Automatic detection of onset and cessation of tree stem radius increase using dendrometer data and CUSUM charts

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Abstract. Dendrometers are devices, which measure continuously the stem radius of a tree. In this work, we studied the use of cumulative sum (CUSUM) charts for automatically and, thus, objectively determining the onset and cessation dates of radial increase based on dendrometer data. We used data measured in two forest stands in southern Finland to demonstrate the idea and to test the performance of the CUSUM chart. In order to produce reliable results, one has to choose suitable parameter values for the chart. Once configured properly, the method produced results similar to those determined by an expert.

1 Introduction

Formation of wood depends on various endogenic and exogenic factors and it is restricted to a certain period in the year, e.g. [1]. Wood formation is regulated by several factors including genotype, site, silviculture, and climatic variation. In spite of the basic nature of the underlying process, our present knowledge concerning the timing of the various phases and the rate of increment during a growing season is still far from complete. This lack of knowledge is largely due to difficulties in measuring wood formation at short intervals. Dendrometers have traditionally been used for measuring the intra-annual wood formation of trees with high precision, e.g. [2, 3].

Changes in stem dimensions are not solely a result of wood formation; they are often caused by other processes, especially changes in stem hydration, e.g. [4]. Because of the large and frequent changes in stem radius associated with fluctuations in stem water potential, it is difficult to use dendrometer measurements to determine the onset, cessation, and rate of wood formation, i.e., radial increment due to formation of new cells, e.g. [5, 6, 7].

In recent years, few studies have been published describing the timing of radial increase or weather-growth relationship based on dendrometer data, e.g. [7, 8, 9]. However, the definitions and approaches for identifying the onset and cessation of radial increase have been different between the studies. Thus, criteria

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and methods for determining onset and cessation dates are not yet generally accepted.

The problem in this study is to objectively and automatically detect the onset and cessation of radial increase period based on dendrometer data. We tested the suitability of the cumulative sum (CUSUM) charts [10, 11] for performing this determination automatically solely based on the data, cf. [12].

2 Dendrometer data

Dendrometer data was collected from two sites located 300 m from each other in southern Finland (Ruotsinkylä, 60° 21' N, 25° 00' E). In both stands, sample trees without visible damage were selected from the dominant tree layer. In the first stand (altitude 45 m a.s.l.), the Norway spruce trees were growing in a pure spruce stand on fertile mineral soil ($H_{100} = 30$ m, dominant height at age 100 years) classified as *Oxalis-Myrtillus* forest type [13]. Mean stem diameter of the sample trees at breast height was 27 cm and relative crown length was 68%. The sample trees were monitored during the growing seasons of 2001–2005. In the second stand (altitude 60 m a.s.l.), four Norway spruce and four Scots pine trees were monitored during the growing seasons of 2002–2003, and another four spruce and four pine trees during the growing seasons of 2004–2005. They were growing in a mixed spruce-pine stand on a relatively fertile mineral soil classified as *Myrtillus* forest type ($H_{100} = 27$ m) [13]. The total number of observations (year × tree combinations) was, thus, 57. Mean daily temperatures and precipitation sums were obtained from a meteorological station of the Finnish Meteorological Institute located about 5 km from the study stands.

Stainless-steel band-dendrometers were installed on each tree at a height of about 2 m. Before installing the band, the outer bark under the band was lightly brushed to ensure smooth contact with the trunk. The girth band consists of three basic elements: 1) a stainless-steel band encircling a tree, 2) a sensor (rotating potentiometer) reacting to movements of the stainless-steel band and 3) an aluminium-body and fastening mechanism (Fig. 1). The fastening mechanism consists of three parts: 1) a constant force spring, 2) a fastening arm, and 3) an adjustable foot (Fig. 2). The spring stretches the steel band around the tree with a force of about 3 N, making the band capable of reacting to small variations in girth but without damaging the tree.

Changes in tree girth were measured at a resolution of 0.1 mm, corresponding to diameter change of about 0.03 mm. The output of the dendrometers was stored as hourly averages. Examples of dendrometer data showing the change in the stem radius during one year are shown in Fig. 3. From these measurements, the daily values of stem circumference were calculated as the mean of hourly values and the circumference changes were converted to radial changes assuming a circular stem cross-section. The dendrometer has been described in more detail in [3].

