Woody debris research:
Overview

CTFS Global Forest Carbon Research Initiative
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Introduction

Fallen and standing woody debris constitute a large portion of total above-ground carbon in tropical and temperate forests (Keller et al. 2004; Rice et al. 2004). In addition to being an important carbon pool, aboveground necromass is important in nutrient cycling, water retention, fuel load, and as resources for many organisms. Despite its importance and possible sensitivity to global change, relatively few studies have evaluated stocks of woody debris or standing dead trees in tropical ecosystems and even fewer have quantified their fluxes (Figure 1). Inputs from branchfall and outputs due to fire are particularly poorly quantified. Data collection has been much more extensive in temperate ecosystems (Harmon et al. 1986).

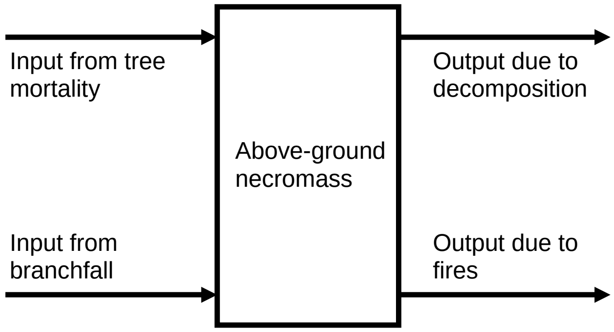

Figure 1. Schematic representation of principal inputs and outputs of above-ground necromass in a forest ecosystem.

CTFS's Global Forest Carbon Research Initiative was funded by the HSBC Climate Partnership with the aim of improving understanding of tropical and temperate forest carbon budgets by quantifying carbon pools and fluxes and investigating the mechanisms determining spatiotemporal variation in these pools and fluxes in CTFS plots around the world (www.ctfs.si.edu/doc/plots). Given that aboveground necromass is estimated to contain an average of 5-10% of total forest carbon stocks, measurement of this pool and of the fluxes in and out of it are among the major objectives of this research program. This document provides an overview of the woody necromass research being conducted under this initiative; separate documents provide detailed protocols for the field and lab measurements.

Objectives

Our objectives are to

1) Quantify the necromass of fallen and standing woody debris on each plot;
2) Quantify the inputs to and outputs from the total above-ground necromass pool; and
3) Quantify interannual variation in the pools and fluxes of above-ground woody necromass.

Three complementary field studies

Because both destructive sampling and long-term monitoring of woody debris are required in order to fulfill all the objectives, no single methodology is sufficient. Furthermore, the penetrometer, a newly developed instrument for measuring the force required to penetrate a piece of woody debris, which we use to nondestructively estimate the necromass, is suitable only for use on pieces at least 200 mm in diameter (i.e., coarse woody debris, or CWD). Thus separate methods are required to nondestructively monitor fine woody debris (FWD), that is, pieces with diameters of at least 20 mm and less than 200 mm. Our methods thus consist of three complementary field studies:

1) **Long transects**: An inventory of fallen coarse and fine woody debris that involves destructive sampling as well as nondestructive measurements. These transects provide data on pool sizes of fallen coarse and fine woody debris and enable development of models linking nondestructive measurements with true necromass of individual pieces. Because samples are taken destructively from pieces along each transect, any subsequent censuses (in later years) are not done on the same transects.

2) **CWD dynamics**: A repeated inventory of fallen and standing CWD involving no destructive sampling, only nondestructive measurements. In conjunction with the models linking these nondestructive measurements to true necromass (obtained from 1), this repeated inventory provides data on pools, inputs, and outputs of CWD and their interannual variation.

3) **FWD dynamics**: A repeated inventory and field decomposition experiment of fallen FWD involving destructive sampling. This study provides data on pools, inputs, and outputs of FWD and their interannual variation. *Note that this protocol has not been published in the website as only a draft version exists. We are currently testing the protocol.*

Long transects

We quantify the dry mass of fallen woody debris per area using line-intersect surveys (Warren and Olsen 1964). The diameter of each piece of woody debris intersecting a transect is measured at the point of intersection, and this information together with information on dry mass of wood samples taken is used to calculate the dry mass of woody debris per unit area.

We recommend doing a total of 5 km of transects in long parallel lines spanning the width of the plot – for example, 10 parallel lines of 500 m or 5 parallel lines of 1 km for a 500 x 1000 m (50 ha) plot.

