

Chapter 4

Estimating Carbon Stocks and Stock Changes in Forests: Linking Models and Data Across Scales

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Abstract The increasing amount of atmospheric carbon has been linked with changes in climate, prompting efforts to reduce the amount of carbon emissions. Estimates of forest carbon stocks and stock changes are needed, along with how these change over time, and how sequestration might be increased through forest management activities such as afforestation, reforestation, stand management, and forest protection. Carbon is accrued through increased live biomass and/or increased dead organic matter and soil carbon, whereas carbon is released to the atmosphere through respiration, decomposition, and burning. For large land areas, estimating the amount of carbon sequestration into and out of a forest system involves integrating a number of data sources and models at a variety of spatial and temporal scales. The methods used to integrate data and models across time and spatial scales vary. In this paper, we present a discussion of methods used to obtain information on carbon stocks for very large land areas, using reported analyses as examples.

4.1 Introduction

Concerns over the impacts of atmospheric changes on the global climate system have resulted in a global emphasis on altering anthropogenic activities to reduce the rate of atmospheric change. The atmospheric concentration of carbon dioxide (CO₂) rose from 280 ppm prior to the industrial revolution to ~380 ppm in 2005 and other greenhouse gases have also increased (e.g., methane from 715 to 1774 ppb¹) (IPCC

¹<http://www.unfccc.de>; accessed February 14, 2006.

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2007). Increases in the amount of atmospheric carbon have been linked to changes in climate, including a 0.74 °C temperature increase in the last 100 years (IPCC 2007). Christensen et al. (2007) note that all land regions will likely warm in the twenty-first century.

Efforts to reduce the amount of carbon and other emissions are being made, as there is increasing evidence that this warming, particularly over the past 50 years, is partly attributable to human activities. The United Nations Framework Convention on Climate Change (UNFCCC) has been developed to initiate global action including examining the causes and magnitudes of carbon sinks and sources, with a view to possibly increase carbon uptake or reduce carbon losses through management. As part of this initiative, monitoring and annual reporting of emissions and removals is one of the commitments made by parties to the UNFCCC.

Forests have been identified as possible sinks that may offset emissions produced by burning fossil fuels (e.g., Myneni et al. 2001; Binkley et al. 2002; Vågen et al. 2005). In forests, carbon is accrued through increased live biomass and/or increased dead organic matter and soil carbon, whereas carbon is released to the atmosphere through respiration, decomposition, and burning. Harvest transfers result in subsequent release of carbon from decomposition during wood processing and decay of wood products in use or in landfills. Harvest also transfers biomass to dead organic matter (slash) in the forest from where carbon will be released through decomposition. Activities such as afforestation and reforestation promote the extent of forests, whereas fire, harvest, disease, and insects reduce live forest biomass. Nabuurs et al. (2007) concluded that the expected carbon mitigation benefits of reducing deforestation would be greater than the benefits of afforestation, in the short term.

Procedures to estimate the amount of carbon in forests are sometimes labeled as “carbon budgeting”. Estimates of past and current forest carbon stocks are needed, along with future projections and estimates of possible sequestration increases through forest management activities such as afforestation, reforestation, stand management, and forest protection. Countries that have committed to the Kyoto Protocol will need to provide detailed reports on land use, land-use change, and forestry (LULUCF) activities (Penman et al. 2003). Although reporting may be for a large land area (e.g., country-wide), more localized information will be needed to detect changes and related causes (land transition matrix), and to forecast effects of management activities. These reporting needs have prompted a variety of methodological approaches to integrate a number of data sources and models at a variety of spatial and temporal scales into a reporting system.

In this paper, we present a discussion of methods used to obtain information on carbon stocks, using reported analyses as examples. We begin with some of the challenges in obtaining the necessary information. Methods used to integrate data and models across time and spatial scales, including stratification into large ecosystems, and imputation and regression methods to expand data to unsampled locations, are then discussed. In the summary, we list some of the research needs for improving these linkages and resulting estimates. As there are many articles relating to carbon budgeting, a full review is not given. Instead, examples of research, weighted to more current articles, are referenced.

4.2 Monitoring Challenges

Monitoring forests for changes in carbon utilizes many of the methods developed for forest inventory of any variable of interest (e.g., forest growth and yield). However, monitoring for carbon introduces additional complexity over commonly measured forest inventory variables, since below-ground components (e.g., ephemeral fine roots, coarse roots, soil carbon) and additional above-ground components, including litter and dead organic matter (IPCC 2007), are of interest (Fig. 4.1).

