters is that they tend to operate on a well-honed intuition of dynamical systems and only sparingly on rigid, narrowly-focussed statistical models. The objective of this section is to take some of the mystery out of the forester's intuition by describing new and emerging paradigms that are helping to give a better understanding of forest dynamics. The terminology is somewhat novel to forestry. Fortunately, there are many insightful internet sites and software packages which give the terminology and demonstrate the basic principles of dynamical systems paradigms. These come under the heading of "experimental mathematics" and are much more graphical than mathematical, per se.

A case in point, is the abject failure of a pine plantation at Trepassey on one hand; while, on the other hand, a few kilometres to the west, is the phenomenal growth of Sitka spruce in three small plots such that the basal areas of some trees are off the scale in growth and yield tables for prime boreal forests. 50 years ago, a forester who would have predicted the pine plantation would fail would be considered wise. On the other hand the same forester would have been ridiculed for predicting correctly that the Sitka spruce would have grown to 12-16 m tall with 50+ cm dbh in less than 50 years on a most abominable site by current forest classification standards. However, the results, i.e., the failure of the pine and successes of the spruce, would not surprise those who have acquired an appreciation of the intricacies of environmental factors. The late H.L. Lewis, who planted the spruce plots, but not the pine plantation, naturally had in mind reasonable expectations of good survival and growth, that was based on an intuitive sense of landscape dynamics. However, even the late Mr. Lewis would not have imagined such spectacular results in so short a time.

Like architects and engineers, foresters rely on Euclide's "perfect" dimensions of length, area and volume, i.e., topological having dimensions 1, 2 and 3 respectively, to provide a generalised description of the size of trees and extent of forests. Likewise foresters rely on standard statistical models and ecological classification schemes to establish conventions of 'normal' and 'aberrant' forests and forest practices. In forestry, as in politics, there is no such thing as 'normality' - only constant change. That is why forest regulations and silvicultural guidelines are constantly being revised.

In architecture and engineering, Euclidean dimensions and standard statistics works well simply because extreme precision in building and manufacturing processes is achievable in controlled environments. By contrast, a forest is the product of an uncontrolled natural environment. In other words, the irregular dynamics of the natural environment begets the irregular geometry of the forest such that Euclidean dimension and standard statistics can describe them only in the crudest terms. Naturally, foresters are cognizant of the fact that the harsher and more dynamic the natural environment the more irregular and unpredictable is forest growth. Unfortunately, foresters bound by conventional practices and policies, often don't factor in the dynamics of the natural environment into silvicultural routines. A simple example, planting is still laid out in square blocks and straight rows on exposed sites where irregularity of planting and species composition would produce better results. Another example is the wind-throw risk models. Unfortunately, 'risk models' are often redundant (when they explain the obvious), unreliable (as in simple linear-regression models) and somewhat symptomatic of inappropriate silvicultural practices with respect to the physical environment.

It hardly needs stating that the harsher the physical environment, the faster and more complex are the ecological changes. And while it is acceptable to have reasonable predictions as to how a plantation will develop, it is foolhardy to hang on tenaciously to one's expectations in the face of constant economic and environmental changes. Of course, many changes in the landscape are obvious. What is not so obvious, is innumerable unpredictable and imperceptible small natural events which initiate wholesale changes in the landscape. More to the point, because of these small changes it is not possible to give a precise set of

silvicultural prescriptions and specifications with a degree of precision approaching say a set of building codes or ISO standards for accounting procedures. Each site must be assessed on its own merits on the basis that predictions of forest/plantation development are short-term at best. The plantation forester who literally has a sixth sense of the physical dynamics of forest landscapes is most likely to succeed.

From a practical standpoint, dynamical systems theory is a comparatively new paradigm. And, like circular statistics, which has rather ancient but generally obscure roots, it has only been within the last decade or so, with the advent of personal computers, appropriate software and very valuable internet sites, that the practical application of dynamical systems approach to understanding the environment, such as pattern-forming phenomena in forest landscapes, has come into widespread use.

One should keep in mind that the application of dynamical systems theory to understanding the complexities of forest landscapes does not necessarily improve predictability. Quite the opposite in many cases. Its strength lies in inculcating a better appreciation toward isolating phenomena which are wholly predictable from those that are only partially or completely unpredictable.

Working with dynamical systems one soon develops the knack for sorting out a testable hypothesis, i.e., those which explain the obvious, as opposed to an untestable hypothesis. From a dynamical systems perspective, it is fair to say that growth and yield of plantations is only partially predictable at best. One never knows when a positive or negative event will occur in the lifetime of a plantation. The best that can be done is to create plantation designs and management strategies that will dampen negative effects. This section outlines some of the basic principles of dynamical systems as a tool for understanding the influence of environmental change on forests and plantations.

Sustainable forestry is usually defined in terms of the maintenance or enhancement of productive capacity and biodiversity of forests, emphasising the biological capabilities (productivity) of the land base. But the notion of sustainable forest development is very subjective.

For example, current land capability for sustainable forest productivity, is based largely on soil capability and the growth and yield of natural forests which currently occupy the region. However, silvicultural experience, urban forestry and experimental plantations clearly show that potential forest productivity can be increased many-fold. Furthermore, analogous to the rise and fall of civilizations and dynasties, the productivity of forest ecosystems also declines and falls on many time scales with or without the influence of humanity.

