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Uncertainty in Below-ground Carbon Biomass for Major Land Covers in Southeast Asia

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Abstract
Owing to difficulties associated with measuring root biomass accurately in space and time, below-ground root biomass is often calculated indirectly from above-ground biomass measurements via general allometric equations. Of concern is that general equations may not provide accurate site-specific calculations for accurate carbon stock assessments. This review comparing more than 100 root-related studies conducted in SE Asia shows highly variable and uncertain below-ground woody carbon (BGC) biomass estimates for many vegetation types associated with on-going land-use changes throughout the region. Most BGC data exist for Indonesia, Malaysia, and Thailand; only a few studies have been conducted for Brunei, Cambodia, Lao PDR, Myanmar, Papua New Guinea, Philippines, Singapore, Timor Leste and Vietnam. While substantial data exist for a variety of forests and timber-plantations, little work has focused on key transition land-covers including rubber, oil palm, swidden fallows, agroforests, grasslands, and croplands. Mangroves (12-219 Mg C ha^{-1}), peat forests (11-71 Mg C ha^{-1}) and other forest types (11-74 Mg C ha^{-1}) have the highest BGC values. The limited data for rubber plantations (5-32 Mg C ha^{-1}), oil palm plantations (4-22 Mg C ha^{-1}), swidden fallows (3-16 Mg C ha^{-1}), non-swidden agroforestry (3-16 Mg C ha^{-1}) indicate modest differences in the amount of BGC for several land covers that are at the heart of ongoing debates regarding the human and environmental impacts of agricultural intensification. The paucity of data currently in existence for the region highlights the need for additional field investigations—following—accepted protocols, of root biomass to facilitate efforts to improve carbon stock estimates. Government agencies, private enterprises, and development agencies could help lead the way in developing a better forest carbon database by teaming with researchers to assess total ecosystem carbon stocks prior to vegetation being removed for construction, mining, or stand rotations.

Keywords: carbon stocks, land-cover change in the tropics, mangroves, oil palm, peat forest, root shoot ratio, rubber plantations, shifting agriculture

1. Introduction

Roots contribute up to half of the carbon cycled annually in forests; and they may account for approximately one-third of global annual net primary production (Vogt et al., 1996; Jackson et al., 1997). Coarse roots provide structural support and access to deep water (e.g. tap roots), while fine roots absorb water and nutrients from the surrounding soils (Jackson et al., 1997; Körner, 1994; Schulze, 1983; Shi et al., 2008). Although the two root sizes are functionally different and turnover at different rates, they are both important stores of biomass carbon (Clark et al., 2001; Rasse et al., 2005). Carbon sequestered in roots during root growth and maintenance is eventually transferred to the soil when they turnover or die (Albrecht et al., 2004; Chalermchatwilai et al., 2011; Srivastava et al., 1986). As root-derived carbon has a long residence time (cf. Abiven et al., 2005; Rasse et al., 2005; Sanaullah et al., 2005), below-ground woody carbon biomass (BGC) is an important component of the terrestrial carbon budget. When soils are tilled, organic matter previously protected from microbial action is decomposed rapidly because of changes in water, air, and temperature conditions; and the breakdown of soil aggregates accelerates erosion (Sundermeier et al., 2012). Erosion, tillage, and other activities that overturn and expose the soil can lead to important losses of below ground carbon. In addition, biomass burning is a major source of terrestrial carbon transfer to the atmosphere in gas form (Quéré et al., 2009). Much attention is currently focused on reducing the loss of terrestrial carbon in both above- and below-ground stores following land-cover conversion, particularly in tropical regions (Ziegler et al., 2012).