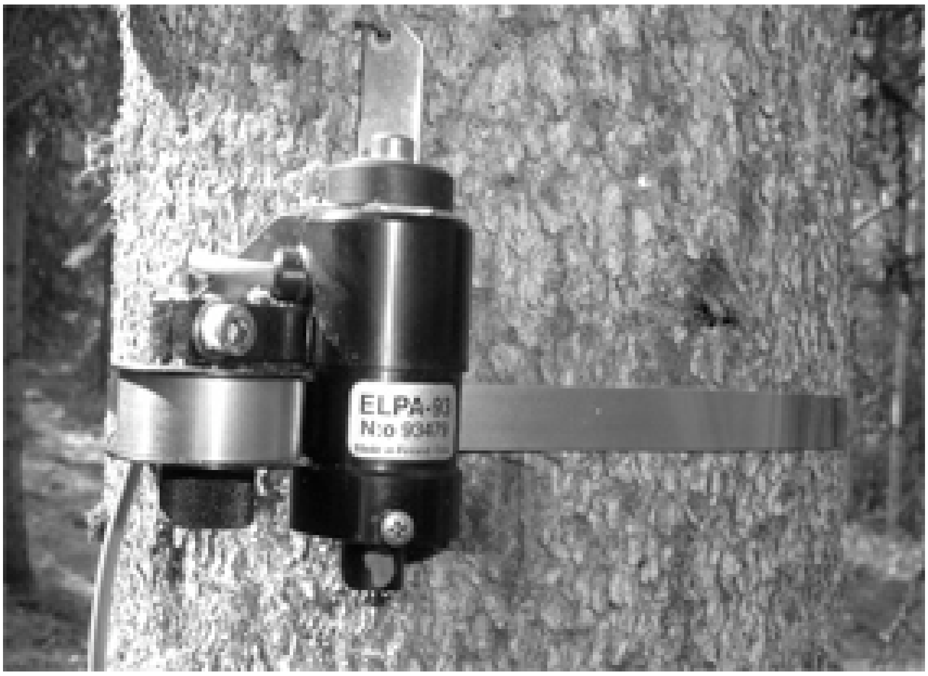

Fig. 1: The girth band mounted on a tree.

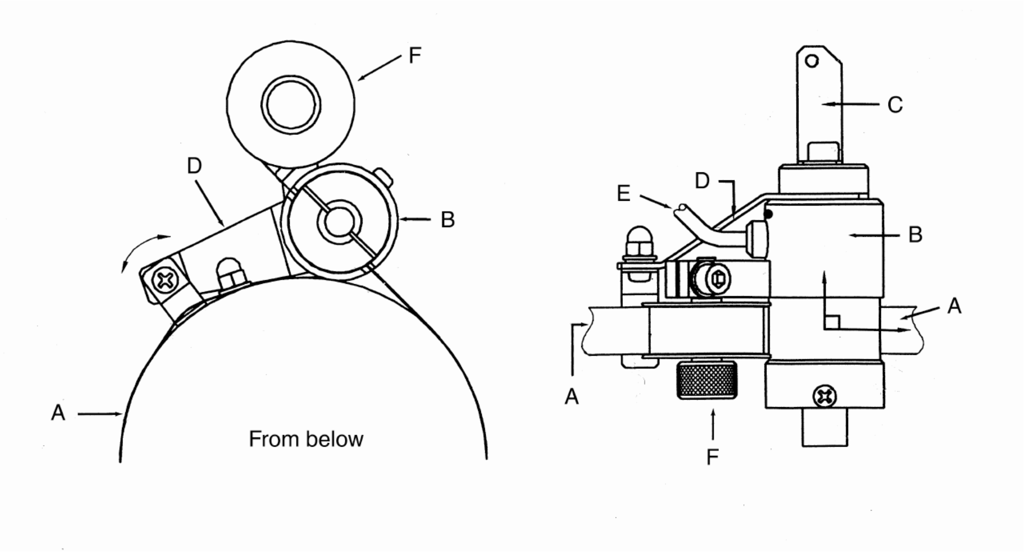

Fig. 2: Structure of the girth band: A = stainless-steel band; B = rotating potentiometer; C = fastening arm; D = adjustable foot; E = cable; F = spring.