The problem of defining sustainable forestry is compounded by the complexities of environmental change. For example, a slight change in say the mean trajectory of the jet stream over a relatively short time span of a decade or so can dramatically change the forest productivity in Newfoundland. When the jet stream tracks a little further west than normal, the Avalon Peninsula gets mild, relatively frost-free winters and, perhaps damp foggy summers; where as, tracking a little eastward than normal results in frosty, snowy winters and warm dry summers (and a higher frequency of forest fires). On one hand, the productivity and spread of forests increase because of longer (frost-free) growing seasons. On the other hand, forest productivity decreases due to the repetition of wildfires. A more earthly example that alters forest landscape dynamics is the not-so-subtle changes in the predator-prey relations which directly affect the extent of browsing by rabbits, moose, bugs, fungi, etc., on natural regeneration and plantations. Slight shifts of the jet stream and the extent of browsing are just two of the countless natural influences which are essentially outside the limits of predictability beyond the very short term.

The problem with the standard approach to defining forest sustainability is to treat ecophysical

relationships as if they were predictable: if not now, at least in the future concomitant with advances in modelling - i.e, as **linear systems**. For example, in commonly-used parametric statistics, it is considered that variances are normally distributed and that most events are normally distributed. The problem with this approach is that it cannot deal with the myriad of interscale relationships and cannot deal with the fact that new phenomena are encountered as one scales up or down between, for example, plot, forest type, landscape mosaic and biome.

However, natural and cultivated environments are **nonlinear dynamical systems** that are inherently historical, evolutionary and irreversible. Consequently, it is not possible to address the question of sustainable forestry from the standard approach.

In plantations and precommercial thinning, sustainable forest management implies that forests can be genetically and technologically engineered for a specific regional climate but rarely, if ever, for the vagaries of weather or, rather, weather extremes. However, the ability to describe the coupling between forests and climate depends on how well we understand wind, small-scale turbulence within a forest canopy, the passage of frontal systems and shifts in the mean seasonal position of the jet stream.

Forests respond differently to abiotic factors at climate and weather scales. For example, the extent of wind-throw in a forest is primarily a function of strong winds associated with the passage of frontal systems. However, dieback, which makes shallow-rooting, monospecific stands prone to wind throw from less severe storm winds, is mainly a function of a seasonal climate. At longer time-scales, changes in the trajectory of frontal systems associated with shifts in the mean position of the jet stream, as a result of climate change, have considerable influence on forestry. These would include changes in wind regimes, regional rainfall patterns and rates of evapotranspiration which affect forest stability, tree growth, biodiversity, wood quality, regeneration, fire hazard, and human activities.

The climate of a particular type of forest is usually thought of as average weather: which does not change much over the long term; but comprising many short-term physical processes that are largely beyond human control. When planting or thinning forests, silviculturists tend, intuitively at least, to treat climate and weather as separate entities. Different emphasis on climate depends also on the different philosophical viewpoint of the dynamical nature of forests.

Also, from an applied climatological perspective, there is the paucity of standard meteorological stations located within forested environments.¹ One reason is that few people live within large, forested regions. Another has to do with the different criteria used for standard meteorological stations compared with those used for a specialized forest climatological station. Standard weather stations are designed to monitor only the very basic weather and climate variables. To assess the potential for plantation forestry, we'd be more interested in meteorological instrumentation that quantifies the basic energy cascade or the complex aerodynamics within and around forests. (See section on **Energy Cascade**) Unfortunately, such biomonitoring systems are complex and prohibitively expensive and somewhat limited to small-scale environments. But even at these small scales, they demonstrate unpredictable dynamics for the most part.

Basically, there are two basic schools of thought: the 'climax' or 'equilibrium' theorists and 'mosaic-cycle' or 'dynamical' theorists, respectively.

¹There are no standard meteorological stations in typical forested areas on the Avalon Peninsula. The official climate stations are on upland exposed sites at St. John's Airport and CDA Experimental Farm on Brookfield Road, respectively and close to the shore in a few other communities around the coast.

Climax theory

According to this school of thought, forests are generally long-lived and have a slow response to climate change. That is, forests develop within a unique set of predictable climatic limits such that climate and forest are in equilibrium. In other words, forest succession trends toward a final climax state determined by the local climatic and biophysical environment. This concept of a natural ecosystem is, in a dynamical system's parlance, a **fixed-point system** whereby its long-term trajectory trends toward a fixed point (climax). This is useful in forest policies with an immediate or relatively short-term interest in the resource - such as plantations and pre-commercially thinned forests.

Climax theorists tend to stress the biological aspects so that when shifts in climate occur, then forest succession comprises a series of definable units of an ecosystem which trend toward a new climax. However, the variability of climate and weather constantly changes the forest dynamics so that forests are rarely, if ever, in equilibrium with the climate. This means that it is virtually impossible to define and predict the impact of an 'average' climate on a particular forest type beyond the crudest circumstances. For example, when climax theorists discuss the role of disturbance in gap formation, they focus primarily on **biotic factors** and rarely ask how gaps are formed and expanded by abiotic factors. One reason for this, of course, is the paucity of reliable **abiotic** data due to the difficulty in measuring environmental variables over any but the shortest spatiotemporal scales.