Many of these components are spatially very variable, resulting in difficulties in measuring carbon (e.g., soil carbon). Ecosystem carbon pools such as dead organic matter, litter and soil carbon are typically not included in conventional forest

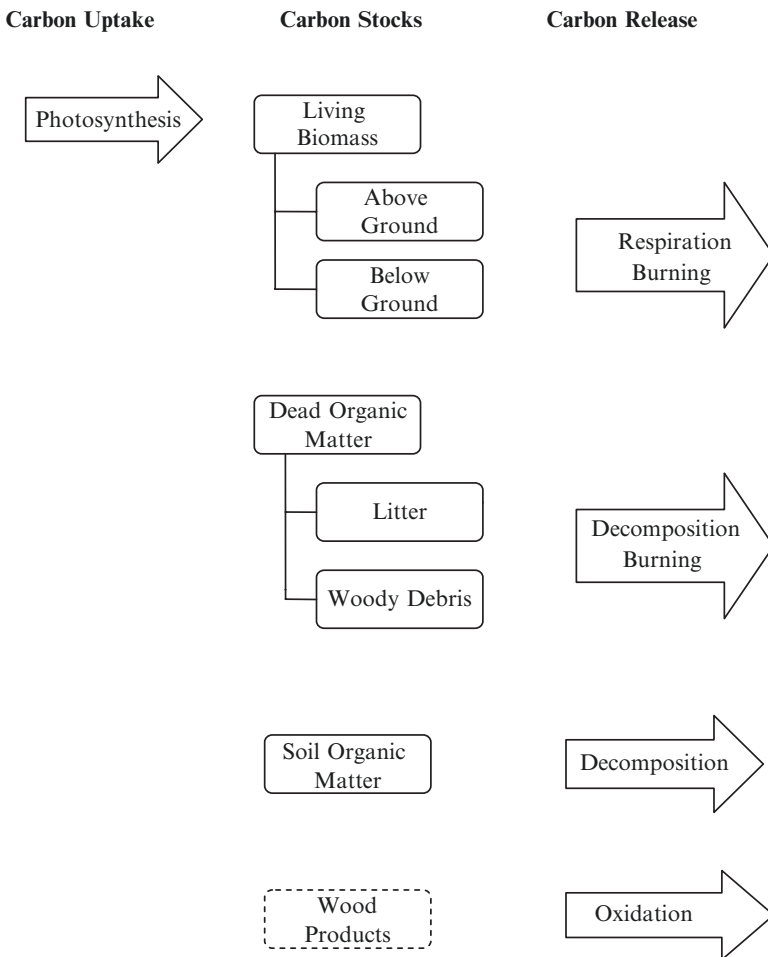


Fig. 4.1 Breakdown of carbon stocks and processes that result in changes to carbon stocks

inventories. The process of greenhouse gas exchange is more difficult to estimate and model than tree growth. Further, emissions of non-CO₂ greenhouse gasses associated with wildfires, forested wetlands, and forest management (e.g. nitrogen fertilization) are difficult to quantify, and are also a reporting requirement.

Although there are unique circumstances in each administrative unit, regardless of size of that unit, the process of obtaining estimates of past, current, and future forest carbon stocks generally involves:

1. Identifying the current extent of managed forest land
2. Estimating the changes, additions (e.g., afforestation, encroachment) and deletions (e.g., deforestation such as conversion to urban areas) to the forest land base that have occurred during the monitoring period (forest land transition matrix)
3. Estimating the carbon stocks and stock changes for all managed forest land, including:
 - (a) Above- and belowground biomass, including stems, foliage, tops and branches and fine and coarse roots
 - (b) Dead organic matter (litter and dead wood) and soil organic carbon
4. Forecasting future carbon/biomass, given
 - (a) Natural ecosystem dynamics and disturbances
 - (b) Human-caused disturbances, including: harvesting, reforestation, afforestation, change to other uses (e.g., urban, agriculture) and insect/disease management

As well as estimating past and current carbon stocks, the reasons for these changes are needed. This information can be used to assess the impacts of past management activities, and to recommend future forest management activities that may increase sequestration and decrease carbon release.

4.2.1 Extent of Managed Forest Land

The definition of forest land given by FAO, by UNFCCC, and under the Kyoto Protocol differ. For example, using some definitions for numbers or areas covered by trees, cities with extensive urban tree cover, such as Vancouver, Canada, would be largely classified as forest land. Also, defining the forest land boundary is not always clear, the definition of stand edge has also been disputed (Luken et al. 1991). Because some definitions of forest include recently disturbed forests that are expected to revert back to forest, knowledge of current land cover alone may be insufficient for land classification. Forest lands designated for conservation, harvest, water protection, etc., can all be part of the managed forest and need to be included in the monitoring process.

4.2.2 Forest Land Transition Matrix

Information on changes in forest land area and distribution by type (forest land transition matrix), and the causes for these changes are needed. The land transition matrix describes the area remaining in each land category and the area transitions between land categories resulting from human activities such as afforestation, reforestation, deforestation and other land-use changes. In addition, information is required on the changes in carbon stocks due to natural disturbances and forest management. Obtaining information on forest changes due to human and/or natural disturbance involves gathering information on a variety of scales, often from a number of agencies, including private companies and land owners.

