A volume change index for forest growth and sustainability

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Summary

A volume change index is suggested that is derived from growth components that can be estimated from remeasured plots. The new index incorporates more information than the traditional growth over removals ratio. The new index directly indicates whether the standing volume will be increasing or decreasing if current conditions persist, whereas the ratio of growth over removals obscures the impact of mortality. The details of estimating the components of growth are discussed with regard to interpreting the new index. The effect of spatial scale on the index is explored and a variance estimator is suggested. The new index is estimated from US Department of Agriculture Forest Service annual inventory data for two example applications. The first application looks at spatial trends in the index. The second application applies the index to a mill working circle.

Introduction

Forests provide numerous goods and services, and trees are harvested on private lands by an array of independent actors. These actors may be seeking wood for lumber, energy, or pulp. Their independent localized actions impact the regional forest sustainability in ways that may not be obvious. It is therefore important to monitor forest sustainability at a broad scale to determine if the combined effect of the various local timber harvest activities is sustainable. The regional information on sustainability may influence decisions at the local level to bring growth and removals into balance where needed. For example, decision makers are unlikely to locate new mills in areas that are already experiencing sustainability issues. Likewise, existing mills should not increase capacity in these areas. The work being presented here is intended to provide this type of information to decision makers.

Forest certification also provides justification for this work. Data on forest growth and removals from inventories are required by forest certification organizations as part of the certification process (Rametsteiner and Simula, 2003) to ensure sustainability. Forest certification is an important market-driven mechanism (Cubbage *et al.*, 1995; Prisley and Malmquist, 2002; Cashore *et al.*, 2004; Hansen *et al.*, 2006) for encouraging sustainable forest management. There are also calls by international working groups, such as the Montreal Process and the Helsinki Process (Brand, 1997; Hall, 2001) to use forest growth and removals as indicators, e.g. Montreal Process Criterion 2: *Maintenance of Productive Capacity of Forest Ecosystems*. This suggests that there are many potential uses for new indicators of forest growth and sustainability.

There are numerous indexes for assessing aspects of forest sustainability, such as fragmentation (Butler *et al.*, 2004). A general approach to

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assessing sustainability could be based on looking at multiple indexes (Mendoza and Prabhu, 2000; Diaz-Baltero and Romero, 2004). The focus here is on developing an index that combines the major components of forest growth with an emphasis on monitoring harvest sustainability.

We define the components of growth and the new sustainability index in the following section. Subsequent sections develop variance estimators and apply the index to two examples that use publicly available US Department of Agriculture (USDA) Forest Service forest inventory and Analysis (FIA) data (USDA, 2005).

Definition of growth components

Consider the components of growth as described by the following equation:

$$V_2 = V_1 + G - R - M, \tag{1}$$

- V_j is the per acre volume at year j, $j = 1, 2$,
- G is annual per acre growth,
- R is annual per acre removals,
- M is annual per acre mortality.

The components in equation (1) can often be estimated from inventory data with repeated plot measurements, but there are alternative approaches to estimating these components (Roesch, 2007; Van Deusen and Roesch, 2008). The approach that we are advocating here will be referred to as the accounting method. This implies that the right-hand side components (equation 1) should add up to V_2.

The accounting approach is implemented by computing the components of growth for each remeasured plot. Suppose a particular plot had three trees with merchantable volume at time 1 and four trees with merchantable volume that were on the plot after time 1, but not necessarily at time 2 (Table 1).

The survivor, ingrowth and mortality trees remain on the plot at time 2. However, the mortality tree has no merchantable volume at time 2 by definition. The harvested tree is gone before time 2, but its growth is still estimated. The accounting approach for this plot gives the results illustrated in Table 2. This demonstrates that the components for each remeasured plot will add up as indicated in equation (1).

Growth component computation for each remeasured plot is simple and guarantees additivity, much like balancing a chequebook. However, many inventories also have plots that were measured only at time 1 or time 2. This will tend to destroy perfect additivity in the growth component estimates unless constraints are applied. Annual inventories, such as the one conducted by the USDA Forest Service, also cause difficulties for the accounting approach. These data consist of annual measurements from a small subset of the plots that would not give a good estimate for the components on an annual basis. Annual inventory data are typically analysed by grouping plots measured over several years and analysing them as if they were measured in the same year. FIA calls these evaluation groups. Special methods are developed below for deriving a volume change index from annual inventory data.