Mosaic-Cycle Theory

This is a sort of a compromise to overcome the weakness in climax theory. The cornerstone of mosaic-cycle theory is that ecosystems consist of patches of 'mosaic stones' which cycle continuously through a set of states, with adjacent patches cycling asynchronously (out of step). The dynamical systems approach, is embodied in the '**shifting mosaic steady state**'. The concept of a shifting mosaic cycle is an apt description of patterning in managed forests or, stated another way, patterning in managed forests is a function of shifting forestry priorities to reflect market and social demands plus climate and weather effects.

From a forest's standpoint, the dynamical systems approach is a more enlightened concept for two reasons. First, it tends to stress the role of climate and weather more so than classical climax theorists do. Second, it has a more direct link with other scientific disciplines, notably atmospheric, geophysics and mathematical modelling, which are firmly rooted in dynamical systems theory. The Amazonian forest is a typical example of mosaic cycling. Fifty per cent of Amazonia is covered by typical rain forest on terra firma whereas the rest of the region is composed of a vast number of much more dynamic vegetation types, resulting from much more frequent natural and human disturbances. In addition, there is an increasing amount of secondary growth (capoeira) arising from ancient practice of shifting agriculture.

A prime example of a shifting-mosaic which is a product of abiotic factors, namely wind, which causes gaps in the forest which develop into the peculiar mosaic cycle of a wave forest phenomenon characterized by dead tree strips moving across the landscape. These natural and human-induced wind-shaped forest mosaics are common throughout Newfoundland, especially on the Avalon Peninsula

From a different perspective, in central Europe, strong solar radiation causes beech dieback at crucial times in the mosaic cycle. Most of the forests in Europe, which have been manipulated by humans through all or part of their history, are examples of economic' mosaic cycling. The man-made barrens on the Avalon Peninsula are also in a sense mosaic cycles created by strong, persistent dry winds in summer and frost-heaving in winter. Eventually, trees colonize the barrens which, when tall enough, are harvested mostly for firewood, then the soil drying and frost-heaving cycle starts all over again.

Most studies of climate-forest interactions, including those by mosaic-cycle theorists, are based on conventional climatological, statistical and physical models that are necessary to provide a basic understanding of 'average' relationships between climate and forests and between weather and forestry. Conventional approaches necessarily involve reliance on and improvement of a formidable array of classical measurement and modelling of forest climatological techniques.

Spatiotemporal Chaos

Before we can define, describe and utilize the relationship between climate and forests, we must improve our understanding of their interactive spatiotemporal characteristics. More precisely, we should focus on initial (deterministic chaotic) events which trigger particular pattern formations and explain how these evolve through disruptive processes throughout the course of the interrelationship between climate, weather, forests and forestry.

Spatiotemporal chaos is variously referred to as self-organizing complexity', 'nonlinear determinism', 'patterned but unpredictable', 'patterned instabilities' and other seemingly contradictory terms. From a forest-climatological viewpoint, our interest in this phenomenon is aimed at describing the deterministic processes such as the pattern-forming instabilities which govern the dynamics of vegetation mosaics in forested and deforested landscapes. Chaos is the initial condition that results in a patterned but only partially predictable instability, such as a phase change from rain to freezing rain.

Various dynamical states evolve from both natural and human non-equilibrium pattern-forming processes with a large number of deterministic chaotic elements and localized random shocks. In some respects, the relationship between silvicultural operations and extreme climatic events is a prime example of a non-equilibrium pattern-forming process.

On the one hand, silviculture (such as thinning) is representative of deterministic chaos which equates with stabilizing (exploitive) processes; whereas, localized random shocks (e.g., wind throw or frost damage), embedded within the deterministic chaotic system, are responsible for the noisy (disruptive) transient states. In natural forests and plantations much the same thing happens through spatiotemporal adaptations (deterministic chaos) in response to disruptive changes in climate and weather (random shocks).

The interaction between forests and climate is a system of interlocking stable and unstable states with a large number of chaotic (nonlinear) elements which characterizes atmosphere-forest-soil interactions. These interlocking states include homogeneity (stable), periodicity, quasi-periodicity and spatiotemporal chaos.

Spatiotemporal chaos arises from a phenomenon known as intermittency. This is an abrupt change from one dynamical state to another, such as damage to parts of a forest caused by an episode of freezing rain or wind-throw caused by moderate winds from an unusual direction. More often than not, the impact of these small, brief weather events is the catalyst for major transformations in terms of the forest architecture. Furthermore, spatiotemporal chaos is both the bane and a product of forest policymakers. This is because the coupling between climate change and changes in forestry, trade and land-use priorities is viewed as a complex interactive process which has a huge number of chaotic elements that are impossible to describe and predict.

Fortunately, for human understanding, comparatively few 'effective' elements are involved in creating extreme variability over a wide range of time-scales. The most effective way to recognize these 'effective' elements is to study their fractal (self-similar) dimension.

Fractal geometry has been called the '**calculus of heterogeneity**'. Fractals are not defined in a formal,

legalistic statement but are expressed by mathematical and graphical representations - of which there is an abundance of personal computer software that are easy to understand and apply.