Forest carbon conservation in developing countries is suggested as an effective means of reducing greenhouse gas emissions (Stern, 2007). For example, the United Nations Framework Convention on Climate Change (UNFCCC) program for Reducing Emissions from Deforestation and forest Degradation (REDD+) is designed to preserve/increase the storage of terrestrial carbon, meanwhile fostering beneficial ecosystem services and promoting human livelihoods (UNFCC, 2010; 2011). Under REDD+, developing countries would receive payments from industrialized nations for achieving long-term reductions in deforestation and/or replacing some land-use activities with others that sequester more carbon (UNFCC, 2010; 2011). Approximately US$4 billion was pledged for REDD+ programs between 2010 and 2012 (Ballesteros et al., 2011). As of September 2013, Southeast Asia hosted number of early REDD+ type projects (Table 1): Indonesia (44 projects), Cambodia (four projects), Malaysia (one project), Vietnam (seven projects), Thailand (one project), Papua New Guinea (four projects), the Philippines (four projects), and Lao PDR (one project). Several countries in the region have also started national-level preparations to engage with a future REDD+ mechanism (CIFOR, 2011; FCPF, 2011); for example, of the 16 countries globally that have established UN-REDD national programs, seven of those are located in the Asia-Pacific region (Cambodia, Indonesia, Papua New Guinea, the Philippines, Solomon Islands, Sri Lanka; Vietnam, UN-REDD Programme, 2009).

Ideally, eligibility for financial remuneration by REDD+ requires participating countries to have accurate estimates of carbon stocks and emissions associated with all important land cover transitions (Brown, 2002; UNFCCC, 2009). While above-ground carbon of various land covers is frequently measured, and new techniques are emerging to make AGC calculations more reliable (cf. Gibbs et al., 2007; Tollefson, 2009), much less work has addressed estimating below-ground woody carbon biomass (cf. Mokany et al., 2006; Vogt et al., 1996; Ziegler et al., 2012). In a recent meta-analysis based on more than 250 studies, we found great uncertainty in total ecosystem carbon for several major land covers that are related to important land-use transitions in SE Asia (Ziegler et al., 2012). Some of this uncertainty stemmed from our calculation of BGC from a limited number of root:shoot ratio (RSR) data readily available in the literature. Herein, we improve upon these carbon stock estimates by reviewing relevant studies/papers of below ground root biomass from the SE Asia region. In addition to providing a summary of BGC estimates and root:shoot ratios for vegetation types that are commonly associated with on-going and projected land-cover change, we also assess data availability and quality, as they affect the accuracy of carbon accounting for land-cover change scenarios.

2. Review of below-ground woody carbon biomass

The countries considered in this review are Brunei, Cambodia, southern China, Indonesia, Lao PDR, Malaysia (Peninsular and Insular combined), Myanmar, Papua New Guinea, the Phillippines, Singapore, Thailand, Timor Leste, and Vietnam. Many of these countries are affected by on-going and drastic land-cover conversions, including forest conversion to permanent cropping systems and/or plantations (e.g., rubber, oil palm), transitions from swidden agriculture (shifting-agriculture) to more permanent agriculture types, logging, wetland forest (mangroves, peat forest) degradation or conversion, afforestation/reforestation, and abandonment of marginal lands. We focused on the following eleven major land covers related to important land-cover/land-use (LCLU) transitions now taking place in the region (Fox et al., 2012; Ziegler et al., 2012; van Vliet et al., 2012): forest (FOR), logged over forest (LOF), mangrove (MAN), peat forest (PF), orchard and tree-plantation (OTP), non-swidden agroforest (AGF), rubber plantation (RP), swidden fallows of any length (SF), oil palm plantation (OP), grassland, pasture or shrub land (GPS) and permanent cropland (PC). For each land cover, we collated literature-reported estimates of root carbon biomass and root:shoot ratios (RSR). Except for Indonesia (the country with the most data), and low end-members Brunei, Laos, and Myanmar (countries with only one forest study), no correlation existed between data availability and the number of proposed/ongoing REDD+ type projects (Table 1). Some countries with substantial REDD+ activity (excluding Indonesia) had limited data—e.g., Vietnam, Papua New Guinea, Cambodia, and the Philippines.

Characteristics of individual land-covers appearing in the 11 categories, and notes regarding the biomass determinations for each study, are listed by country in Table S1. Biomass values for more than 300 sites/plots were found throughout the 12 SE Asia countries (Table S1). Only a handful of the studies reviewed reported carbon values, therefore, most of the BGC values we refer to were converted by us from biomass estimates by multiplying by 50% (cf. Smith et al., 2010). Owing to insufficient data, we were not able to separate land-cover classes according to climatic regimes or geographical variables that may have affected plant physiology. Because of a lack of standardization of vegetation classification nomenclature (cf. Maxwell, 2004), a variety of vegetation types were lumped into some common land-cover classes. For example, forests combined both evergreen and deciduous lowland forest types. In addition savannah forests and ambiguous forest types were also placed in this class. We did however separate mangroves and peat forests because of their known high soil organic carbon (SOC) contents. The orchard and tree plantations group included a range of timber and fruit-bearing trees: e.g., *Acacia* sp., *Eucalyptus* sp., teak, cocoa, cinnamon, mango, and longan. Because of insufficient data, we also use a general swidden fallow group, as opposed to splitting into short-, medium-, and long-fallow classes (Zieger *et al.* 2012). The permanent croplands category included a range of crops, including corn, cassava, and rice.