4.2.2.1 Human Disturbances

Areas that are more populated are likely to have a large diversity of human disturbances including conversions from forest to agriculture, mining, infrastructure development, or urban use (and vice versa). Under the UNFCCC and the Kyoto Protocol, changes in land type through land management activities must be reported separately from other human activities. Obtaining information on these human-caused land-use changes involving forests involves gathering and merging information on a variety of scales, often from a number of agencies, including private companies and land owners (e.g., Mouillet and Field 2005; White and Kurz 2005). This information is needed to separate deforestation losses, due to urbanization and other land use changes, from temporary loss in forest cover due to natural causes such as wildfire or forest harvest.

4.2.2.2 Forest Management

Forest management activities from site preparation to stand tending to final harvest all affect forest carbon dynamics. Information on the area affected by forest management activities and on the magnitude of the management impacts on carbon stocks is required. Recent policy shifts towards continuous forest cover management, have led to the more common practice of partial removals for extracting timber, including removals of single trees, and regularly and irregularly shaped groups of trees that are difficult to monitor. Delineating boundaries on any land change is often very difficult, even when the change is dramatic, such as with clearcutting or conversion to urban land, but this is especially difficult for small-scale disturbances and partially harvested stands.

4.2.2.3 Natural Disturbances

In many forests of the world, natural disturbances play a dominant role in forest carbon dynamics (e.g., Kurz and Apps 1999; Li et al. 2003b; Mouillet and Field 2005). Catastrophic natural disturbances, such as fires or epidemic insect outbreaks,

are more visible, whereas regular smaller-scale disturbances, such as windthrow and landslides are harder to monitor, but may be of regional significance. Encroachment of trees into non-treed areas can be a very slow process, but may occur along forest edges (e.g., alpine tree-line, forest/grassland edges, etc.). When these areas of forest change are in remote, sparsely populated areas, monitoring can be more of a challenge, as these events are not detected unless a formal, regular monitoring program has been implemented.

4.2.2.4 Stand Dynamics

In addition to changes in forest land due to disturbances, change due to stand dynamics must be monitored. Stands may have been disturbed and regenerated during the monitoring period. Also, changes in species composition, density, and tree sizes, particularly for fast-growing forests, will impact the forest carbon dynamics. For example, areas that are primarily deciduous (hardwood) at the beginning of the monitoring period, may be mixed deciduous/coniferous at the end of the period through successional changes. These changes in stands will be associated with changes in other components, such as litter, woody debris (e.g., Ganjgunte et al. 2004), etc., associated with these changes in above-ground live biomass.

4.2.3 *Estimates of Carbon Stocks and Stock Changes*

Estimates of carbon stock and stock changes at the national, regional or landscapescale for the managed forest are needed. Individual forest stands can be carbon sources or sinks, depending on the stage of stand development (e.g., Gower et al. 1996). Shortly after disturbance, the rate of carbon uptake in growing trees can be less than the carbon loss from decaying slash and other dead organic matter. Vigorously growing stands, such as young even-aged stands, will have higher rates of carbon uptake, while stands with older trees, take up carbon at lower rates, but store the largest quantities of carbon per hectare.

Where detailed inventory information is available at the beginning and the end of the monitoring period, the average annual carbon stock changes can be estimated by calculating the difference in carbon stocks divided by the number of years in the monitoring period. Care must be taken, however, to not confound the estimates of carbon stock changes with changes in managed forest area. Alternatively, a single estimate of carbon stocks, for example at the beginning of the monitoring period, combined with detailed information on forest change, such as tree growth, dead organic matter and soil carbon dynamics, and changes resulting from land-use change, forest management and natural disturbances can be used to estimate annual changes (termed a “carbon budget” model). The advantage of this second approach is that detailed annual estimates of carbon stock changes can be provided, including an account of the inter-annual variability brought upon by variations in harvest rates or natural disturbances (Kurz and Apps 1999).