The line transects are censused using a nested sampling strategy in which the whole length is censused for coarse woody debris (at least 200 mm in diameter), while only 5% (1 m in every 20-m segment) is sampled for fine woody debris (20 – 199 mm in diameter). (The minimum diameter for sampling throughout the segment may be reduced below 200 mm in plots where there are many fewer large trees.)

For each piece of coarse woody debris encountered, we record the orientation and measure hardness using a newly developed penetrometer (Larjavaara and Muller-Landau 2010). The penetrometer penetrates the piece of woody debris with a standardized amount of kinetic energy. The orientation data are used to correct for nonrandom distribution of fall angles (without such a correction, the use of parallel transects leads to bias in cases where treefalls are more common in some directions than others).

Samples are taken by cutting a slice of typically 20 - 50 mm thick perpendicular to the main axis of each piece. Smaller slices are taken back to the laboratory in their entirety for oven-drying and subsequent weighing. For larger slices, the fresh weight and thickness of each slice are measured in the field and a representative subsample is taken and brought to the laboratory for weighting, oven-drying and reweighing to determine the ratio of fresh and dry masses.

Please see the specific protocol for this study for information on many additional details of the methods.

CWD Dynamics

The CWD dynamics field study encompasses repeated inventories of fallen and standing CWD, as well as of standing FWD. As in the Long transects, fallen CWD is inventoried using line-intersect methods. Here, the transects for censusing CWD are short (40 m), and span small subplots (40x40 m) throughout which standing CWD is censused, and in a subset (79 m^2) of which standing FWD is censused. In particular, four 40-m transects, 2 in each of 2 perpendicular directions, span each 40x40 m subplot. *At sites where dendrometers are installed, the subplots used for the CWD dynamics study should be the same as the ones used for installation of dendrometers.* Woody debris on these transects and plots is inventoried repeatedly every 12 months, to provide data on input and output, as well as on stocks and temporal variation. We recommend 100 40x40 m subplots in each 25-50 ha forest dynamics plot, for a total of 16 km of transect sampling for fallen CWD and 16 ha of plot sampling for standing CWD.

Fallen CWD is censused in much the same way as in the long transects, except without the destructive sampling. That is, on each piece at each census, the diameter is measured at the point where the piece crosses the transect and a penetrometer measurement is made. In addition, each piece is marked to allow it to be tracked over time and distinguished from newly fallen debris in the next census. We also record the tag number of the tree from which the piece came, if discernible.

We inventory standing dead trees within the 40x40 sub-plots. Standing CWD with a diameter of at least 200 mm is censused throughout the whole subplot, while standing FWD with diameter from 20 mm to 199 mm is censused only in the central area with a radius of 5 m. For each standing dead tree greater than 200 mm in diameter, we measure dbh (or diameter above buttress), height and hardness (by using the penetrometer at an angle of 45 degrees from vertical). In addition, we categorize the abundance of branches remaining (<10 %, 10 – 90 % or > 90 %). In the case of stumps, we measure diameter at half way between the top and ground and use the penetrometer as with standing dead trees. We record the main plot tag number or, if the tag has been lost, record sufficient information about the stem (location, dbh) to find the tag number in the plot database; this then links the record to data on species identity, size at death, and growth history. We mark individuals to allow us to associate records of the same individual from multiple inventories.

Please see the specific protocol for this study for information on many additional details of the methods.

FWD Dynamics

Tracking dynamics of fallen FWD presents different challenges than tracking dynamics of CWD because we lack a nondestructive means of reliably estimating the mass (not just the volume) of each piece, and because decomposition occurs more quickly. To add to the data on pools of fallen FWD pools and obtain data on inputs thereof, we conduct repeated inventories of line transects. To obtain data on outputs via decomposition, we conduct a field experiment using pieces sampled from the transects.

Specifically, our methods call for inventorying all fallen FWD along two 20-m transects within twenty 40x40 m subplots (the same subplots that are used for the studies of CWD dynamics and dendrometers). Diameters are measured on every piece encountered.
For each piece that is 500 mm or longer, a section of 500 mm is cut, and then 50-mm pieces are cut from each end of this 500-mm piece, leaving a central section of 400 mm. The 400-mm samples are weighed in the field and placed under a net in the middle of the 40 x 40 m sub-plot. The 50-mm pieces from the ends are weighed in the field, taken back

to the lab, oven-dried, and reweighed to determine the water content and estimate the dry mass of the 400-mm samples. All pieces of FWD, regardless of length, are removed from the transects.