Great variation existed within each category, which often lumped together a variety of species, of both young and old ages. In the sub-sections below, we report our strategy for determining ranges of plausible values for below-ground biomass and root:shoot ratios. Basically we excluded cases where values result from the sampling of only fine and/or shallow roots, or where very shallow soil depths were sampled. The ranges also exclude outliers associated with very young vegetation that are likely not representative of the mature land-cover class. In a few instances we eliminated outliers that were extreme compared with the rest of the data. Several values were also excluded due to a lack of information on sampling protocols. The final adjusted ranges represent the best-available estimates of below-ground woody carbon and root:shoot ratios for mature facies of each land-cover group, based on empirical research. We do caution that in some site-specific instances the true carbon stock values could be outside our summary ranges. For both variables we report median and mean values that may be useful for preliminary estimates of BGC. These values are not true mathematical medians and means, as they are determined from the entire population of minimum, maximum, mean, and median values in adjusted ranges. In addition, we report the midpoints values of each range. We also compute RSRs by examining scatterplots of AGC versus BGC (Figure 2).

Mangrove Forest

More below-ground biomass data were available for mangroves than any other land-cover in the region (Table 1): 115 values were determined for sites/plots mostly located in Vietnam (55), Thailand (27), and Indonesia (23). Biomass data were reported for a range of species, as well as a range of ages (e.g., from 1-year to mature stands). The BGC values had the highest range of all land covers, as well as the highest values: <1 to 255 Mg C ha^{-1} (Figure 1a; Table S1). Most of the low values (< 6 Mg C ha^{-1}) were associated with stands < 8 years of age. Some low outliers were determined solely from soil cores. The highest BGC values (> 200 Mg C ha^{-1}) were attributed to the mangroves in Ranong, Thailand. In their assessment, Komiyama et al (1987) considered several root classes (from < 2mm to > 50 mm), and estimated biomass from soil blocks, a root density model determined from excavated trenches and published allometric equations. Several BGC values at these sites are > 110 Mg C ha^{-1}, higher than the maximum BGC values associated in most other locations. Despite the extensive work performed in the biomass calculations at the Ranong site (trench excavations), we considered the highest value as an outlier. Therefore, our adjusted range of BGC values for mangroves is 12-219 Mg C ha^{-1} (Figure 1a). The reported range of RSR was 0.02-5.60 (Table S1). The high value was for a high intertidal zone inhabited by 3 year old Ceriops decandra (Griff) Ding Hou. The unusually high RSR was due to the inclusion of dead roots (Alongi and Dixon, 2000). In most places RSR did not exceed 0.55. Our adjusted range of RSRs for this land cover class is 0.11-0.95, for which the median and midpoints are 0.40 and 0.53, respectively (Table 2; Figure 1b). The RSR derived from fitting a line through the AGC and BGC data is 0.40 (Figure 2).

Forest

Of the approximately 61 BGC values for forests, most were determined from biomass estimates made in Malaysia (18), southern China (12), Cambodia (10), and Thailand (9). Forest BGC values ranged from 1-90 Mg C ha^{-1} (Table S1). The highest forest value was associated with a lowland evergreen rainforest in Sabah, Malaysia, for which coarse roots (> 20 mm) were sampled (Sim and Nykvist, 1990). The next highest BGC values (74 Mg C ha^{-1}) were based on allometric equations determined from root excavation for two forest types in Xishuangbanna (China) by Zheng et al. (2000; 2006). Across all sites, many values were determined from published allometric equations (i.e., not determined from *in situ* measurements). Most of the low outliers we excluded in this class were determined in studies that only considered fine roots. In other cases we excluded values for which we could not assess the sampling protocol. Thus, from the range of original values, we identify the adjusted range of BGC for this class to be 11-74 Mg C ha^{-1} (Figure 1a). The corresponding range for RSRs was 0.08-0.35 (Table 2, Figure 1b). In comparison, summary studies for the tropics report RSR ranges of 0.09 to 0.34 (Cairns et al., 1997; GOFC-GOLD, 2009; Jackson et al., 1996). The median for this range is 0.17; and the midpoint is 0.22. From Figure 2, the graph-derived RSR is 0.18.