For smaller land areas and for experiments, carbon components may be measured directly (e.g., Yang et al. 2005) for each time period. However, for larger land areas, direct field measures are often not possible (Li et al. 2002). Instead models are used to estimate some or all of the carbon components from variables, measured or imputed, over the entire land area (e.g., Beets et al. 1999; Li et al. 2002, 2003a). Some components, particularly above-ground carbon from live biomass, are easier to measure and/or estimate from commonly used forest inventory measures. Biomass estimates are commonly obtained from other measured variables (e.g., tree size, stand merchantable volume, vegetation indices from remotely sensed data) obtained from a sample, in the case of ground-measured variables, or the complete coverage of the forested area, in the case of remotely-sensed variables. Fang et al. (2001) used a carbon expansion factor to estimate above-ground tree carbon from merchantable timber volume. Myneni et al. (2001) used the normalized difference vegetation index (NDVI) and National Oceanic and Atmospheric Administration series satellites 7, 9, 11, and 14 coupled with ground data (stem wood volume) to estimate the biomass and used this to estimate change in terrestrial carbon storage and sinks in Northern (hemisphere) forests. The biomass equations are often critical to carbon estimation (Rohner and Böswald 2001), since they often are the linkage between forest inventory measures, and carbon stock estimates. Due to the cost and destructive nature of data collection to develop biomass equations, these equations are often developed for large land areas. Jenkins et al. (2003) used a meta-modelling approach with previously developed equations for many locations and species, to develop country-wide hardwood versus softwood biomass equations for the US, for example. They noted that these would not be accurate for lower spatial scales, however. For areas with many species, such as tropical forests, development of volume, and therefore, biomass, from size or other inventory measures is difficult (Akindele and LeMay 2006). Chave et al. (2005) used an extensive database to develop biomass equations for tropical species by grouping all species into broad forest types.

Other more difficult to measure components, including below-ground components, may be estimated from the above-ground live biomass in a system of estimating equations, rather than measured directly over the forest land area (e.g., Kurz and Apps 1999; Cairns et al. 1997; Li et al. 2003a). Bi et al. (2004) discuss the issues in obtaining additive biomass components and recommend estimating the set of equations as a system to obtain logical consistency, and to improve estimating efficiency, the approach later used by Lambert et al. (2005). Estimating dead organic matter, litter, and soil carbon pools is much more difficult, since the amount of carbon in these pools is affected by the current vegetation, the time and type of last disturbance, and other site and climatic factors (e.g., Ganjgunte et al. 2004). Approaches based on correlation with current vegetation have had limited success. Smith and Heath (2002) used a meta-modelling approach to summarize information on forest floor carbon mass for the US. Alternative approaches involving detailed vegetation and site analyses or modelling of past disturbance history and stand dynamics (e.g., Kurz and Apps 1999) are being developed and refined.

4.2.4 *Forecasting Future Carbon/Biomass*

Estimates of future carbon stocks are of interest to evaluate management alternatives or policy options. Nelson (2003) noted that models to obtain landscape level information are often difficult to explain, since the number of model components is often great and analysis is difficult to conduct and repeat. Also, the use of different models can lead to different results. For example, Nuutinen and Kellomäki (2001) present results using three different models to estimate timber production and carbon components. For short time periods, good agreement between estimates of change may be obtained. However, for long time periods, there is greater uncertainty, both in terms of carbon dynamics, and disturbance types, frequency, and impacts.

Models of carbon uptake and release are frequently used in estimating net carbon storage (e.g., Kurz and Apps 1999; Schimel et al. 2000), and may be used to forecast changes using assumptions about future rates of management activities and natural disturbances. Forested landscapes are carbon sources if the sum of the stand-level carbon stocks is decreasing, for example as the result of increases in harvest rates or rates of stand-replacing natural disturbances. Conversely, reduction in rates of natural disturbances, or lengthening of harvest rotations are changes that typically bring about landscape-level carbon sinks (Kurz et al. 1998). Approaches involving stand to landscape-level scaling of carbon stock changes are well suited for landscapes with uniform, even-aged stands. Estimating changes due to management practices will require detail for individual stands (i.e., similar species, age, height, etc. composition), or, groups of stands (strata/ecological units), and basic research to calibrate and/or create models (e.g., Ganjegunte et al. 2004; Li et al. 2003b; Oliver et al. 2004; Kurz et al. 2002; Yang et al. 2005). The complexity of harvest patterns has increased, even in temperate forests, and more complex stand structures and cutting patterns make estimation of carbon stock changes increasingly difficult. In tropical areas, the large species diversity increases the complexity of modeling carbon stock changes. Finally, predicting changes due to possible management regimes is complicated by the interactions between management impacts and expected changes in species ranges and growth rates due to climatic shifts (Cao and Woodward 1998). Forecasting requires models that can reflect the stand (or strata) changes, and methods to scale these up to the larger land unit.

4.3 **Integrating Multiple Data Sources Across Spatial Scales**

There are many variations in approaches used to obtain information across spatial scales at one time period, or at more than one time to obtain change data. Following Zeide (2003), these can be loosely divided into:

1. “Bottom-up” approaches, based on an extensive network of repeatedly measured, telescoping ground plots (nested plots of decreasing sizes), that are aggre-

gated to information for higher scales. In forest inventory literature, this is often termed a continuous forest inventory (CFI).

2. “Top-down” approaches, where remotely sensed data are connected to available inventory data and other remotely sensed images, via imputation, and spatial/non-spatial modeling. Information at lower scales is obtained via disaggregation.