The volume change index

The proposed new index of volume change is simply $I_C = V_2/V_1$, which is generally computed as

$$\hat{I}_C = \frac{\sum_{i=1}^{n_2} V_{2i}/n_2}{\sum_{i=1}^{n_1} V_{1i}/n_1}, \tag{2}$$

where n_1 and n_2 are the numbers of plots, and V_{1i} and V_{2i} are the volumes on plot i at times 1

Table 1: Tree volumes on a plot at two times

Tree	Volume 1	Volume 2	Growth	Status
1	100	120	20	Survivor
2	100	120	20	Harvested
3	100	0	0	Mortality
4	0	80	80	Ingrowth

The growth and tree status for growth component estimation are indicated.

Table 2: Growth components for the plot measurements in Table 1

V_2	V_1	G	R	M
120 + 80	100 + 100 + 100	20 + 20 + 80	120	100

and 2. This is easy to compute and interpret. The index suggests a sustainably managed forest when $\hat{I}_C \geqslant 1$. There is cause for concern and further investigation when $\hat{I}_C < 1$. If the components of growth are properly estimated, then $\hat{I}_C$ directly indicates whether the standing inventory (growing stock) can be expected to increase or decrease over time if the management strategy that existed when the inventory data were collected persists.

The index is conceptually simple, but there are some data-related complications that need to be considered. Most continuous forest inventories have plots that were not measured at both times. For this reason, it makes sense to compute this index as a ratio of means rather than a mean of ratios. This results in an index that expresses mean volume at time 2 over mean volume at time 1. As such, it has the scale-free quality of an index, since volume units are irrelevant. Annual inventories present a further complication that is discussed below.

A midpoint index for annual inventory data

Annual inventory data, as collected by the USDA Forest Service, typically have 10 or 20 per cent of the total plots being measured each year, but this varies by state or region of the US. Suppose one has data from a state where exactly 20 per cent of the plots were measured each year and the survey has been underway for 8 years. The USDA Forest Service packages these data into evaluation groups that generally include the most recent set of plot remeasurements. Therefore, the evaluation group for this hypothetical state would include 5 years of plot measurements, where the most recent 3 years would be the remeasured plots. The oldest 2 years worth of measurements would be from the 40 per cent of plots that have only been measured once.

The estimation approach suggested here for annual inventory data is to use only the remeasured plots. These plots are put into a common pool which allows for the estimation of the following components: V, G, R and M. Each component estimate represents a value at roughly the midpoint year for the set of pooled plots. In general, the time that the estimates represent depends on the mix of measurement times in the pooled data. Regardless, we refer to these pooled estimates as midpoint estimates and denote the midpoint volume change index as $\tilde{I}_C$.

The midpoint estimates are used to produce a modified volume change index as follows:

$$\tilde{I}_C = 1 + \frac{\tilde{G} - \tilde{R} - \tilde{M}}{\tilde{V}}. \qquad (3)$$

This is motivated by the idea that the generic sustainability index, $I_C = V_2/V_1$, can be derived by dividing the right-hand side components of equation (1) by V_1. The midpoint index has the same interpretation as the regular volume change index. A value of 1 or greater indicates sustainability and values less than 1 suggest a declining inventory.

Each of the component estimates in equation (3) must be a valid estimate for the inventory design being used. The USDA Forest Service annual inventory design uses mapped plots, so these estimates should come from estimators that account for mapped plot characteristics (Van Deusen, 2004; Bechtold and Patterson, 2005).

Variance estimator

Standard errors of volume change index estimates can be estimated with equation (2.46) from Cochran (1977). The finite population correction factor is ignored here, since a very small proportion of the population is being sampled by most inventories. The standard error estimator is

$$s(\hat{I}_C) = \frac{1}{\sqrt{n}\bar{V}_1}\sqrt{\frac{\sum(V_{2i} - \hat{I}_C V_{1i})^2}{n-1}}, \qquad (4)$$

where n is the sample size, V_{2i} and V_{1i} are the volumes from plot i and $\bar{V}_1$ is the mean of the time 1 volumes.

The standard error estimator for the midpoint index can be approximated by using an analogy to equation (4):

$$s(\tilde{I}_C) = \frac{1}{\sqrt{n}\bar{V}}\sqrt{\frac{\sum(C_i - \tilde{r} V_i)^2}{n-1}}, \qquad (5)$$

where $C_i = G_i - R_i - M_i$ is the change component for plot i, V_i is the current volume for plot i, $\tilde{r} = \tilde{I}_C - 1$ and $\bar{V}$ is the mean of the plot volumes.