Peat forests

Peat forest BGC ranged from 3-71 Mg C ha^{-1}, for nine sites/plots in Indonesia and Malaysia (Table S1). A minimum BGC value of 2.8 Mg C ha^{-1} was determined from small and fine roots via metal coring tubes in 3-m peat deposits in Sumatra (Brady, 1997). The highest BGC value (71 Mg C ha^{-1}) was determined similarly for 12-m peat deposits (Brady, 1997). The minimum value at the site was 15 Mg C ha^{-1}, demonstrating great variability. The BGC values associated with the lone Malaysian study in Sarawak allowed for a comparatively high range of values (29-45 Mg h^{-1}), for which the biomass estimates were derived from a published allometric equation (cf. Verwer and van der Meer, 2010; van der Meer and Verwer, 2011). Our adjusted range for this class is 11-71 Mg C ha^{-1} (Figure 1a). This range is slightly lower than the general forest category, despite these forests having thick organic layers and high soil organic carbon contents (Jaenick et al., 2008; Page et al., 1999; Wibisono et al., 2011; Warren at al., 2012). From the original range of 0.06 to 0.23 we determined an adjusted range of 0.08-0.23. The median of the handful of values in this range is 0.14; and the midpoint is 0.16 (Table 2; Figure 1b). Based on the comparison of AGC and BGC, our graph derived estimate of RSR is 0.17. The low value for peat forests could be due to limited research on this land cover.

Other tree plantations

Other tree plantation BGC values range from 1-49 Mg C ha^{-1} (Table S1). The lowest values were associated with young plantations, including *Acacia* sp. and cashew, in Indonesia and Malaysia. Values < 3 Mg C ha^{-1} were determined with established root:shoot ratios for longan and mixed fruit plantations in Vietnam (Zemek, 2009). The highest BGC value was determined for mature (17-22 years) teak plantations in northern Thailand (Hiratsuka et al., 2005)—but the site had a very high RSR of 1.11. Only two other BGC values exceeded 20 Mg C ha^{-1}. They were associated with a coconut-cassava plantation (20 Mg ha^{-1}) and a mixed orchard in the Khlong Yai sub-watershed in Thailand (24 Mg C ha^{-1}). For both, an arbitrary root:shoot ratio of 30% was applied (Gnanavelrajah et al., 2008). Only a handful of the studies performed sampling to measure root biomass *in situ* (e.g., Nykvist et al., 1996; Yamada et al., 2000; Miyakuni et al., 2004; Hiratsuka et al., 2005; Syahrinudin, 2005; Heriansyah et al., 2007). From the original range, we determine an adjusted range of 5-33 Mg C ha^{-1} (Table 2; Figure 1a). Root:shoot ratios for this class ranged from 0.07 to 1.11 (Table S1). Again, the high value was for a mature teak plantation in Thailand (Hiratsuka et al 2005). Both the second highest value (0.57) and the lowest value was determined for a young (4 year) *Acacia* sp. plantation in Sabah, Malaysis (Nykvist et al., 1996). After removing outliers, we derive an adjusted range of 0.11 to 0.39. The high end of this range is associated with 10-year cashew and 9-year cocoa plantations. The median and midpoint of our adjusted range was 0.21 and 0.25 (Table 2; Figure 1b). The graph-derived value is 0.23 (from Figure 2).