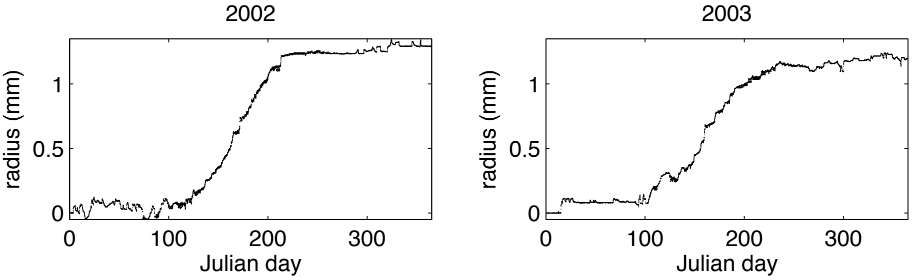

Fig. 3: Examples of the dendrometer data; a Norway spruce tree in Ruotsinkylä measured in 2002 and 2003. The zero level is the first observation of the year. The resolution the measurements is one hour.

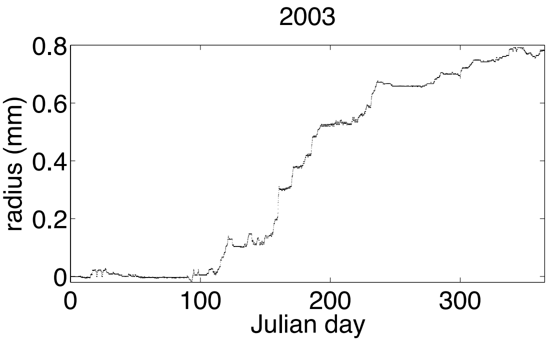

Fig. 4: Example of a difficult growth pattern. It is difficult to distinguish when the actual radial increase starts: on around day 115 or around day 150. Also, only based on the curve it is difficult to tell whether the increase ceases on around day 190, 235, or 340.

We visually evaluated the methods used in the previous studies (cited in the introduction) for determining the onset and cessation dates of radial increase from dendrometer data. All the methods had difficulties in identifying the onset and cessation dates because of stem hydration changes, i.e., they were not sufficient for identification of the crucial dates for all trees and years. It may happen, for example, that during spring stem radius starts to increase at a certain time point, but then stays constant for a rather long time, before the increasing trend reappears (Fig. 4). It is difficult to say, whether new xylem has actually been formed or whether the stem has just swollen.

We ended up, therefore, determining the onset and cessation dates visually from the dendrometer data to obtain labeling for training purposes. It should be emphasized that manual determination of the crucial dates is laborious and is likely to result in observer-related subjective differences and human errors. The dates identified visually are called below as the ‘expert choice’.

The tests can be done with all the data. Alternatively, difficult cases (Fig. 4) can be left outside the data in order to get more reliable results. We labeled an onset or cessation date of radial increase as a difficult case if there was a clear jump-like increase of at least about 0.07 mm in stem radius before the onset date or after the cessation date or if the minimum achievable difference between the predicted date and the ‘expert choice’ was at least 10 days. Altogether, there were 22 and 16 difficult cases for onset and cessation, respectively.

3 Cumulative sum chart

The cumulative sum (CUSUM) chart is a statistical process control tool, which detects small changes in the mean μ of a signal. It monitors the cumulative sum

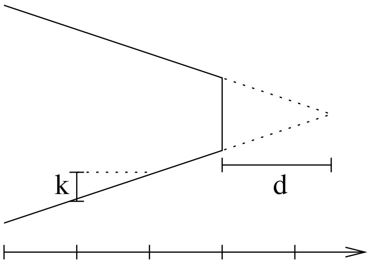

Fig. 5: Parameters d and k of the CUSUM chart define the shape of the V-mask. The shape affects how soon and how large changes are detected.

of previous observations x.

$$X \sim N(\mu, \sigma^2) \tag{1}$$

$$S_m = \sum_{i=1}^{m} (x_i - \mu) \tag{2}$$

The cumulative sum S_m at time step m is the sum of the differences between the previous observations and μ. The CUSUM chart detects up or down drifts and abrupt changes in μ, which is assumed to be known. The chart has 2 parameters: d and k, which depend on standard deviation σ, size of detectable change ΔX, and probabilities of type I (α) and type II (β) errors. The parameters define the shape of a so-called V-mask (Fig. 5), which is used to detect the changes in the mean. In case a previous value of S_m is outside the mask, it is concluded that the mean has changed (see Fig. 6).