The justification for equation (5) follows from the fact that $\tilde{I}_C - 1 = \sum C_i / \sum V_i$. Therefore, it is a ratio estimator of the type that equation (2.46) of Cochran (1977) was designed for. If equation (5) is applied to FIA-mapped plots, a few modifications are required. In particular, $\bar{V}$ would be a mapped plot mean and the sample size, n, would need to be adjusted to account for the plot mapping (Van Deusen, 2004; Bechtold and Patterson, 2005). The adjusted sample size would be $\tilde{n} = \sum a_i$, where a_i is the proportion of plot i that is in the condition of interest.

Applications

For the first application, the midpoint index is estimated from USDA Forest Service annual inventory (FIA) data for Alabama, Georgia and South Carolina. Each of these states is covered with a hexagonal grid where each hex contains 5937 acres (2.47 acres = 1 ha). Each plot is assigned to the closest hex centre to facilitate producing spatial displays. Each hex that was assigned a plot is filled with a shade of gray to represent the index value for the location. Hexes that are not assigned to a plot are not coloured in the final display. FIA plot locations are available to the public to within 0.5 miles (1 km = 0.62 miles) and some plot locations are swapped with other plots in the same county, so the resulting maps have a limited resolution. This application is useful for locating areas where the sustainability index is either high or low.

The second application computes the midpoint index for all plots contained in a circle with a radius of 100 miles (160 km) centred in Alabama at latitude 31.916 and longitude −87.738. This demonstrates how the index could be used to assess the sustainability status within a mill working circle. The variance estimate (equation 5) is of interest for this type of application.

For both applications, remeasured FIA plots from the most recent evaluation group are used. Only timberland plots are included, where timberland is defined as forested land that is not legally reserved and that can produce at least 20 cubic feet per acre (1.4 m^3 ha^{-1}) per year. The midpoint index incorporates estimates for growth, removals, mortality and volume for each remeasured plot. The growth component is based on growth of growing stock trees that were on the plot at time 2 and trees that were removed prior to time 2 to be used for products. The removals component is based on the estimated volume at time of removal for trees that were alive at time 1 and removed for products prior to time 2. Mortality trees were alive at time 1, but dead at time 2. They only contribute to the mortality component. It is assumed that mortality trees did not grow and have no salvable volume at time 2. The estimates for growth, removals and mortality are annualized. The volume estimate is based on the net cubic foot volume at time 2 of live trees from a 1-foot stump to a 4-inch top outside bark diameter or to where the central stem breaks up into smaller branches.

The computational details are important to keep in mind when interpreting the index. In this case, the index is based on merchantable volumes and annualized change estimates. The index, as computed here, represents an annual relative change in merchantable volume. Therefore, an index of 1.05 implies an annual increase of 5 per cent in merchantable volume.

Example 1: Computing the index at different spatial scales

The matter of spatial scale has not been discussed yet. This application uses annual inventory data and the midpoint index (equation 3). One spatial extreme would be to compute the index for each plot, and the other would be to compute a single index for the tristate region. Neither approach would be very informative in a spatial display. The former would be too variable and the latter would show no variance.

We approach the issue of spatial scale by using a specified number of nearest neighbours to compute an index for each hex that has a growth plot assigned to it. Index values are computed based on 100, 50 and 25 neighbours for each hex. The set of indices based on the 100 nearest plots will show less spatial detail than the indices based on 50 or 25 neighbours. Each FIA plot represents approximately 6000 acres (2428 ha). Therefore, the 100 neighbour computation could be thought of as representing 242 800 timberland hectares around each hex. The clusters of neighbours are approximately circular for interior plots but are skewed towards the forest for plots near non-forest areas or water.

Other smoothing techniques, such as Kriging, could also be applied to this index. Kriging would have the advantage of providing a variance approximation for each location. However, the selected method of looking at three maps based on 25, 50 and 100 neighbours is easy to understand and interpret visually.

Example 1: Results

The plots used in this analysis are classified as privately owned timberland and have a remeasurement. Some general plot summary statistics are given in Table 3. The median year is a good measure of the year that the midpoint index represents. The hectares row (Table 3) is an estimate of the total number of private timberland hectares that were represented by this set of remeasured plots. The hectares/plot row indicates how many hectares each plot in this analysis represents.

The midpoint sustainability index estimates for Alabama, Georgia and South Carolina are displayed in Figure 1 separately for softwoods and hardwoods and for each spatial scale. As expected, the spatial variability increases as the number of neighbours used in the computations decreases for both softwoods and hardwoods. The index values are displayed in four categories. Index values less than 0.95 are shown in black, values between 0.95 and 1.0 are shown in dark gray and values that are greater than 1.0 but less than 1.05 are light gray. White indicates either non-forest or an index greater than 1.05. White indicates areas where there should be little concern about harvest sustainability. Black denotes areas where harvest sustainability could be an issue if recent levels of activity persist.