After a period of 1-12 months what remains of the 400-mm samples is collected, dried and weighed to calculate the dry mass loss due to decomposition. In addition, the transects are re-inventoried to quantify the input of FWD.

Note that this protocol has not been published in the website as only a draft version exists. We are currently testing the protocol.

Labor Requirements

On Barro Colorado Island, recent surveys encountered 30 pieces of coarse woody debris and 32 pieces of fine woody debris per 1 km transect (with fine woody debris sampled in only 5% of the transect length, or 50 m in total). At this density, a survey of 5 km in the inventory of long transects encounters on average 308 pieces to be measured and sampled. Thus, a team of two people will be able carry out the field work for the inventory in approximately 40 hours of working time (excluding breaks) in the plot. The weighing and drying will require an additional 10 hours of working time for two people.

Inventorying a km of transects for CWD dynamics goes much faster as samples are not taken and fine woody debris is not censused.

Naturally, the numbers of pieces of woody debris, visibility and walking speed greatly influence the time required for the field work, and vary considerably among plots. In addition, the travelling time to the plot and any divergence from the suggested transect lengths and areas for measuring standing dead trees need to be taken into account when estimating time requirements.

Organization of the Field Work

It is advisable to start with the study of transects with long transects or the study of CWD dynamics. The study of long transects does not need to be repeated, but if it is, the same transects cannot be used because the sample collection during the previous census could influence encounter and decomposition rates. The study of CWD dynamics should be repeated, preferably at least once a year for ten or more years to get a good picture of the inter-annual variation in CWD input. Note that if cutting slices out of pieces of woody debris is not allowed, then only the protocol CWD dynamics can be followed on the plot. In this case, the study of long transects and the study of FWD dynamics should be carried out in an area with similar wood characteristics and climate (ideally very close to the plot). If topography is different in the reference area, a correction should be made based on inclinations measured in both locations for a sample of pieces of woody debris. FWD is a relatively small fraction of the woody debris pool, inputs, and outputs, and thus the study of FWD dynamics has lower priority than the others.

Analyses

The traditional way to calculate necromass based on line-intersect method is to calculate volume using the equation

$$V = \frac{\pi^2}{8L}\sum d_i^2 , \tag{1}$$

where V is the volume (m^3) per hectare, L the total length of the transect (m) and d the diameter of the i^{th} piece of woody debris encountered (m). To calculate dry necromass from volume then requires an estimate of density (dry mass per estimated volume or nominal volume, which thus includes accounting for void space). The non-circular cross-section of most pieces of woody debris further complicates the calculations and if not taken into account can lead to errors and potentially bias.

As the main interest is in mass, we introduce a variable called cross-section dry mass (c), that is the mass of a given piece of woody debris per unit length (kg/m) at the intersection of the central axis of the piece of woody debris and the transect (Larjavaara and Muller-Landau 2011). We can then calculate the total mass (M) per unit area (kg/m^2) directly based on cross-section masses without estimating volumes and densities first:

$$M = \frac{\pi}{2L}\sum c_i . \tag{2}$$

Equations 1 and 2 assume a uniform distribution of directions of central axes of pieces of woody debris relative to the transect directions. We make this assumption, and thus use Equation 2, for FWD in the inventory of long transects and for CWD in the study of CWD dynamics in which we have transects on two directions. CWD is more likely than fine woody debris to exhibit a nonrandom distribution of orientations (depending for example on the wind directions in storms). Therefore in the inventory of long transects in which all transects are parallel, we will measure the orientation of each piece of coarse woody debris and use the following equation

$$M = \frac{1}{L}\sum \frac{c_i}{\left|\sin\theta_i\right|} , \tag{3}$$

where θ_i is the angle between the central axis of the i^{th} piece of woody debris and the transect (varying from 0 to 180 degrees and not from 0 to 360). The probability that θ_i is 0 is 0 but is a potential value for θ_i due to rounding. E.g. if rounding is to the nearest 5 degree and θ_i represents all angles from -2.5° to +2.5° the value halfway between 0° and 2.5° i.e. 1.25° should be used in Equation 3. For other angles than 0° and 180° the rounded angle itself can be used.