<u>Logged-over forest</u>

Data existed in seven countries from which the range for BGC could be estimated for logged-over forests (Table 1): 1 to 33 Mg C ha^{-1} (Table S1). The low value was for a disturbed forest in Sulawesi (Leuschner et al., 2009; Leuschner et al., 2006; Harteveld et al., 2007); and the high value was associated with an artificial tropical forest in Xishuangbanna, China (Tang et al., 2003). The former study investigated fine roots < 2 mm; the later study excavated the roots of all forest plants. The next highest BGC values, 26 and 22 Mg ha^{-1}, were from a secondary forest in Singapore (Ngo et al., 2013) and a logged dipterocarp forest in Sabah (Pinard and Putz, 1996). Both studies used direct sampling methods. At the low end, BGC values of 4-5 Mg h^{-1} were associated with secondary forests at least 5-10 years of age in some sites in Xishuangbanna, China (Shi et al, 2001; Tang et al., 1998). Thus, we selected the value of 5 Mg C ha^{-1} for the low end of our adjusted range of 5-26 Mg C ha^{-1} (Figure 1a). Most studies including both fine and coarse roots tended to yield RSRs ranging from 0.09 to 0.36; and we adopt this as our adjusted range (Table 2; Figure 1b). The median and midpoint of this range of values are 0.18 and 0.21, respectively. The graph-derived RSR is 0.16 (Figure 2).

<u>Rubber Plantations</u>

Below-ground biomass data for rubber plantations existed for only six sites in Cambodia, China, and Thailand (Table 1). In Thailand, a BGC value of 31 Mg C ha^{-1} was associated with determinations made from above-ground biomass using an arbitrary root:shoot ratio of 30% (Gnanavelrajah et al., 2008). Through sampling, BGC values ranging from 5-32 Mg C ha^{-1} were derived for three rubber clones of stand ages 10-50 years (Mizoue, 2009). Cheng et al. (2007) performed field sampling in a 30-year-old rubber stand on Hainan Island (China), leading to BGC estimates of 17 Mg C ha^{-1}. Obtained by excavation of coarse and small roots, the biomass values of Tang et al. (2009) suggest BGC ranges of 7-13 Mg C ha^{-1} and 13-16 Mg C ha^{-1} for rubber stands 13-19 and 25-47 years, respectively. From these data we identify an adjusted range of 5-32 Mg C ha^{-1} (Figure 1a). The corresponding adjusted range for RSR is 0.10-0.30, for which the midpoint, median, and graph-derived values are all 0.20.

<u>Oil Palm Plantations</u>

A narrow range of low oil palm BGC values could be estimated for 15 plots/sites in Malaysia and Indonesia (Table S1): 2-22 Mg C ha^{-1}. The maximum value was based on field sampling (cores to 5-m depth, excavation of the trunk) in a 30-year-old plantation in Sumatra (Syahrinudin, 2005). The lowest values were determined in a 50-cm soil pit in peat soil (> 1 m) in Sumatra, for coarse, live and dead roots (Persch et al., 2011). Several values ranging from 3-8 Mg C ha^{-1} were associated with several plantations 9-16 years of age (Henson and Chai, 1997; Henson and Dolmat, 2003). From these data we identify an adjusted range of 4-22 Mg C ha^{-1} for mature oil palm (Figure 1a). Reported plantation oil palm RSRs ranged from 0.18 to 0.41 (Table S1). Several sites in Malaysia occupied the low end of this range: 0.18-0.19 for 16-23 year-old oil palm in Johor and Perak (Khalid et al., 1999; Henson and Dolmat, 2003). High values ranging from 0.39 to 0.41 were determined for stands in both Malaysia and Indonesia (Henson and Chai, 1997); Syahrinudin, 2005). Here we use the original range of 0.18 to 0.41 (Table 2; Figure 1b). The median and midpoints are 0.22 and 0.30. Plots of AGC and BGC suggest a RSR of 0.30 (Figure 2).

<u>Swidden Fallows</u>

Swidden fallows BGC values ranged from 3-16 Mg C ha^{-1} for 10 site/plots in China, Indonesia, and Malaysia (Table S1). Trends were not straightforward in this category, which included young, intermediate, and long fallows. For example, the lowest value 3 Mg C ha^{-1} associated with a 12.5-year secondary forest, was similar to that of much younger (1-3 years) sites in central Kalimantan: BGC = 3 versus 3-4 Mg C ha^{-1} (Koopmans and Andriesse, 1982 in Kenzo et al., 2010; Brearley, 2011). The highest BGC value (16 Mg C ha^{-1}) was for a 6-year bamboo site in west Java (Christanty et al., (1996). We adopt the original minimums and maximums to define the range (Figure 1a): 3-16 Mg C ha^{-1}. The swidden fallow root:shoot ratio values ranged from 0.12-1.86 (Table 2). The highest RSR for was elevated by the presence of bamboo—a grass that is sometimes found in swidden fallows (Christanty et al., 1996; Nikolic et al., 2008; Rerkasem et al., 2009; Schmidt-Vogt, 2001). Another site in Indonesia with bamboo had a RSR value of 0.69 (Christany et al., 1996). The low value in the range (0.12) was associated with the 12.5 year-old secondary forest in Sarawak. We consider a realistic range for this category is 0.12 to 0.36, unless it contains bamboo and could be greater than one (Table 2; Figure 1b). The median of our adjusted range is 0.25; the midpoint is 0.24. The plot of AGC versus BGC shows much scatter, but the patterns support a value of 0.26. Here we recognize that BGC of certain fallows may in some cases be more accurately represented by the range of values for other groups: e.g., GPS (for short fallows), LOF (for long fallows). In this case the values could either be higher or lower. We also emphasize again that the presence of bamboo will elevate both BGC and the RSR.

