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PLOT INTENSITY AND CYCLE-LENGTH EFFECTS ON GROWTH AND REMOVALS ESTIMATES FROM FOREST INVENTORIES

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Abstract. Continuous forest inventory planners can allocate the budget to more plots per acre or a shorter remeasurement cycle. A higher plot intensity benefits small area estimation and allows for more precision in current status estimates. Shorter cycles may provide better estimates of growth, removals and mortality. On a fixed budget, the planner can't have both greater plot intensity and shorter cycles. Therefore, it is important to understand the trade-offs involved. Growth over removals ratios are important indicators of sustainability, and can be adversely affected by changes in cycle length. However, it might be possible to ameliorate negative impacts of longer cycle lengths with judicious use of aerial imagery. Increasing the cycle length reduces the value of an inventory for monitoring, but reducing the number of plots increases the variance of both current status estimates and trend estimates. There may be no optimal statistical solution to this quandary, but the best solution will depend on policy and management objectives. Continuous forest inventories use permanent plots that are remeasured to provide information on growth, removals and mortality. Typically, all plots are remeasured within a narrow time span, but the USDA Forest Service has popularized a variant referred to as an annual forest inventory where a percentage of the permanent plots are remeasured every year. We discuss trade-offs between number of field plots and cycle length and provide some insight with example applications showing how these decisions impact growth and removals estimates. We also discuss a variant of the traditional growth over removals ratio estimator that limits degradation in estimate quality as cycle lengths increase.

Keywords: Forest inventory, Remote Sensing, Remeasurement Cycle, FIA data

1 Introduction

Continuous forest inventories that cover large regions must consider 3 main design factors that affect costs: plot intensity, remeasurement cycle, and field work requirements. For example, the USDA Forest Service Inventory and Analysis (FIA) program (Bechtold et al. , 2005) has a base plot intensity of 1 plot per 6000 acres. The remeasurement cycle originally mandated in the 1998 Farm Bill was 5 years. FIA field work requires nearly 1 day per plot for a 2 person crew. The field work required to satisfy the diverse users of a national forest inventory is necessarily greater than what is needed by a survey of private property. Hence, a private timberland survey will typically measure many more plots per day than a public forestland survey.

Statistical theory (Cochran , 1977; Thompson , 2002) provides general guidance on plot intensity (sample size), when a single variable is of interest and precision limits are well defined, such as in Skidmore et al. (2014) and Strimbu (2014)), but this theory is of limited value in multiple objective inventories. Forest inventories usually involve numerous variables and users often create tables of estimates where each table cell will have a different sample size. For example, some users might want a table that estimates growth by diameter class and species. Sample sizes that would ensure adequate precision for each table cell would often be too costly.

If change and trend were secondary concerns, then remeasurement cycle length would be a minor issue. However, forest monitoring implies that trend estimates are paramount. Estimates of growth, removals, and mortality (GRM) generally depend on remeasured plots and are impacted by the remeasurement cycle. GRM estimates may also require more complex analysis methods and assumptions than estimates of current-state variables, such as standing volume.

There may not be an optimal balance between plot intensity, remeasurement cycle and field work. However, we believe that it is possible to understand the trade-offs involved between increased plot intensity and longer cycles. Field work requirements influence the budget, which affects plot intensity and remeasurement cycle. However, field work is determined by the purpose of the inventory rather than statistical issues, and we leave that discussion to others (Condit , 1998; FAO , 2011).

2 Plot Intensity and Cycle Length Trade-offs

Suppose there are N field plots and they are all remeasured over a cycle of length C. All else being equal, this requires an annual budget sufficient to measure n_C plots per year, where $n_C = N/C$. It's obvious that n_C increases as N increases and decreases as C increases. Also, n_C can stay the same if N and C are changed proportionately. For example, having $N = 5000$ and $C = 5$ results in the same amount of work each year as $N = 10000$ and $C = 10$. This is a complicated way to say that the same annual budget can support twice as many field plots if the cycle length is doubled. This ignores the initial establishment costs of the extra field plots.