The cross-section mass of a given piece can be calculated quite simply. If a full slice (cross-section / disk) is taken and dried, then

$$c_i = \frac{w_i}{t_i}, \tag{4}$$

where w_i is the dry mass (g) of the slice from the *i*th piece and t_i is its fresh thickness (mm). When only a smaller sample is taken to the laboratory for drying,

$$c_i = \frac{w_{i,sample} f_{i,full}}{f_{i,sample} t_i}, \tag{5}$$

where $w_{i,sample}$ is the dry mass (g) of the sample taken from this slice, $f_{i,sample}$ is the fresh mass (g) of the sample, and $f_{i,full}$ is the fresh mass (g) of the full slice. When the average thickness of the edge of a slice is not the same as thickness in the middle the average thickness of the whole slice is calculated by weighting the edge with 2 and the middle by 1.

No samples are taken in the study of CWD dynamics, and *c* needs to be calculated differently for pieces encountered there. For each piece, *c* will be estimated from *d* and *p*, the average penetration of the penetrometer per hit using a regression equation obtained by fitting site-specific data from the long transects in which *c*, *d*¸and *p* are all measured directly.

Calculation of fluxes of mass into and out of the woody debris pool requires data from two or more repeated censuses of the same transect or area. The annual decomposition rate ($r_{i,t}$) for a given piece of fallen woody debris in a given census interval is calculated from its cross-section masses at two successive censuses as

$$r_{i,t} = 1 - \left(\frac{c_{i,t+1}}{c_{i,t}} \right)^{t_{i,t+1}}, \tag{6}$$

where $t_{i,t+1}$ is the time between the censuses in years (note that a year has on average 365.24 days), $c_{i,t}$ the initial cross-section mass and $c_{i,t+1}$ the cross-section mass at the end. We will use these estimates of decomposition rate to fit models for decomposition, models that could incorporate initial diameter, taxonomic identity, taxon-specific wood density, climate, site, and/or initial penetrometer penetration. To get the average decomposition rate for a site, the individual cross-section masses are substituted with the sums of all cross-section masses.

Because some decomposition can occur between the time a piece falls (or dies) and the first census in which it is recorded, a correction needs to be made. The expected cross-section mass of piece *i* at the time it fell, $c_{i,0}$, can be calculated as

$$c_{i,0} = \frac{c_{i,1}}{t_{\max} \ln(1-r)} \left[1 - \frac{1}{(1-r)^{t_{\max}}} \right] \tag{7}$$

where $c_{i,1}$ is the cross-section mass of the piece in the first census when it was recorded, and t_{max} is the time (in years) since the previous census (at which the piece was known to not yet have fallen), and $r_{i,1}$ is the rate of decomposition of the piece between the first and second censuses in which it was recorded. This equation is based on the assumptions that it was equally likely for the piece to fall at any time in the intervening census interval, and that the decomposition rate of the piece is constant in time. The resulting estimate of the initial mass at the time of falling is the appropriate quantity to use in estimates of input rates, as it corrects for any decomposition happening before the census. Note that it can only be applied once at least three repeated censuses have taken place (it can only be used on pieces that appear for the first time in the second census, and are remeasured in the third census).

For those pieces that do not classify as CWD at a certain inventory, it is assumed that they passed the threshold at any of the time in the intervening census interval as for freshly fallen pieces.

Computation of the necromass of standing dead trees is based on dbh, height (for broken stems), proportion of crown remaining, and penetrometer measurements where feasible. Equations for biomass of living trees (e.g., Chave et al. 2005) alone are sufficient for trees that are newly dead and otherwise intact. These estimates are then decreased based on estimates of the proportion of biomass that is in branches vs. the trunk (Chave et al. 2003), the proportion of the branches that have been lost, and the change in cross-section mass (as estimated from dbh and penetrometer measurements) from that expected for a living tree (given what is known about the species's wood density). Calculation of the input and output of necromass in standing dead trees follows the same principles as in the case of fallen woody debris.

Uncertainties in the Estimates

As with most field work, there are numerous potential sources of bias and error. Here we discuss a few that are either likely to be particularly important, or are specific to novel aspects of our methods.