Agro-forestry

All ten non-swidden agroforestry BGC values originate from Indonesia; and they ranged from 0.04-16 Mg C ha^{-1} (Table 1, S1). The lowest values were associated with the first year of cropping of bamboo talun-kebun agroforestry system (Christanty et al., 1996). The highest (16 Mg C ha^{-1}) was reported for a Javanese home garden, featuring trees mixed annuals and shrubs (Jensen, 1993). Values for other mature land-covers had BGC values of 7-9 Mg C ha^{-1} (Roshetko et al., 2002; Smiley and Kroschel, 2008). In general there were few land covers with mature trees in this group, thus the high value of our adjusted range of 3-16 Mg C ha^{-1} may be low (Figure 1a). The derived RSRs for the reviewed studies ranged from 0.01-2.15. Both the lowest and highest values were determined for crops planted along with bamboo in a Talun-Kebun agroforestry system in West Java (Christanty et al., 1996). If we eliminate these extremes, the range of values reported elsewhere was 0.25-0.49 (Table 2; Figure 1b). The corresponding median for this range is 0.36; and the midpoint is 0.37. The plots of AGC and BGC suggest a RSR value of 0.33 (despite one obvious outlier; Figure 2). Like the swidden fallow class, the presence of bamboo would increase BGC and the RSR.

Grasslands, pastures, and shrublands

Grasslands BGC could be derived for five sites/plots in Thailand and Indonesia. Values ranged from 1-4 Mg C ha^{-1} (Table S1). The highest value was for *Imperata* grasslands in East Kalimantan in Indonesia (Syahrinudin, 2005). The low value was for shrubs in Sumatra (Solichin et al., 2011); for which, the original biomass values were determined from the allometric equation from Cairns et al. (1997). Values in Thailand (2-3 Mg C ha^{-1}) were associated with unburned, semi-natural humid grasslands. These biomass data were determined via soil cores (5 cm diameter) taken down to a depth of only 15 cm (Kamnalrut and Evenson, 1992). These limited data support an adjusted range of 2-4 Mg C ha^{-1} (Figure 1a), for which the corresponding adjusted RSR range is 0.48-1.92. The median and midpoints for RSR are 1.11 and 1.20. The graph-derived estimate of the RSR is 0.78. We note that the RSR could be either very low or very high for this diverse land-cover category, depending on the species composition of the land cover—however, too few data exist to make an accurate assessment.

Permanent cropland

Eight values of BGC for permanent crops could be derived from two locations in Thailand and one in Vietnam (range = 1-5 Mg C ha^{-1}; Table S1). Of these, only the value (2 Mg ha^{-1}) from a mixed agriculture site in northern Thailand was based on *in situ* sampling (Pibumrung et al., 2008). While this site included a mixture of rice paddy, corn fields, fallows, and orchards, we have chosen to include them in this vegetation class, rather than AGF. The lone site in Vietnam had a BGC value of 1 for a banana plantation (Zemek, 2009). Most of the BGC values of the PC class were calculated for the Khlong Yai subwatershed site in Thailand from an arbitrary root:shoot ratio of 30% by Gnanavelrajah et al., (2008). The highest value (5 Mg C ha^{-1}) was associated with sugar cane. These limited data support a BGC range of 1-5 Mg C ha^{-1} (Figure 1a). Again, seven of the eight RSR values associated with permanent agriculture (0.26-0.31) were literature values used to calculate below-ground biomass. The only value determined by sampling (0.31) was associated with a mixed agriculture site in northern Thailand (Pibumrung et al., 2008). Thus, we use the original range of 0.26-0.31 for the RSRs in this class. The median is 0.30; the midpoint, 0.29. The plots in Figure 2 suggest a value of about 0.30, but this is an artifact of nearly all the AGC and BGC values being derived from RSRs, not field sampling.