Example 2: Computing the index for a working circle

FIA plots used for this analysis are located on timberland within a 160-km radius circle centred near Thomasville, AL. There were 1592 plots in Alabama, 72 in Florida and 590 in Mississippi for a total of 2254 plots in the circle. The median measurement year for these plots was 2004. The results were similar for hardwood and softwood (Table 4).

The conclusion for this particular working circle is that the current harvest levels are barely sustainable, and any increase in harvest levels are likely to decrease the standing inventory over time. An approximate 95 per cent confidence interval lower bound can be obtained by subtracting two standard errors from the midpoint estimates in Table 4. The resulting lower bounds are slightly less than 1.0 for both hardwoods and softwoods within this circle. This is not a dire situation, but it suggests that there is little room for increased harvesting without commensurate effort to increase the wood supply via plantation establishment or other management actions.

Discussion

The midpoint volume change index was applied to achieve two different but related purposes. The

Table 3: Summary statistics to describe the FIA plots used in the analysis

Item	Alabama	Georgia	South Carolina	All
Number of plots	3431	3636	1652	8719
Year range	2001–2007	1998–2006	2002–2006	1998–2007
Median year	2005	2004	2004	2005
Hectares	7 782 540	8 006 737	3 462 504	19 252 187
Hectares/plot	2268	2202	2096	2208

These are privately owned timberland plots that have been remeasured.