There are some obvious limits and trade-offs between cycle length and number of plots. For example, there is scant value in remeasuring forested plots each year, especially in temperate forests with little annual change. At the other extreme, remeasuring plots on a cycle that exceeds half the rotation age would provide poor information about GRM. For example, a rotation age of 15 years in conjunction with a 10 year cycle leads to the distinct possibility that 2 consecutive measurements of the same plot are in different rotations. A 5 year cycle could also lead to consecutive measurements being in different plantations with a 15 year rotation, but the necessary extrapolations to estimate GRM are less onerous. However, placing an upper limit of half the rotation age for remeasurement cycles is clearly a "rule of thumb" that may not always apply.

The "rule of thumb" for uneven-aged stands is that the remeasurement cycle should not be greater than half the average time between harvests. This will reduce the probability of 2 harvests occurring between consecutive plot measurements. The average harvest-cycle can be estimated from the proportion of timberland that is harvested each year. For example, a 20 year harvest-cycle corresponds to a 5% annual harvest.

The focus here will be on the trade-offs between a 5 year cycle and a 10 year cycle and how this impacts estimates of growth over removals ratios (G/R). We show that these impacts can be surprisingly large and also suggest an estimator that reduces the impact. We discuss plot intensity effects and point out that the impacts of changing plot intensity are relatively easy to understand. However, this does not change the fact that maintaining a sufficient number of plots to achieve estimation goals is very important.

2.1 Plot intensity effects It is often more useful to base inventory sample size on how much area each plot represents, rather than on statistical sample size equations that were developed for other purposes. For example, 20 plots placed in a 100 acre stand is 1 plot per 5 acres, and this might be more than adequate for estimating total volume. However, 1000 plots for the state of Maine with 17.6 million acres of forest (1 plot per 17,600 acres) is probably inadequate even though a sample size formula would suggest otherwise. The size and configuration of the plot also has some influence, but we are leaving that issue to others (Condit , 1998; You , 2011).

FIA plot intensities are determined by the quality of estimates required for large regional areas, such as a state or multiple counties. The current FIA base intensity of 1 plot per 6000 acres satisfies FIA's official reporting and accuracy requirements, but it is considered inadequate for county level estimates (Bechtold et al. , 2005). Some states have contributed extra funding to support double intensity, e.g. Michigan, Minnesota and Wisconsin; evidently they decided that the FIA base intensity is inadequate. This notion is supported by the fact that FIA installed 1 plot per 2200 acres in the southeastern states in the past. This was justified due to higher levels of timber management in the coastal plain regions. This suggests that 1 plot per 6000 acres is sparse for other managed areas, and may reflect budget limitations rather than statistical adequacy.

2.2 Remeasurement cycle effects As discussed above, a 1 year cycle would rarely be necessary in a forest inventory and a cycle that is longer than half the rotation age might provide unreliable change information. It seems likely that a remeasurement cycle ranging from 5 to 10 years would be adequate in the contiguous US. However, 10 years might be too long in some of the southern states and 5 years might be too frequent in some of the northern states.

To put things in perspective, the southern US produces about 18% of the global round-wood delivered to mills from only 2% of the global forested area (FAO , 2011; Prestemon and Abt , 2002). According to FIA data, around 40% of the harvested volume in the south comes from plantations. This suggests that plantation rotation ages, which can be as short as 15 years, should be a major determinant of the cycle length for the FIA program in the southern US. Our rule of thumb says that 5 years is an overall minimum for the US, and a 5-7 year cycle would be justified for a 15 year rotation.

We remind the reader that our "rule of thumb" isn't sacrosanct. A 5 year cycle will result in better GRM estimates than a 7 year cycle with 15 year rotation ages. GRM estimates are important for monitoring sustainability in regions where the ratio of G/R is close to 1.0. Therefore, the budget for a 5 year cycle is justified in the southern US, given how intensively managed it is. It follows that a 10 year cycle in the southern US could compromise the value of FIA data for monitoring sustainability.