3. Data limitations and uncertainty

We considered all reported data in our effort to develop plausible ranges of below-ground carbon and root:shoot ratios, despite potential flaws and differences in collection methods. In order to increase the pool of available BGC data, we have included studies that were undertaken for a variety of purposes, not solely biomass estimations. Adjusting the ranges by eliminating distinct outliers, in part, addresses the issue of underestimating total root biomass by some studies. Admittedly, the minimum values for many of the ranges still do appear too low for mature stands. If this is the case, using the medians, means, or range midpoints as a typical value for a particular class would also be low. The high frequency of use of general allometric equations—including root:shoot ratios—is of concern for generating this summary because these data may not be truly representative of mature vegetation at the particular study site. Amalgamating land covers that contain myriad different plant species into the various operational categories (e.g., forests, OTP) also created uncertainty. However, a more important source of uncertainty was the non-standardization of sampling methods. Here we discuss some of the limitations we encountered during the review.

The methods employed in any one case often depended on geographical variables affecting accessibility, as well as the type of vegetation considered. In general, soil cores were used for determining fine root biomass; and published allometric equations were often used to determine total root biomass (fine + coarse roots). The most popular method applied in forests was allometric relationships, followed by soil cores, soil pits and root excavation. Similarly, BGC from orchards, tree and rubber plantations were mostly derived from indirect methods, whereas biomass data from logged forest, oil palm, agroforest, peat forest, swidden fallows and grasslands were determined largely from direct methods such as cores and pits. The few available permanent crop BGC data were determined from indirect methods; all but one was determined by root:shoot ratios. Mangrove values were determined from a fairly equal mix of direct and indirect methods. Again, of concern was the dependence on pre-existing allometric relationships rather than the determination of new site-specific ones (eg. Komiyama et al., 2005). Granted, it is extremely difficult to perform destructive sampling to make these determinations, but the point we are making is that failing to do so introduces uncertainty in the determination of below ground biomass and the associated carbon.

Soil coring was a popular method that provided estimates for small localized points (Komiyama et al., 2000; Oliveira et al., 2000). A general limitation with coring is that sampling of coarse roots with small cores is practically impossible. It is also difficult to obtain samples near the base of the tree where root density may be highest. Soil compaction during coring may also skew results (cf. Makkonen and Helmisaari, 1999; Park et al., 2007). For both coring and excavation methods, samples are also difficult to extract in wet, sandy soils or stony soils. Total root excavation is the best method for measuring large and deep vertical roots; however, very deep tap roots extending down many meters and/or anchored into bedrock are often not sampled sufficiently. Nevertheless, roots will inevitably be lost during the excavation process due to accidental breakage. The great need for manpower and/or machinery to facilitate root removal is likely one of the reasons that only about 10% of the data were derived from root extraction methods.

Studies using multiple methods arguably provide more accurate biomass estimates. Pinard and Putz (1996), for example, used soil monoliths (pits) to study coarse roots (>5 mm diameter) and soil cores to measure fine roots (<5 mm diameter) in logged over forests in Sabah, Malaysia. Sim and Nykvist (1990) combined results from two different methods to derive a single carbon biomass value for coarse roots > 20 mm in a lowland evergreen forest. Specifically, roots were cut 3 cm from a central stump for trees with a DBH > 19 cm. For smaller trees, 50 x 50 x 50 cm sample pits were excavated to study the root systems in detail. Elsewhere, Nguyen (2009) collected soil cores and soil blocks to quantify belowground root carbon in mangroves. With these exceptions, most studies use only one direct method (i.e. cores, pits or root excavation) to quantify coarse or fine root biomass, thereby failing to counterbalance the shortcomings of any one method (cf. Hertel et al., 2009; Kitayama and Aiba, 2002; Hendricks et al., 2006; Leuscher et al., 2009). The importance of choosing the one method over another was demonstrated by Park et al. (2007), who found that fine root biomass determined from soil cores was 27% higher than that determined from soil pits.