Kauppi (2003) divided the approaches similarly using the terms “inventory” versus “non-inventory” approaches. A discussion of these two types of approaches is given here. However, in practice, a mixture of “top-down” and “bottom-up” approaches is often used, which Zeide (2003) termed the “U approach”.

4.3.1 “Bottom-Up” Approach

For any forest inventory statistic, the “bottom-up” approach involves a base of repeatedly measured plots (CFI) that are aggregated for higher spatial scales (Fig. 4.2). This approach is often very labor intensive, but may require lower technological costs.

The CFI approach is largely data driven, with commonly accepted methods for data analysis based on the inventory approach used. A number of desirable statistical properties are associated with a CFI approach, including:

1. The probability associated with each plot (subplot) is known for each inventory cycle. Unbiased estimates of each measured variable of interest (e.g., carbon stocks by stratum) can be obtained.
2. Relationships across the scales of measurement represented by the telescoping plots can be examined and used in estimation. For example, soil carbon can be related to overstory stand characteristics.
3. Variance estimates are also easy to obtain for variables that are directly measured. For variables that are estimated from measured variables (e.g., biomass estimated from tree size measures), variance estimates can be calculated, but commonly model estimates are treated as true measures with no variance.
4. Since the CFI is repeated over time, estimates of the forest land transition matrix, and reasons for these changes are unbiased and more precise than using separate inventories at each time (Cochran 1977).

The results are then less disputed, and repeatable by different users of the data (e.g., Kauppi 2003). Methods used are often easier to explain in fairly simple terms, increasing the trust and confidence in the estimates. As part of the inventory process, information on current land use can be gathered.

Commonly, a systematic layout of ground plots is used in a CFI. Post-stratification is easily implemented, and can be changed over time. For example, China used a national forest inventory system of ground plots to estimate forest area and other statistics at provincial levels (Fang et al. 2001). At each plot location, telescoping

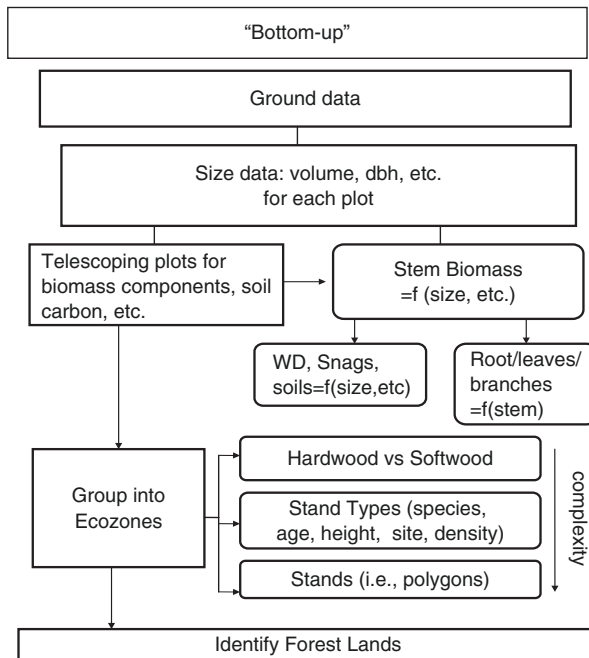


Fig. 4.2 “Bottom-up” approach beginning with an extensive network of telescoping plots, aggregated into strata, and used to delineate forest land where WD is woody debris

plots (i.e., nested plots) can be used to efficiently measure live biomass, dead organic matter, and soil carbon pools. Larger plots can be used for larger-scale components (e.g., stem biomass) whereas smaller plots can be used for smaller-scale components (e.g., soil carbon and fine roots). Consistency can be maintained across spatial scales, since all estimates could be based on the same network of plot data.

A major disadvantage to the “bottom-up” approach can be the cost of obtaining the information to achieve a desired level of precision. Few plots are needed to obtain desired precision for the larger-scale components, whereas many plots may be needed for smaller-scale components since the between-plot variability is much greater. Where labor costs are very low or the managed forest land area is smaller, a CFI may be very cost effective. For very large land areas (e.g., forests of Brazil, Canada, and Russia), with limited road access, transportation costs (e.g., helicopter access) would limit the CFI to a very low intensity of plots. This would preclude the possibility of obtaining accurate estimates for smaller subsets of the land area (i.e., scaling down in space). Also, delineating the spatial boundaries to determine the area associated with each stratum is challenging when plots are widely dispersed in space.

Where costs are very high, sampling with partial replacement has been used, although this can be quite difficult to analyze with more than two time measures (e.g., Roesch and Realms 1999; Johnson et al. 2003). Using spatial modeling,

including kriging approaches (e.g., universal kriging), estimates of carbon components at smaller spatial scales (e.g., soil carbon) can be obtained for any place in the inventory area (e.g., Mueller and Pierce 2003). The use of spatial modeling increases the complexity of analyses resulting in more difficult explanations, and repeatability is not assured, as a model of the spatial variability must be selected, and this can be somewhat subjective. Spatial models will not be very accurate, when ground plots are widely dispersed on a highly diverse land area (e.g., mountainous terrain). Also, some biomass components, such as above-ground biomass, are often spatially clumped, and difficult to model using spatial models. The recent shift to continuous cover forestry and partial harvests has increased the challenge of monitoring even using ground plots, because of the increasing spatial variability (Iles and Smith 2006).