3 Concomitant Data to Allow for Longer Remeasurement Cycles

Longer remeasurement cycles result in less accurate GRM estimates. This is due to having multiple disturbance events or a stand being harvested and replanted in the interim between plot measurements. This results in growth and removals estimates that depend heavily on models and assumptions about when harvests took place. Additionally, although not explored further here, Roesch (2007) showed that in the presence of non-linear growth, growth estimates calculated from inventories of different cycle lengths are actually estimates of different population parameters. Regardless, sequential aerial images provide a potential method to obtain useful concomitant data to improve GRM estimates. Low cost, high resolution digital imagery, such as from the National Agricultural Image Program (NAIP) in the US, is available and other researchers have demonstrated that change estimation from images is feasible (Webb et al. , 2012).

Suppose we had remotely sensed data giving the year when a harvest occurred for each field plot and want to use this information to adjust modeled GRM estimates. Consider a plot that was measured in year t and again in year $t+10$. At $t+10$ the field crew records the location of harvested stumps, dead trees, and measures the residual live trees. Suppose back in the office, from remote sensing, it is possible to determine that the harvest occurred at $t+1$. The stumps can be matched with the standing tree measurements from time t, and growth for residual trees is estimated from the two consecutive plot measurements.

The remotely sensed information can be used to improve removals and growth on removals estimates by providing an estimate of the harvest year. Little growth will occur in 1 year, so one might assume that growth on removals is 0 when harvest occurred at time $t+1$. Likewise, removals for a harvest at $t+1$ are practically assumed to be the same as the volume of the removals trees at time t, ignoring residuals left on site. If the harvest happened at time $t+8$, then more complex modeling assumptions should be used to estimate removals and growth on removals.

It should be clear that remotely sensed data on time of harvest can be used to improve estimates of growth and removals. Such data could potentially justify trading increased cycle lengths for more plots, since the ability to estimate harvest times reduces the uncertainty created by the longer cycle. This could allow for benefiting from more plots without increasing the budget or decreasing the quality of GRM estimates.

4 Estimates From Remeasured Plots: The components of growth

It is possible to estimate all of the components of growth from remeasured plots. Our focus here is on estimating growth and removals, and a short review shows how they fit in with the other components.

The components of growth are often based on computations from plots that are measured at 2 times:

$$V_2 = V_1 + G - R - M$$

- V_j is the per acre volume at year j, j=1,2,
- G is per acre growth from time 1 to time 2,
- R is per acre removals from time 1 to time 2,
- M is per acre mortality from time 1 to time 2,

The concept is still relevant for continuous inventories, but there are multiple time periods to consider, i.e. $t = 1, ..., T$. Note that G, R and M would only be annual if V_1 and V_2 are separated by 1 year.

Remeasured plots are essential for monitoring forest sustainability and allow for computation of various indices of sustainability (Brand , 1997; Hall , 2001; Van Deusen and Roesch , 2008; Van Deusen and Roesch, 2009). For example, G/R ratios have the advantage of being easily interpreted, i.e. $G/R > 1$ implies that current harvest levels are sustainable (at least in the short run) and $G/R < 1$ can be viewed as an indication that a potential sustainability problem exists. Although G/R ratios are a valuable index, they should not be the sole measure for deciding that current harvest levels are unsustainable (Prisley and Malmquist , 2002). Also, there are some nuances discussed below that influence how to interpret G/R. For example, does G represent gross or net growth?

4.1 Nuances of growth estimates FIA typically provides net growth estimates which subtracts recent mortality from recent growth. This means that the entire volume or biomass of trees that died since the previous measurement is subtracted from the growth of the other live trees. Likewise, FIA removals estimates typically contain trees that were removed due to land-use conversion. For the purpose of monitoring trends, it may be more meaningful to use gross growth and harvest removals (Van Deusen and Roesch , 2008). Mortality and land use conversion can be evaluated separately. Net growth is also problematic for estimating carbon sequestration, because each dead tree's total biomass is immediately subtracted from gross growth even though that biomass or carbon may take decades to return to the atmosphere.