A fractal is quantified by its fractal dimension which essentially measures how efficiently an object fills space. For example, a plantation is likely to have smoother edges and a lower fractal dimension, than the edge of a natural forest. Apparently, fractals are products of **dynamical (spatiotemporal chaotic) systems** and, as such, may provide a link between the abiotic processes (i.e., wind, freezing rain, soils,) and the resultant biotic effects on the architecture of plantations and forests (deformation, height, dbh, stand density, species composition).

For example, on a poor, exposed site, trees have heterogeneous (asymmetric) profiles with a high fractal dimension; whereas, on a fertile, sheltered site, trees tend to have homogeneous (symmetrical) profiles with a low fractal dimension. In the case of forest mosaics, the magnitude of a fractal dimension of patches that make up a forest mosaic reflects the geometrical and dynamical complexity of the forest. The geometric complexity can be described by a simple fractal diversity index which relates the roughness of a particular part of a plantation compared to other parts of the plantation.

For example, as illustrated in the section on **Tree indices of wind**, trees growing on an exposed site have heterogeneous (asymmetric) profiles with a high fractal dimension whereas, on a rich and sheltered site, trees tend to have homogeneous (symmetrical) profiles with a low fractal dimension.

In the case of forest mosaics, the magnitude of a fractal dimension of patches that make up a forest mosaic reflects the geometrical and dynamical complexity of the forest. The geometric complexity can be described by a simple fractal diversity index which relates the roughness of a particular forest patch. Fractal diversity is very useful for modelling forest dynamics. These include predicting the susceptibility, intensity and rate of spread (percolation) of disturbances, particularly weather related disturbances, across a heterogeneous landscape.

Excellent examples occur in the 1950's pine plantations at Tilton, Broad Cove, Marysvale and Avondale, where different patterns of growth, survival and mortality (wind-throw) have developed as these plantations matured. As the fractal diversity index of edges of patches increase, (i.e., the fractal dimensions of edges become more elaborate) it is a clear sign the plantation is undergoing a phase transition between stable (uniform growth) and unstable (endemic and severe wind-throw).

Even more conspicuous is the dynamics of extensive wind-throw of balsam fir stands in central Avalon. Wind-throw gaps that appeared about 5 years ago (1995) displayed a high fractal diversity - indicating a very active, unstable dynamics. But as wind throw decreases (because stands susceptible to wind-throw have declined) the fractal diversity of the forest mosaic also declines. Of course, we know that patterns of wind-throw are more a function of the distribution of fragipan in Cochrane and to some extent Portugal Cove soils, than wind-per se.

The central question with respect to silviculture is whether we can develop a storm proof design for plantations by focussing on relatively few dynamical systems which govern the relative stability of a plantation such as tree form, stand density, species composition, soil type and, above all, relative exposure to a particular wind regime. Probably we can. But only if we understand the dynamics of the landscape we are dealing with and whether a monoculture vs mixed culture is appropriate. For example, sheltered sites are comparatively benign, dynamically speaking, and therefore, monocultures are appropriate. But most of the decent plantation sites lie between very being moderately dynamic to benign, and therefore will probably require a mixture of genotypes and/or mixed-species (on the windward edges) and monoculture in the lee of them - the so-called shelter-wood strategy.

The problem is that we don't have appropriate classification techniques, such as those based on spatiotemporal chaos, for bioclimatic zonation. For example, bioclimatic zonation for plantations and to some extent silviculturally treated forest, have very different criteria from those of natural forest ecosystems. Similarly, in boreal spruce forests in Finland, the boundaries between various classes of productivity of natural (untreated) forest and potential productivity has shifted, with most regions showing a dramatic increase due to advances in silviculture.

The main difficulty in developing criteria for estimating the potential production of various afforestation and reforestation scenarios is that large-scale plantation forestry is a unique or relatively new experience in the Boreal biome. Regardless of what baseline data and input data we deploy in developing classification techniques for plantation forestry, they must include some form of dynamical system's model that is based on a more efficient and effective process for rationalizing various levels of predictability.

Complexity

Complexity is the most frequently-used word associated with this new-age way of describing and analysing the impact of environmental disturbance on landscape patterning and their influence on forest growth.

First principles of complexity

- *fractal geometry*, the calculus of heterogeneity
- *dynamical systems*, the power spectrum of change
- *chaos*, the origin of pattern
- *percolation*, drift of diversity
- *directionality*, madly off in all directions.

The most important of them from a planting point of view, directionality, is demonstrated in the section **CIRCULAR STATISTICS**.

Fractals

In forest surveys we rely on three dimensions, line (dimension 1) square (dimension 2) and cubical (dimension 3) shapes. These are the 'perfect' dimensions handed down to us from the ancient Greeks. Useful as they are in simplifying survey measurements, they don't really describe the shape of forests or tree crowns; nor do they tell us much about the dynamical aspect of forest patterns. Or more to the point, using 'perfect' dimensions, I can't convey to the forester the shape of a shelterwood or a wind break that will allow us to manipulate wind flow in ways that promotes tree growth. For that we need a new measure of 'imperfect' dimensions of roughness which lie between a line and a square (i.e, having a value between 1 and 2), and between a square and a cube (a value between 2 and 3). The new language of **fractal geometry** serves that purpose for, as the computer scientist Barnsley says "Once you speak it, you can describe the shape of a cloud as precisely as an architect can describe a house." What is more important, from a forester's point of view, is that fractal geometry is at the heart of our ability to understand forested landscapes as dynamical systems.