We use cross-section mass as the central variable in our analysis, a departure from the traditional approach for line transects. Our method of calculating the cross-section mass from the mass and thickness of a slice is unbiased if the cross-sectional mass changes linearly. This is seldom the case. For example, if diameter changes linearly, the cross-sectional mass changes exponentially, and the equation 4 will provide an overestimate of the real cross-sectional mass. However, the bias is extremely small as long as the difference in diameter between the two sides of the sampled disc is small, as we expect it to be for all samples taken in the first study (long transects). For the study of FWD dynamics, however, the 400-mm long samples allow the possibility of more substantial bias. For example, if a piece tapers linearly from 30 mm to 50 mm, then cross-section mass in the middle will be overestimated by 2.1%.

In order to track CWD dynamics, we tag individual pieces and remeasure them with a penetrometer at each census. It is possible that the tagging and/or previous penetrometer measurements can directly affect the decay rate. Penetration by the penetrometer or nails might speed decomposition if the wood was previously intact, while the application of paint could slow decomposition. In addition, it is likely that not all age-related variation in cross-section mass is captured by changes in diameter and penetration, and in the equations utilizing these. A study on BCI is being conducted to evaluate this possibility, and quantify any related bias, if present.

Estimating the necromass of standing dead trees and stumps poses additional challenges in our study as we plan no destructive sampling of this group, and instead rely on the results of previous destructive studies and resulting allometric equations (e.g., Chave et al. 2005). Given the variation in tree allometry among regions, the resulting allometrically based estimates are quite likely to be biased for particular regions. In addition, the dependence of density on penetrometer penetration could be different for fallen and standing woody debris.

The study of FWD dynamics has a number of potential biases. The cutting could speed decomposition if decay enters the piece from the ends. Short pieces are excluded from the decomposition experiment and they probably decompose faster than the longer pieces. The samples are initially representative of longer pieces on the plot as a whole in their decomposition status, but become more decomposed than average over time. And some pieces are likely to decompose completely during the experimental interval, making estimates of their decay rates problematic.

The error and thus the confidence limits associated with overall estimates of the pools and fluxes of necromass in woody debris depends strongly on the structure of temporal and spatial variation in these pools and fluxes. By the end of 2008, we will have some estimates of confidence limits related to the studies suggested, and data on spatial correlations in woody debris stocks. Analyses of temporal correlations in woody debris will be done when multiple years of data are available.

Potential Publications

Scientists at each site will be able to write at least two papers using necromass data from their site, one on pools (similar to Baker et al. 2007) and one on dynamics (similar to Palace et al. 2008). The dynamics paper could potentially be split into two, with one manuscript on CWD and one on FWD. The pools paper can be drafted as soon as the first set of inventories is complete. The dynamics paper would ideally be drafted after 3 or more years of data.

Finally, we plan manuscripts that compare patterns across sites. We plan one paper on the carbon pools, and one on the carbon fluxes related to above-ground necromass. Personnel from all collaborating sites will be coauthors on these papers. We hope to draft the first paper in 2011, and the second in 2013.

Potential Complementary Studies

The methodologies described above will provide information on the pool sizes of fallen woody debris and standing dead trees and overall rates of input and output to these pools. Additional studies could potentially assess other components of necromass input, output and pool size. Here we mention just a few possibilities.

Pools and fluxes of other above-ground necromass: The studies described in this document provide data on aboveground woody debris with a diameter of 20 mm or larger. Smaller pieces of wood, as well as leaf litter, reproductive litter, etc., constitute another (smaller) necromass pool. Another aspect of the CTFS Global Forest Carbon Research Initiative involves litter trapping to quantify the input of leaves, reproductive parts, and woody litter (pieces of wood less than 20 mm in diameter). See the litter trapping protocol for additional information.

Decomposition rates of slowly decaying species: For slowly decaying species, it will take many years before our protocols provide information on species-specific decomposition rates in the late stages of decay. Data on these rates could be obtained earlier by visiting a sample of individuals of slowly decaying species reported dead in earlier main tree censuses, and taking data on their state of decay.

Carbon content of necromass: To estimate the total carbon pools in necromass, we need to know what fraction of dry biomass is carbon. This is generally assumed to be 50%, but is known to vary somewhat among species, stages of decay, etc. The actual percentage in a given study site could be determined through chemical analysis of the samples collected in the inventory of long transects (e.g., with a CHN analyzer, as used in the soil carbon studies).

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