4.2 Nuances of removals estimates All remeasured plots provide a growth measurement, but removals data have a binomial characteristic that should be considered. Specifically, many plots have $R_{it} = 0$, since no harvesting will have occurred since the previous measurement. Hence, we could compute overall per acre mean removals, $\bar{R}_t$, or a conditional mean, $\bar{R}_{t|h}$, which gives the per acre mean for plots where a harvest occurred. The conditional mean and the unconditional mean are related as follows,

$$\hat{R}_t = p_h \hat{R}_{t|h}$$

where p_h is the proportion of plots where harvest occurred. The concept of conditional means applies to any variable that does not occur on every plot condition, but it is particularly relevant for removals.

Although removals occur within a single year, FIA spreads removals over the plot remeasurement cycle to give the appearance that an equal amount occurred each year. The purpose is to turn removals into an annual number that would seem to better correspond to growth, which occurs annually. Hence, the estimation of G/R would seem to be simplified by annualizing removals. We show in the following example application that this can lead to estimates that could be misleading.

5 Example Application

Consider data (Tab 1) for a single plot on a 5 year remeasurement cycle. The volume units are irrelevant for this example. The plot data are volume (V) , annual growth (G), removals (R) and annualized removals (R5). Volume in year t is volume in year "t" plus growth in year "t". The plot was measured in years 1 and 6. A harvest occurred in year 2, and 200 volume units were removed. Growth in a harvest year is assumed to have been removed to simplify the example. Mortality is not included in this example. The actual growth and removals numbers in the tables are chosen simply to make the computations easy and to demonstrate the concepts.

Table 1: Example data: 5 year cycle

—plot data—					—G/R ratios—	
yr	V	G	R	R5	$c(G/R)$	$i(G/R)$
1	400	0	0	0		
2	200	20	200	40	0.50	0.10
3	220	20	0	40	0.50	0.20
4	240	20	0	40	0.50	0.30
5	260	20	0	40	0.50	0.40
6	280	20	0	40	0.50	0.50

The last 2 columns (Tab 1) give G/R ratios based on different estimation schemes. The year 6 entry of the $c(G/R)$ column gives the standard FIA estimate based on dividing cumulative annualized growth by cumulative annualized removals over the plot remeasurement cycle. We are calling the $i(G/R)$ column instantaneous growth over removals. It is computed from cumulative growth over cumulative actual removals (not annualized removals). As would be expected, $c(G/R)$ and $i(G/R)$ give the same result at year 6. However, the intermediate $c(G/R)$ estimates give an optimistic view of G/R, whereas $i(G/R)$ shows a realistic progression of G/R over time.

Now we take the 5 year plot cycle data (Tab 1) and extend it to what it might look like for a 10 year cycle (Tab 2). In this case, the plot would be measured in years 1 and 11. There is still a harvest in year 2 and the annualized removals data are shown in column R10. The G/R options (Tab 2) show trends that are similar in nature to the plot under a 5 year cycle (Tab 1). There is convergence of $c(G/R)$ and $i(G/R)$ at the year 11 remeasurement. However, the standard $c(G/R)$ estimate indicates that G and R are in balance over the entire cycle, but $i(G/R)$ shows that balance does not occur until year 11. Notice that the year 6 estimate based on $i(G/R)$ is identical for the 5 year cycle or the 10 year cycle, but the $c(G/R)$ estimate is quite different. This is an artifact of artificially annualizing removals.

The $c(G/R)$ and $i(G/R)$ trends (Tabs 1 and 2) both depend on the assumed disturbance year. This is where a remote sensing estimate could provide value. The G/R trends would change if the disturbance year was known to be in year 5, for example, instead of year 2. Without any specific information, FIA will assume that the disturbance occurred at the midpoint of the measurement cycle. This would result in the plot for the 10 year cycle yielding different G/R trends than for the 5 year cycle even though the disturbance occurred at year 2, for example.