Fractals are not defined by a formal legalistic statement but by mathematical and graphical techniques. I will dispense with the mathematics (which in practical applications is quite simple) and provide graphics showing the fractal dimension (**F**) of familiar objects:



Hedge maple
($F = 1.2$)



Rhododendron($F = 1.00$)



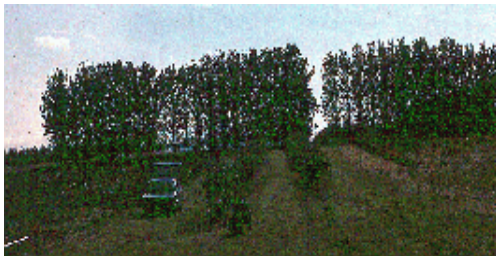
Sweet chestnut leaf ($F = 1.07$)



Uniform canopy ($F = 1.2$)



Irregular Canopy ($F = 1.9$)



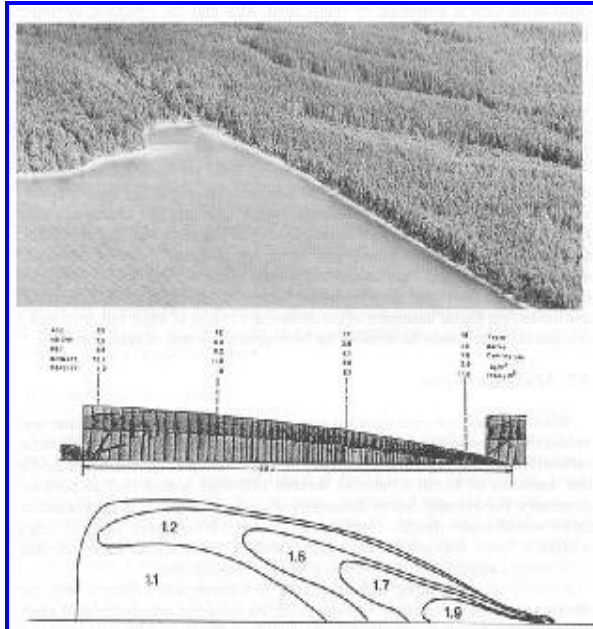
Regular canopy profile ($F = 1.2$)



Regular canopy profile ($F = 1.9$)



3-D complex uneven forested landscape
($F \approx 2.8$)



Bottom multi-fractal dimensions through the profile of a wave forest.



3-D monospecific, even-aged stand ($F = 2..1$)

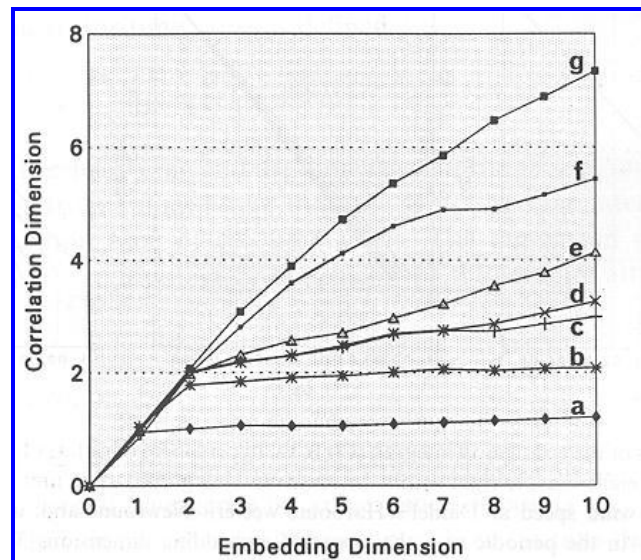


Sweet chestnut husk ($F \approx 2.5$)

| | | IMPACT ON CHANGES | | | | | | Degree of Fractal Dimension of Edges |
|-----------------|---------------------------------|--------------------------|---------------------------------|--|-------------------|---|--|--------------------------------------|
| Type of Habitat | Disturbance Intensity Frequency | Area of Habitat Affected | Undisturbed Forest | | Disturbed Forests | | TYPICAL CAUSE OF DISTURBANCE | |
| | | | #clusters | size | #clusters | size | | |
| Rare | Low | <5% | Minor change | Minor change | Minor Change | Minor Change | Hiking | Low |
| Rare | Low | 55-75% | Decreases | Largest decreases | Increases | Largest increases | Small group ecotourism, mining exploration | Medium |
| Rare | High | <5% | Minor change | Minor change | Minor change | Minor change | ATV's (forest habitats) | Low |
| Rare | High | 75-95% | Declines sharply (phase change) | Largest Declines sharply | Increases sharply | Largest increases sharply | Large group ecotourism (botanical collecting), | high |
| Common | Low | <5% | Small changes | Small changes | Small changes | Small changes | Sports fishing, rabbit hunting, trail construction | Low |
| Common | Low | >50% | | Largest fragmented into high number of clusters | | | Low-level (single tree) lightning strikes propagated to landscape level by bark beetles. Patch cutting followed by natural regeneration, high management cost strategies | Moderately to High |
| Common | Moderate | <50% | Increases | Edges increase | Increases | Edges increase | Selective cutting for sawlogs and Christmas trees | Low |
| Common | Moderate | >80% | | | | Approaches initial structure of undisturbed habitat | Effects of storm winds, freezing rain on growth forest. | Moderate |
| Common | High | >95% | | Initial structure becomes like disturbed habitat | | | Forest fires, disease and insect infestations, light urban encroachment Mixed-species forest | Moderately to high |
| Common | High | >95% | | Initial structure becomes like disturbed habitat | | | Clearcutting, agricultural expansion, monoculture plantations | |