4.3.2 “Top-Down” Approach

The “top-down” approach involves separating the forest land into smaller areas. Information is obtained for each spatial scale by coupling data from a variety of inventory data sources, with spatial or non-spatial modeling, including imputation and averaging, to estimate some or all of these carbon sources and sinks (e.g., Beets et al. 1999; Rohner and Böswald 2001; Li et al. 2002; Wulder et al. 2003). For some approaches, the forest land is divided down to the stand (polygon) level (Fig. 4.3), whereas for other approaches, the smallest spatial scale is the pixel (Fig. 4.4).

Costs of acquiring, processing, storing, and displaying the remotely sensed information are a large part of project costs. For very large forested areas, such as those of Russia, Canada, and Brazil, this in itself is a challenge as a large number of remotely sensed images is needed. Ground data are often used to build and validate models that can be linked to remotely sensed data. In application, often ground data needed to drive the model are much less than for a “bottom-up” approach and imagery can be used to detect larger changes to the land area at reasonable costs (e.g., Franklin et al. 2002).

In the past, the extent of forest land versus other land uses was based on aerial photographs at smaller scales (e.g., 1:50,000 for coarse separation of forest types), whereas lower resolution satellite imagery (e.g., Landsat) is now sometimes used for this purpose. Separating the land into forest land versus other land uses, such as agriculture, is often not possible using only low resolution satellite imagery. For example, young forests can often have similar reflectances to agricultural crops (e.g., Suratman et al. 2004). Also, recent changes to continuous cover forestry, with more partial harvests replacing clearcutting, have made these forest areas more difficult to identify using remotely sensed imagery, since the areas do not correspond well with pixel boundaries of satellite imagery, there is high within pixel variability, and boundaries are harder to determine even on large scale (e.g., 1:2000) aerial photographs or other high resolution imagery (e.g., IKONOS data with 1 m resolution). If forest land can be adequately delineated on remotely sensed images, actual

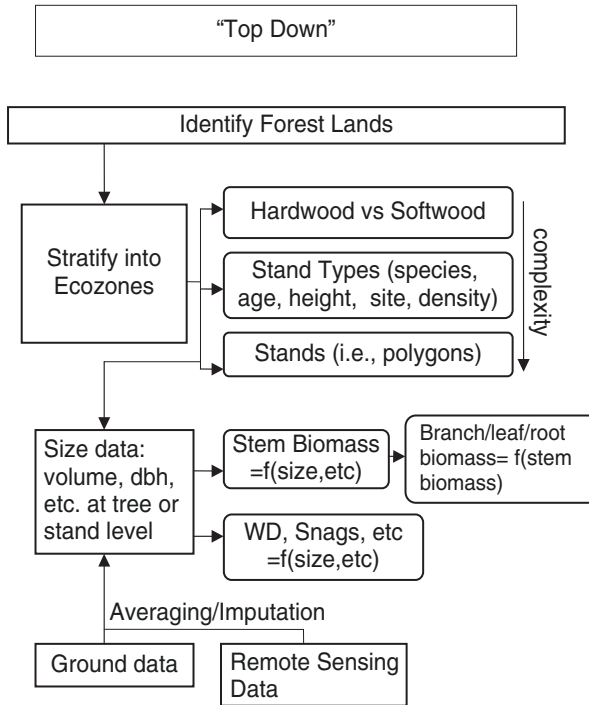


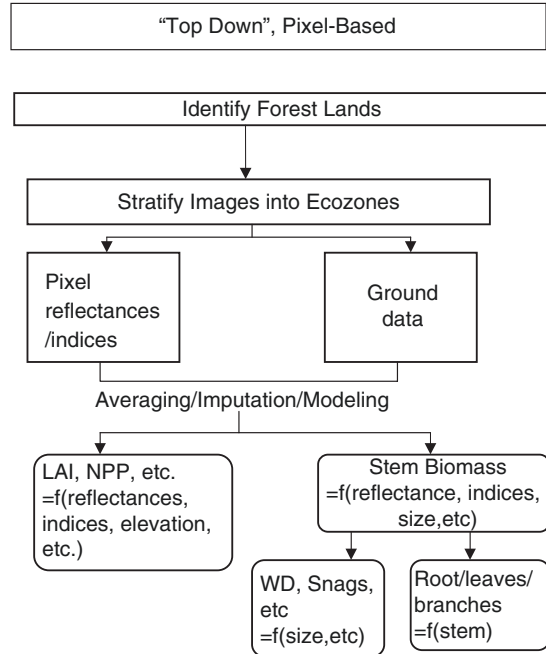
Fig. 4.3 “Top-down” approach using remotely sensed data to identify forest lands, and to stratify the forest land, coupled with ground and other remote sensing detail to obtain information for each stratum, down to the stand level of complexity

changes in forest land can be easily detected using repeated images. Identifying the reasons for these changes (e.g., fires, land slides, harvest, urban conversion, etc.) may require high-level resolution imagery, including aerial photographs, coupled with a mixture of ground information, including land-use surveys.