We studied how to set the parameters of the chart to produce results as similar as possible to the 'expert choice'. One has to choose suitable values for ΔX, σ, α, and β. In addition the onset or cessation levels μ for radial increase have to determined. Cessation of radial increase can be detected by running the chart in reverse time.

The correct values of suitable detectable size of change and magnitude of noise were not known in advance. Therefore, parameters d and k were varied in a wide range: d between 1 and 50 and k between 0.01 and 0.1. The accuracy of the predicted dates was verified by 10-fold cross-validation [14]. In 10-fold cross-validation, the data set is divided into 10 disjoint sets of equal size. The parameters of the chart yielding the minimum error are selected 10 times and each time one of the sets is held out as a validation data set. Parameter values, which yielded the minimum mean absolute deviation e in days (Equation 3) for a training data set, were chosen. The performance of the model is estimated as the mean of the 10 errors obtained using the validation data sets.

$$e = \frac{1}{n} \sum_{i=1}^{n} |a_e - a_c| \tag{3}$$

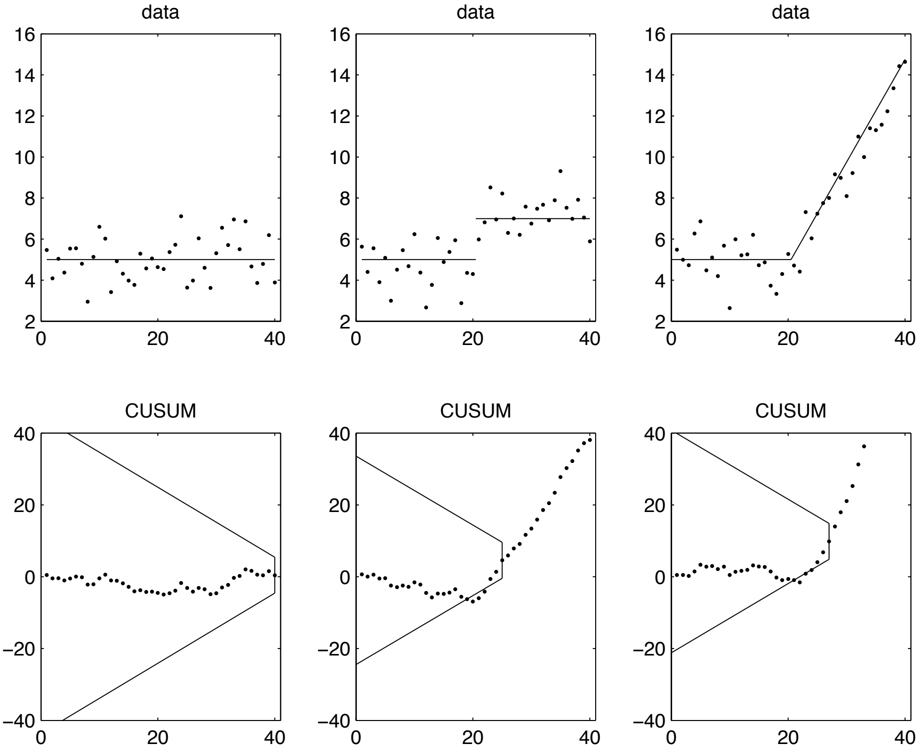

Fig. 6: Artificial data with constant mean (left column) and abrupt (middle column) and gradual change in mean (right column) and the respective CUSUM charts (bottom row). When μ stays the same, the values of cumulative sum S_m stay inside the V-mask. A change in μ is detected, when a previous value of cumulative sum is outside the V-mask.

Above, n is the number of onset or cessation dates in the training or validation set, a_e is the 'expert choice' and a_c is the date predicted by the CUSUM chart.

Performance of the CUSUM chart can be improved by focusing on only upward (onset) or downward (cessation) shifts in mean, i.e., using only one half of the V-mask for detecting the changes. This reduces the number of false alarms. This procedure was used to produce the presented results.