To practice sustainable forestry, one has to be very far sighted. And while we generally conceive silviculture as essentially the management of cyclical cutting rotations, we know very well that in real situations the planned cycle varies between a bad wobble and truncation. So it helps a little to understand that the environment that makes trees grow is made of some events that are more-or-less cyclical and others that are seemingly random (stochastic). The notion of complexity may be a little hard to grasp, but it is well worth the effort to try if you want to understand the necessity for complexity in the natural environment. Without it, there would be no patterns.

Without getting bogged down in the mathematics pertinent to chaos theory (those of you familiar with time series techniques will know where to look), the adjacent graph illustrates the correlation dimension as a function of the embedding dimension. Essentially, what it is telling us is that the steeper the curve the less predictable is the time series. First of all, we establish standard benchmarks for which to compare time series of natural phenomena: **a** is a periodic, **g** is a random (stochastic), and **c** is a chaotic time series, respectively. Thus, for all the curves we have:

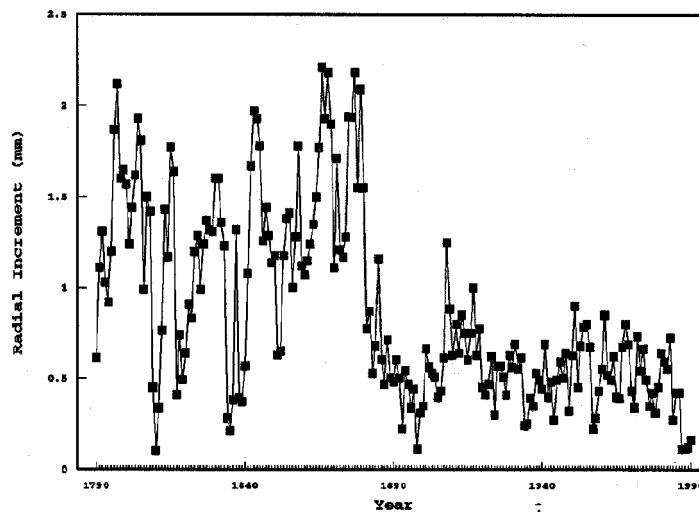


- a)** periodic (cycle)
- b)** chaos
- c)** wind-speed at Gunnarsholt, south Iceland
- d)** tree ring widths
- e)** temperature at Pasadena
- f)** same as **c**, before differencing (i.e., raw data).
- g)** random (stochastic).

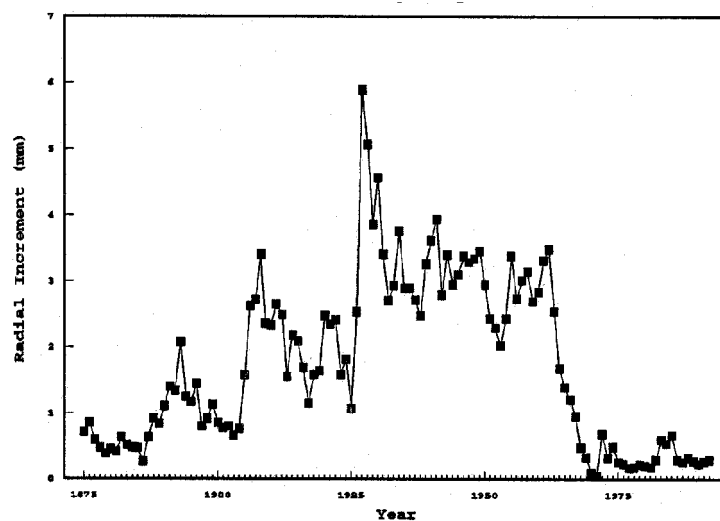
The nearest analogues to a chaotic time series are the peaks and valleys in the wind speed (measured at intervals of milliseconds and averaged every 15 minutes over a period of 18 months). It is sort of cyclical and behaves a lot like the rise and fall of the stock market insofar as we sense a pattern but can't predict precisely when it's rise or fall begins - otherwise there would be no stock market. Temperature, also measured at intervals of milliseconds but averaged every 30 minutes from February-April, has a stock market pattern to it but is less well organized and predictable. Raw data for wind is hopelessly unpredictable since it is virtually random.

Now we step it up a notch to examine tree rings and see if we can infer something about the ecosystem dynamics of the site they occupy.

Mature birch from distinctively different climatic zones, but in similar ecotypes, were chosen as the test species because it has a wider ecological amplitude, distribution and longevity than other native species of trees in Newfoundland. One was mountain paper birch (*Betula x cordifolia* (Reg.) Fern.) located near Hawke's Bay, northwestern Newfoundland, and grew on an exposed ridge within a dense balsam fir forest that was killed by the spruce budworm (*Choristoneura fumiferana* (Clem.)) and was salvaged in 1991. The other was yellow birch (*Betula lutea* Michx.) located close to St. Veronica's, Bay D' Espoir in southern Newfoundland. This birch also grew within a budworm-infested balsam fir forest that was also harvested in 1991.