A variety of approaches have been used to estimate carbon stocks using remotely sensed imagery based on the approach illustrated in Fig. 4.3. Heikkinen et al. (2004) used ground measures of carbon dioxide and methane fluxes in different vegetation types, and coupled these with classification using Landsat TM² imagery to obtain estimates for East European tundra. In other applications, remotely sensed data were coupled with a carbon budget model. For carbon budget models that require stand summary information as model inputs (e.g., Li et al. 2002), a number of research studies have indicated that satellite imagery can be used to separate deciduous, coniferous, and mixed deciduous/coniferous forests. Other carbon models require detailed forest type information including sizes (heights, etc.), ages, and density (or cover) that is difficult to obtain using satellite imagery (e.g., Suratman et al. 2004). In the past, this detailed forest information was obtained via

²Thematic mapper.

Fig. 4.4 Variation on the “Top-down” approach with a greater emphasis on remotely sensed data to obtain information down to the pixel level



labor-intensive photo-interpretation of larger scale aerial photographs (e.g., 1:15,000) to segregate into stand types. Mechanization of this segregation may be achieved via very high resolution imagery such as LiDAR³ (e.g., Lim and Treitz 2004) data, but this is just now being researched, may be too expensive to implement, and would require extremely large databases for storage, retrieval, and analysis. Neeff et al. (2005) used SAR⁴ data to obtain stand structure detail and estimated basal area and above-ground biomass in tropical forests. For other variables, such as ages in complex stands and the amount and type of coarse woody debris, supplemental ground data are needed. Multivariate approaches such as variable-space nearest neighbour methods (i.e., imputation) can be used to obtain estimates at local scales (i.e., scaling down), by using remotely sensed data to impute within stand details for sampled to non-sampled stands (e.g., Maltamo and Kangas 1998; Moeur 2000; McRoberts et al. 2002; Tomppo et al. 2002; Temesgen et al. 2003). However, a very low ground sampling intensity is unlikely to produce good estimates at this smaller scale (e.g., Katila 2004; LeMay and Temesgen 2005a). Moreover, matching ground data to strata (stands or pixels) is often difficult (Halme and Tomppo 2001; LeMay and Temesgen 2005b).

Using the general approach outlined in Fig. 4.4, pixel reflectances and derived indices could be used to obtain estimates of net primary productivity and greenhouse gases for above-ground carbon stocks (e.g., Coops and Waring 2001).

³Light detection and ranging.

⁴Airborne interferometric X and P-band synthetic aperture radar.

Imputation approaches that link ground-measured variables to pixels may be used to estimate non-sampled areas (e.g., Tomppo et al. 2002). Ground-measured variables can also be used to help correct for errors in map data from remotely sensed imagery (Katila et al. 2000). This information typically does not provide insights into below-canopy carbon stocks in dead organic matter, litter, soil carbon or below-ground biomass. This type of approach is already being used for the greenhouse gas accounting system in Australia (Richards 2002).

Determining the accuracy of “top-down” approaches that rely on a mixture of models with remotely sensed and ground data is not simple, or sometimes, not possible. Assessments of individual model or inventory components do not always indicate the overall accuracy, since errors in one model or level in the inventory process may “cancel out” errors in another model or level (Kauppi 2003) or error confounding can occur (Gertner 2003). Validation methods, often using data splitting techniques, are used to check model components, for the original or new populations. If CFI data are available for a particular variable (e.g., measured stem biomass), these data can be used to validate the model estimates at the land area level, and for sub-areas. A complication occurs if the data used to develop the model are also used to test the model, since this test over-estimates model accuracy. Cost often prohibits the availability of independent data for model validation. For carbon models, this is more problematic since, as noted, obtaining measures of some carbon pools is destructive and very expensive.

4.3.3 Models Used in Both Approaches

For the “top-down” approach, models that estimate carbon stocks are often developed for particular species and land areas, and then adopted for use in other populations. Similarly, for the “bottom-up” approach, some components may be estimated from other variables rather than measured (e.g., root biomass estimated from tree diameter). To improve local estimates, mixed-modeling approaches to impute to local areas are becoming more common (e.g., Robinson and Wykoff 2004), along with other imputation approaches (e.g., Katila 2004). Also, as management practices change to more spatially diverse stands, some models may not provide accurate estimates of stand dynamics, and therefore, carbon budgets. Models with process components are often used to help alleviate these problems, rather than strictly relying on empirical prediction equations (e.g., Beets et al. 1999).