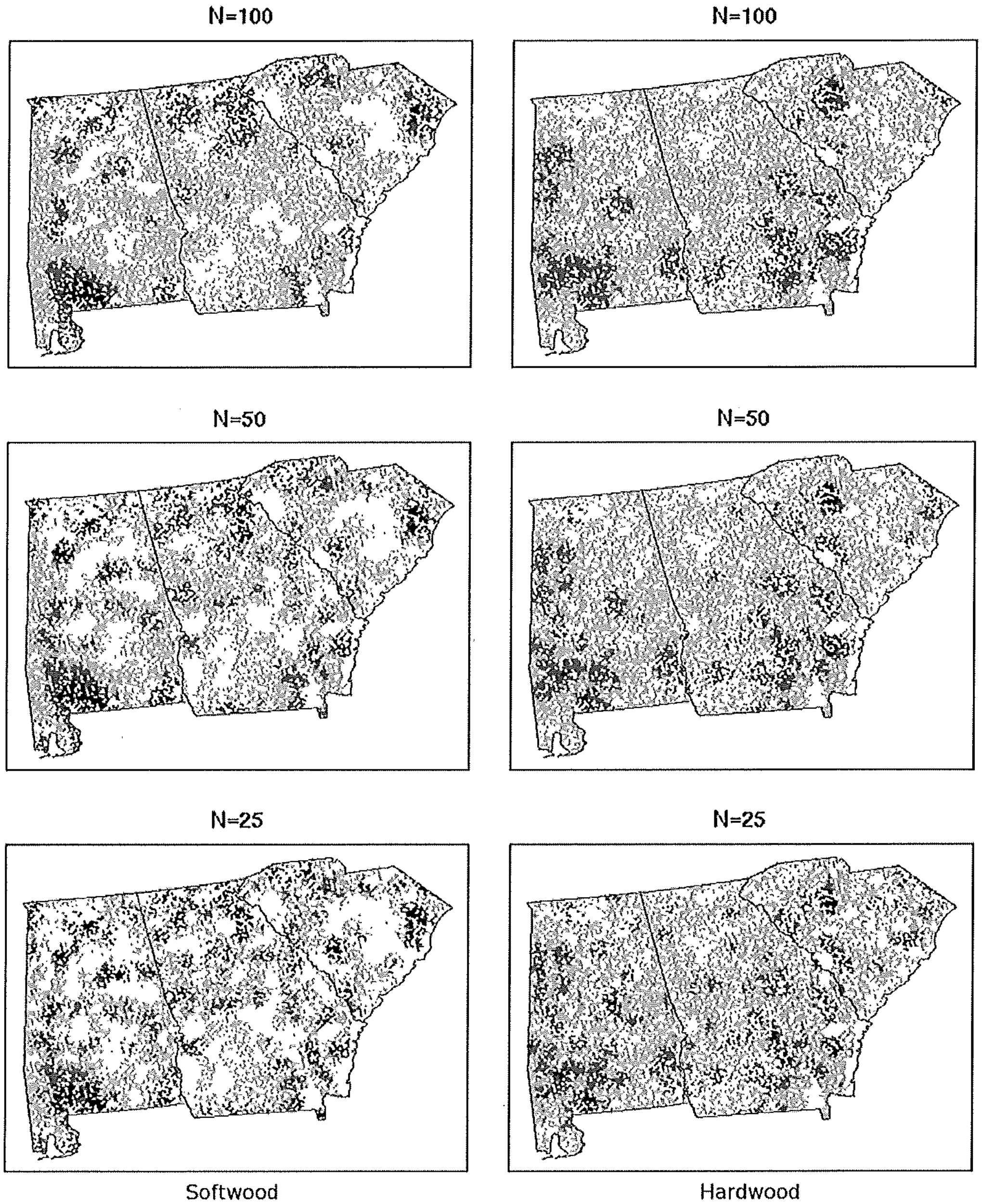

Figure 1. Midpoint sustainability index at three scales for softwoods and hardwoods. The scales are based on 100, 50 and 25 neighbours. Colour code: black = $\tilde{I}_C < 0.95$; dark gray = $0.95 \leqslant \tilde{I}_C < 1$; light gray = $1 \leqslant \tilde{I}_C < 1.05$; white = non-forest or $\tilde{I}_C \geqslant 1.05$.

first example application demonstrates how the index can be applied and viewed spatially to indicate patterns in sustainability levels. The second application is to a working circle where a particular mill might want to assess the sustainability of its wood supply.

The results of the first application are summarized in Figure 1. The darkest areas in each state are zones where the midpoint sustainability index was less than 1.0. This implies that the forest inventory has been declining in these areas in recent years. These results are representative of

Table 4: Midpoint index and standard error estimates for FIA plots in a 160-km radius circle centred in Alabama

	Hardwood	Softwood
Midpoint index	1.003	1.011
Standard error	0.003	0.006

conditions in approximately 2005 and can be updated as new annual inventory data become available from the USDA Forest Service. The results apply to privately owned timberland.

The extent of the dark zones on the maps (Figure 1) depends on the number of neighbouring plots used in the computations. The map based on 100 neighbours indicates zones of a larger extent than the map based on 25 neighbours. The map based on 25 neighbours shows more localized zones that may be eliminated when additional neighbouring plots are included. In general, one might conclude that the darker zones that persist over all three neighbourhood levels are where the sustainability index is most consistent and suggests trends that apply to a larger area.

There are also some differences in where the sustainability index highlights potential hardwood and softwood concerns. In general, the hardwood index is less than 1.05 over a larger area than the softwood index. This is evident from the larger areas of white on the softwood maps. The southwestern part of Alabama is highlighted on all the figures, but some of the dark softwood zones in central Georgia do not show on the 100 neighbour figure. This would imply that the central Georgia dark softwood zones do not have a large spatial extent.

The second application suggested that the wood supply in the selected working circle is marginally sustainable, but there is no room for increased harvesting. This application assesses a specific procurement zone and demonstrates the value of looking at an approximate 95 per cent confidence interval. If the confidence interval lower bound is greater than 1.0, then recent harvest levels can be assumed to be sustainable without improved management.

Conclusions

Indexes to assess sustainability are appealing because they provide a single number that is easy to interpret. The index developed here is particularly easy to interpret, since values greater than 1 imply sustainability while less than 1 implies nonsustainability. The index is based on the simple concept of looking at the ratio of volume at time 2 over volume at time 1. This incorporates more information than an index based on growth over removals. In particular, it includes the impact of mortality in a clear fashion. The new index is not as easy to compute for annual inventories as it is for periodic inventories. The midpoint sustainability index was proposed for annual inventories and demonstrated with FIA data from a number of Southern states.

The midpoint volume change index ($\tilde{I}_C$) suggests that an area is losing inventory when the value is less than 1.0. One could interpret this index using the "rule of 72" that applies to how long it takes an investment to double at a certain interest rate. Suppose the index is 0.94, which is 6 per cent less than 1.0. Since $6 \times 12 = 72$, the "rule of 72" implies that half the standing volume would be lost in 12 years at this rate.

It is likely that the zones where $\tilde{I}_C < 1$ will change over time, so it is wise to avoid projecting a static assessment into the future. These values can be updated each year as new FIA data become available. Monitoring sustainability trends can ensure that problems are averted before they become serious.

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Conflict of Interest Statement
None declared.

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