Tree-ring time series of mountain paper birch from Hawke's Bay, Great Northern Peninsula



Tree-ring time series of Yellow Birch from St. Veronica's, Bay D' Espoir

The results show that tree ring time series from Hawke's Bay on northwest coast of Newfoundland has a noisy random pattern with a very distinctive phase change (or bifurcation point) occurring in 1899. The temptation is to ascribe the phase change from excellent growth to a consistently slow rate of growth to some sort of severe injury perhaps resulting from freezing rain or a windstorm. However, that would only explain the peaks and valleys prior to 1899. Perhaps after 1899 that was the case initially. However, after the sharp decline, which occurred over several years, the tree rings settled to a new stable state characterized by distinctly slower growth, which was more likely due to harvesting followed by rapid regeneration of balsam fir and possibly coupled with deterioration of the climate.

By contrast, Bay D' Esprit time series is what we call low-dimension chaos which is best described as a pattern-forming instability. Were it not for the embedded positive phase changes in the years 1904 and 1925, and negative phase changes in 1929 (the year of great crash!) and 1963 (year of fires!), it is a fairly normal growth curve representative of a stable, sheltered climate (which it still is) that one usually expects of yellow birch forests in this area.

From an ecosystem management point of view, the differences between the tree ring series suggests that a very long-term plan has a much better chance of being carried out to fruition at Bay D' Esprit than Hawke's Bay. Of course, given only two tree rings is an oversimplification. The intention is to show many ways of acquiring the habit of reading the relative ecosystems dynamics without resorting to impenetrable mathematical and ecological theories. The worked examples are intended to put you on the path of thinking dynamically.

Dynamical systems approach to time series analysis

Correlation function, C_r

The correlation function is an average point-wise mass. Given the vector time series $\mathbf{X}(t_i)$, the correlation function, C_r , is calculated

where, H is the Heaviside step function, M is the number of points in the new series, vector time series, $\mathbf{X}(t_i)$. C_r counts the number of pairs with distance $|\mathbf{X}(t_i) - \mathbf{X}(t_j)|$ smaller than r . If the relationship

$$C_r \sim r^d$$

$$C_r = \frac{1}{M^2} \sum_i^M \sum_j^M H(r - |\mathbf{X}(t_i) - \mathbf{X}(t_j)|)$$

exists for sufficiently small r , then d is the correlation dimension of the attractor.

Correlation dimension, d

We use the G-P method to estimate the correlation dimension, d , (a measure of the complexity of the phase-space trajectory) from the tree ring time series to distinguish between stochasticity and chaos. The correlation dimension is the ratio of the logarithm of the correlation function, C_r , to the logarithm of a given length r .

The algorithm for estimating d takes three steps:

1. Embedding dimension, D_e

This is a time-lagged process to determine the *fractal dimension* of a time series vector. The constant τ is a delay time analogous to the number of prongs of the mathematical garden fork. Since the two tree ring time series have an equal time interval \mathbf{X}_{ti} , the vector time series is then defined as

$$\mathbf{X}_{ti} = \{X_{ti}, X_{ti+\tau}, \dots, X_{ti+D_e-1}\}$$

where τ and D_e are the delay time and the dimension of the vector, respectively. τ can be chosen in a range from values larger than the sampling time interval but smaller than the autocorrelation time of the time series. The dimension of vector equals $2D_T + 1$, where D_T is the topological dimension containing the attractor.

2. Information dimension, D_i

The *information dimension*, D_i , is the scaling exponent in the variation of entropy, that is, the *Kolmogorov entropy*, which measures the loss of information as a chaotic system develops. In other words, it characterizes the transition between stochasticity and chaos. D_i , in essence, describes phase changes such as those that occur in the dissipation of energy in hydrological and forest dynamics. Hence, the information is also called *Shannon's entropy*. Essentially, one counts the repetition of a pattern in a time series during phase changes. D_i can distinguish between various stochastic processes in the phase transitions from periodic oscillation, temporal chaos, soft turbulence, hard turbulence and finally fully developed turbulence. More importantly, they showed that different states of turbulence have a higher degree of stochasticity than chaotic states because of scaling factors of D_i .

3. Capacity dimension, D_c

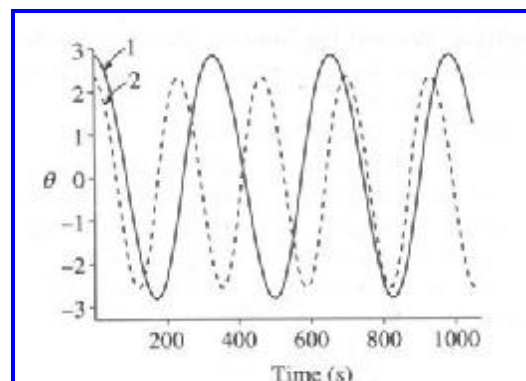
The capacity dimension is calculated by successively dividing the phase space with embedding dimension D_e into equal hypercubes and plotting the logarithm of the fraction of hypercube that is occupied with data points versus the logarithm of the normalized linear dimension of the hypercube. The average slope of the line for the two middle segments is taken as the capacity dimension.

Lyapunov exponent, λ

Lyapunov exponent is a measurement of the sensitivity to initial condition and provides an indication of how far into the future reliable predictions can be made.