Table 2: Example data: 10 year cycle

—plot data—					—G/R ratios—	
yr	V	G	R	R10	$c(G/R)$	$i(G/R)$
1	400	0	0	0		
2	200	20	200	20	1.00	0.10
3	220	20	0	20	1.00	0.20
4	240	20	0	20	1.00	0.30
5	260	20	0	20	1.00	0.40
6	280	20	0	20	1.00	0.50
7	300	20	0	20	1.00	0.60
8	320	20	0	20	1.00	0.70
9	340	20	0	20	1.00	0.80
10	360	20	0	20	1.00	0.90
11	380	20	0	20	1.00	1.00

A plot only contributes data to an FIA estimate when it is measured, so the intermediate values shown for $c(G/R)$ and $i(G/R)$ (Tabs 1 and 2) are somewhat irrelevant. However, they do demonstrate the implicit assumptions being made to annualize GRM estimates. These examples also suggest how an FIA plot could be used to contribute data annually to the estimation process. The annual values are implicitly assumed, but not used for intermediate years. This could potentially reduce the variance of GRM estimates, but further analysis is beyond the scope of this paper.

6 Discussion

Annual inventory cost is determined by how many plots the field crew has to measure. Therefore, cutting the number of plots in half has the same effect as doubling the length of the remeasurement cycle. In fact, number of plots can be reduced in proportion to cycle length and annual cost will remain constant. However, the utility of the inventory data will change in ways that may be difficult to assess.

The effect of changing field plot intensity in a forest inventory is easier to specify than the effects of changing remeasurement cycle. Reducing the number of plots will increase the variance of estimates and generally increase the size of the area where reliable estimates can be obtained.

Cost is reduced by increasing cycle length, but the reliability of important monitoring statistics will be reduced. We demonstrated (Tabs 1 and 2) that traditional approaches that annualize removals estimates could be improved if disturbance year is known.

The FIA method for estimating G/R, i.e. $c(G/R)$, implicitly assumes that harvest is at the cycle midpoint and only incorporates a plot's data from the end of the plot's remeasurement cycle. Our suggested instantaneous accumulation method, $i(G/R)$, assumed that actual harvest year was known and can use data from each plot throughout its measurement cycle.

There is no reason that $i(G/R)$ can't be used by assuming harvest occurs at cycle midpoints, but it could also incorporate concomitant data to enhance estimates from longer cycle lengths. Remotely sensed images could provide improved estimates of the actual harvest year (Webb et al. , 2012), which could be incorporated into $i(G/R)$ so each remeasured plot contributes data for each year of its remeasurement cycles. It would not be prudent to suggest that FIA alter their GRM estimation methods based on the limited analysis done here, but it does seem clear that remote sensing for disturbance detection could have value.

7 Conclusions

Continuous forest inventory costs can be reduced by reducing the number of field plots or increasing the remeasurement cycle length. There are reasons to avoid reducing the number of plots and lean toward increasing cycle length if budgets are reduced. Plots that are discarded are difficult and costly to reestablish. If budgets are later increased, it's relatively easy to reduce the measurement cycle on existing plots and regain much of their former value. Also, an inventory consisting of too few plots offers limited options for analysts regardless of how frequently the plots are remeasured.

Longer cycle lengths reduce the value of an inventory for monitoring, but we demonstrated that alternative analysis approaches offer opportunities to obtain improved GRM estimates when cycle lengths must be increased. The same alternative methods can be used to incorporate remotely sensed information about when harvests occurred to improve monitoring capabilities. An important caveat is that cycle lengths should not violate the "rules of thumb", i.e. do not exceed half the rotation age for plantations or half of the harvest cycle time for uneven-age stands.

Even if budgets are holding steady, it is worth considering the trade-offs between increasing the number of plots and increasing cycle lengths. Improved estimation procedures and judicious use of remote sensing can potentially allow for more plots without sacrificing the ability to adequately monitor sustainability.

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