4.4 Integrating Multiple Data Sources Across Time Scales

Using the CFI approach, the carbon budget can be reported for all of the times represented in the CFI. Change estimates are obtained by subtracting values from the previous time period. However, often this simple subtraction does not result in “real” estimates of change since:

1. Definitions of monitored elements have changed. For example, the definition of what is forest land and administrative boundaries may have changed.
2. Measuring devices may improve in precision over time.
3. Often, some measures are not available (“missing data”) and must be estimated.
4. For variables that are not directly measured, improvements to equations may have resulted in different estimates. For example, equations to estimate biomass from tree diameter may have improved with further biomass sampling.

Some of these issues can be removed by re-analysis of data from both time periods using the same equations, definitions of forest land, etc. However, there is no way to correct for improvements in measurement precision and other differences.

For the “top-down” approach, the remotely sensed data used to stratify the landscape to the desired level of complexity may not be for the same date as other data sources used to obtain within strata detail. For areas that have little change, such as slow growing forests away from human settlements, pooling data sources within + or –5 years may be sufficient. For other areas with more frequent changes, failure to synchronize dates of various sources may have greater impacts on the uncertainty associated with the estimates.

Regardless of whether the “top-down” or “bottom-up” approaches are principally used to estimate carbon for periods included in the inventory, projections to future times (i.e., scaling up in time), and for future differences resulting from climate change, and/or future forest management activities are needed (e.g., Cao and Woodward 1998; Beets et al. 1999; Kurz and Apps 1999). Changes in climate can be incorporated into the models, as many carbon budget models include process model components. Also, since carbon models are inherently designed to estimate across scales via aggregation of smaller scale and/or separation of larger scale estimates, consistency across scales may be well represented (Mäkelä 2003). Estimates of the impacts of natural and human caused disturbances may also be obtained from the models, although many of these impacts are currently being researched.

4.5 Concluding Remarks and Research Needs

Forests can be terrestrial sinks or sources for atmospheric carbon. Changes in forest management practices may increase the ability of forests to act as sinks, offsetting some of the emissions created through burning of fossil fuels. A variety of approaches has been used to estimate forest carbon stocks and changes by administrative unit, and to scale to larger or smaller units. Because of the need to forecast under changes in climate and management activities and to scale down to increasingly smaller spatial scales (small-area estimation) with more variables, the general trend appears to be towards more complex modelling approaches that include:

1. Greater use of remote sensing data as these data become available, particularly for land-use change monitoring, and integration of these with other data sources. This results in growing challenges in database management, storage, and analysis, however, particularly if very high spatial resolution imagery (e.g., IKONOS, coupled with LiDAR data) is used. Also, integration of data sources obtained at different times and for different spatial scales can be problematic.
2. Increased use of more recently developed modeling and estimation methods. These methods include: (1) mixed-models to estimate across scales and obtain logical consistency of estimates for aggregated (e.g., hardwood/softwood) versus segregated (e.g., species) spatial scales; (2) imputation and/or spatial modeling approaches to obtain information in non-sampled areas, to be used as model inputs, and/or in estimating carbon, and (3) systems of equations fitted simultaneously to obtain logical consistency and efficiency.
3. Greater use of models with process-components, to model possible responses to changes in climate and management activities, and to forecast future carbon stock changes.

However, ground measurements of carbon and carbon processes are needed to develop, calibrate, and validate the models used. This is particularly true since calculating accuracy for models coupled with remotely sensed data is extremely difficult. Confidence in the estimates must therefore come from validation of model components and overall estimates, whenever possible.

In terms of monitoring, research on methods for gathering, storing, and processing data for this and other forest inventory projects is needed. In addition, research specifically for carbon dioxide and greenhouse gases is needed. A partial listing of research questions includes:

1. Can high resolution imagery be used to replace photo-interpretation to obtain greater within strata detail (e.g., IKONOS, coupled with LiDAR data and Landsat TM data)?
2. How can multiple sources of information be integrated into an overall imputation approach to improve accuracy with minimal increases in cost, including computational issues and methods issues?
3. How can mixed-effects and systems of equations be best used in estimating between time scales, and to scale down to lower (more detailed) levels, while maintaining consistency across components and across scales?
4. What are the impacts of forest management and natural disturbances on greenhouse gas emissions and sinks, including dead organic matter and soil carbon, and how can this information be used for small and large-area estimation?

Improvements to forest inventory systems, including more detailed ground measurements of dead wood, soil carbon, and other attributes related to greenhouse gas emissions and sequestration, will improve our ability to make decisions regarding changes in forest management practices that may increase net carbon sinks in our forests.

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