One definition of dynamical systems is that it is evolutionary and historical and therefore irreversible insofar as certain events cannot be recreated precisely. From our point of view, it means that insignificant environmental, social and economic factors often result in drastic changes in the forest and forest policy. The familiar ring to that phrase is of course the meaning of chaos.



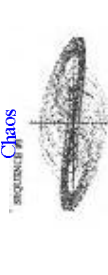
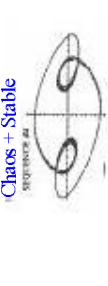






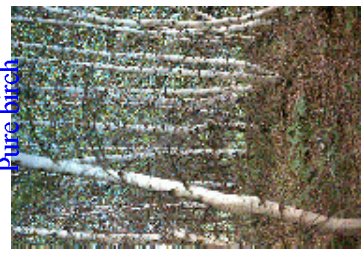
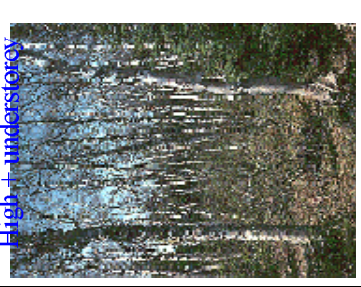


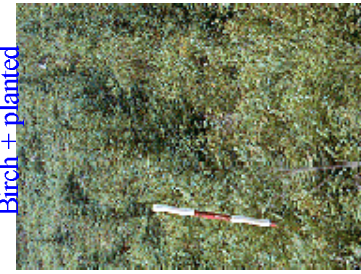
Take the case of the oscillations of an undamped bell. Suppose we start a pendulum swinging at 3° from vertical and plot its motion (solid line) in a



time series shown in the graph (we'll assume that for observation period it doesn't slow down). Next time we start the pendulum at a slightly lower angle, the difference is dramatic. Initially the pair of curves diverge and at $t = 600$ they converge.

If the time series were really long, we would strain our eyes trying to see patterns formed between the pair of time series. A neat way is to plot the converging and diverging positions between the time series in a phase portrait. And look for an attractor - that is, what the system settles down to. For example, if we rolled a ball down the inside wall of a tire and plotted its trajectory it would settle down to a fixed point attractor. If we rolled it around the bottom of the tire a plot of its trajectory would show a circle attractor. And if we wound it up and down around the inside the trajectory would display a torus. The fixed point, circle and torus are known as the classical attractors. In forestry, we'd prefer that the growth and yield curve is nice and smooth over a predictable rotation age for a commercial forest; in other words, the phase portrait of the trajectory of our planned forest would show a circle attractor. But, as experience tells us, the growth and yield across a stand is rough rather than smooth. So what we really get is a strange attractor which retains all the features of the growth and yield curve but it is self-similar (fractal). So when we look for chaos, we examine whether the attractor is classical or fractal. In case you think this is a useless exercise, keep in mind that the search for strange attractors in a stock market time series was the basic principle behind the trillions of dollars made in a few weeks by an infamous hedge fund investment scheme. Despite the mathematical elegance of chaos theory they lost their trillions almost overnight because they couldn't factor in human behaviour. Forestry is a lot like that, where a couple of centuries of work in developing elegant forests can be flattened in 10 minutes by a gale or a fire. No one can prepare for strange attractors, but we can certainly dampen their impact if we learn to think complexity in dealing with the dynamics of forests, people and the environment. The more dynamic the environment you have to deal with, the better you must hone your ability to think complexity. Hopefully the unusual complexity of this set of plantation guidelines will give you a better appreciation of the dominant aspects governing forest development in the very complex environment of the Avalon Peninsula.

The table below illustrates the process of change in easily recognizable patterns associated with dynamical states. Once you get used to the notion of dynamical states in the natural environment they will become as familiar to you as distinguishing varieties in one species of tree. And you will definitely understand the stock market better

| TOPIC | ORIGINAL ATTRACTOR | | FORCING PARAMETER | NEW ATTRACTOR | |
|--|---|---|---|---|--|
| | STABLE | LIMIT CYCLE | | CHAOS+STABLE | STABLE |
| Value of forcing parameter | C = 0.22 | C = 0.3 | C = 0.376 | C = 0.39 | C = 0.4 |
| PHASE PORTRAIT |  Invariant Circle |  Limit Cycle |  Chaos |  Chaos + Stable |  Stable |
| Reynolds number for ind flow Patterns around Trees | $\mathfrak{R} = 10^{-2}$ | $\mathfrak{R} = 20$ | $\mathfrak{R} = 100$ | $\mathfrak{R} = 10^4$ | $\mathfrak{R} = 10^6$ |
| Corresponding wind flow patterns around a tree |  Homogeneous |  Vortex |  Chaos |  Strong-oscillations |  Weak-oscillation |
| |  Pure birch |  High + understorey |  New high forest |  Disturbance response |  Birch + planted |
| Birch Forest | | | | | |

C = A forcing parameter in a difference equation such $x_3 = Cx_2 - 1x_1^3 + 1x_3$; slight changes in C produces dramatically different phase portraits of time series \mathfrak{R} = Rayleigh number is dimension less and expresses a forcing parameter where at certain values \mathfrak{R} the fluid becomes unstable to for new patterns.