4 Results

It was found that the average stem radius during spring or fall is a better value for μ than the average of whole winter due to, e.g., swelling and shrinkage of the stem. The spring was defined as the two week period before the first day with average temperature > 3 °C. Similarly, fall was defined as the two week period after the first day with average temperature < 3 °C after summer.

Lowest average errors obtained with separate parameter values k and d for each tree and year were 1.6 days for onset and 2.9 days for cessation, respectively. The onset and cessation dates of other trees cannot, however, be detected with the same accuracy using these parameter values, because the optimal parameters differed between the trees and years. Same parameter values were, therefore, used for all the trees and years. The average training errors were 8.6 and 9.8 days for onset and cessation, respectively. The average errors in the validation data set were 8.9 and 11.0 days for onset and cessation, respectively.

The relatively high errors were mainly caused by some difficult cases. The difficulty was caused by increasing stem radius related to stem hydration before the actual radial increase begins and during fall after the radial increase has ceased (Fig. 4). These kinds of curves were also difficult for the CUSUM chart, i.e., it detected the onset date too early and cessation date too late. When the difficult cases were left out, the average errors clearly decreased. The average errors in the training data set were 2.5 days and 7.3 days for the onset and cessation, respectively. The average errors in the validation data set were 3.1 days and 8.2 days for the onset and cessation, respectively.

5 Discussion

The development of stem radius or circumference can be monitored with a high time resolution and summed up to long-term results using modern automatic dendrometers. Durability, automated measurement, and low price make dendrometers suitable to be used in a growth monitoring network covering large regions.

Much of the variation in stem radius is, however, independent of xylem formation. In late winter and early spring, rising temperature may increase evapotranspiration, whereby this water loss cannot be replaced by water uptake due to soil frost and it consequently causes a reduced stem radius, e.g. [7]. Later in spring, water uptake will result in an increase of stem radius not related to the formation of new tracheids, e.g. [15, 16, 8, 17]. Onset of wood formation may, thus, be masked by the rehydration of the stem, cf. [18].

Likewise, increases in stem radius in late summer may be caused by stem swelling rather than wood formation, making it difficult to determine the cessation of wood formation from dendrometer measurements. Especially in the slow-growing boreal forests, the daily swelling and shrinkage of the stem is relatively large compared to the radial stem increase caused by cell division and enlargement. In cold regions, such as Finland, wintertime ice formation in stems does further complicate the interpretation of girth band data [19].

In the experiments, the CUSUM chart proved to be a good starting point for detecting automatically the dates when the radial increase of trees begins and ceases. Suitable parameters values for the CUSUM chart are needed to get accurate results. Once configured properly, the CUSUM chart produced results similar to the 'expert choice'. In most cases, the results were accurate for the onset of radial growth. To detect the cessation date is more difficult, because during fall the amount of stem radius increase is small compared to the reversible changes in stem radius, which cause false alarms.

A relatively high number of cases (39% and 28% for the onset and cessation, respectively) were labeled as difficult. The changes in stem radius caused by wood formation and other factors can not always be distinguished using the CUSUM chart. It proved necessary to compare the dendrometer measurement with direct measurements on tracheid formation on the stems. Thus, the results achieved by using the CUSUM chart should always be checked by an expert before using them in further analysis. The amount of manual work needed for identifying the crucial dates can anyway be reduced by the CUSUM chart.

The CUSUM chart is also a useful method for on-line detection of onset of radial increase. In contrast, the cessation of radial increase can not be detected on-line using the CUSUM chart. In retrospective analysis of onset and cessation of radial increase it is probably advantageous to use the observations on both sides of the change point to improve the performance of the detection method.

6 Conclusions

In this study, using the CUSUM chart was studied for automatic detection of onset and cessation dates of radial increase of stems based on automated dendrometer data. At their best, the results agreed rather well with dates determined by an expert. Detecting the cessation of radial increase was a more challenging task compared to the onset date.

In the experiments, trees from two stands were analyzed. The method and the estimated parameters can be used to assign preliminary onset and cessation labels to trees in other stands.

Other change detection methods may also be suitable for the problem. In a future study, the CUSUM chart will be compared with, e.g., segmentation and regression methods and trend tests such as the Mann-Kendall test and F-test. We will also analyse the relationship between environmental factors and the onset and cessation dates of radial increase.

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