Root biomass estimates in the reviewed studies included either or both fine and coarse roots, but there was no standardization for separating the two. In general, two-to-five millimeters was commonly used, although it varied with vegetation type (Kenzo et al., 2010; Pinard and Putz, 1996; Stokes et al., 2009; Zobel, 2005). Arguably, roots should be defined based on functionality, but the lack of knowledge of root ontogeny and morphology often prevents this (Pierret et al., 2005). Some studies defined root vitality classes by either visual or physical criteria, including color, tensile strength, flexibility, and chemistry. However, classification of roots into live, dead, or unknown classes was inconsistent. Lastly, the definition of what constituted root biomass varied, with some researchers combining shrub and herb root biomass together with that of trees. Others calculated only the biomass of the primary species (e.g., trees in a forest association). Again, we point out that the motivation of the reviewed studies was not always for biomass determinations.

Although, rarely mentioned, processing errors may produce underestimates when roots are sampled directly. Root breakage and loss—particularly of fine roots—inevitably occurs during sampling or washing (Clark et al., 2001; Subedi et al., 2006). The amount of care and time spent to extract roots from soils is often a key determinant in influencing root recoveries (Pierret et al., 2005). Also, there was no standardized or best way to recover roots from soils – some studies separated the roots by hand (eg. Ngo et al., 2013) while others washed roots through various size sieves (range: 65 μm to 5 mm) (cf. Syahrinudin, 2005; Pibumrung et al., 2008). Floatation was also suggested (Oliveira et al., 2000). For the floatation method, small roots may remain stuck to clayey soil particles despite repeated washing. Lastly, excess lag time between root storage and processing may result in root death or loss of dry weight via decomposition, thereby affecting the root biomass estimates (Oliveira et al., 2000).

Many of the case studies we reviewed arguably sampled too small an area to capture the spatial resolution of BGC in the stand. For example, the number of replicates in the reviewed studies for forest ranged from 2 cores within a 30-60 ha plot (Pinard and Putz, 1996) to 160 cores within one 8-ha landform unit (Pibumrung et al., 2008). Figure 3a shows the great variability in root biomass at depths down to 1 m for four replicate cores collected in a secondary forest. In addition, root biomass estimated within the upper 2 m of two duplicate soil pits in the same secondary forest differed by almost three-fold (7 versus 18 Mg C ha^{-1}; Figure 3b). These examples demonstrate the need for sufficient sample replicates to capture the spatial variability. With respect to temporal variability, most of the reviewed studies were one-time snapshots, without replication. Thus, seasonal, environmental and age-related variations in root biomass were not captured. In addition, few of the studies sampled below one meter, despite evidence that rooting depths of tropical trees, shrubs and herbaceous plants can reach or exceed depths of 7.0, 5.0 and 2.5 m respectively (Canadell et al., 2006). The importance of deep sampling is demonstrated in Figure 3b: 10-20% of the total root biomass, mostly fine roots, occurred below the depth of 1 m in bamboo and secondary evergreen forests (Figure 3).

Finally, using different means of deriving carbon fractions adds to uncertainty. Most biomass carbon values were calculated as one-half measured root biomass. In cases where carbon content was determined analytically (e.g, with carbon-nitrogen analyzer or Walkley-Black method) values ranging from 0.37-0.53 have been determined (cf. Brearley, 2011; Hertel et al., 2009, 2009b; Kenzo et al., 2010; Leuschner et al., 2009; Pimbumrung et al., 2008).

These limitations, which were not always clearly elaborated upon in the reviewed case studies, contribute uncertainty in the BGC and the RSRs we identify for each land cover. Specifically, the sampling related limitations/difficulties complicate the development of accurate allometric relationships for estimating BGC from AGC. Caution is needed when using generalized relationships because they may not be representative of the characteristics of any one specific study plot, especially in heterogenous facies (Chave et al., 2005; Komiyama et al., 2008). Rarely can the wealth of below-ground biomass for all vegetation be calculated from tree-based allometric relationships. In comparsion, the use of indirect methods in homogeneous landscapes, such as tree-based rubber and oil palm plantations, may be more reliable. However, one must also consider that allometric relationships may change with the age of vegetation and changing resource availability (Hütsch et al., 2002; Laclau, 2003; Shipley and Meziane, 2002; van Noordwijk et al., 2004; Wilson, 1998).

4. Total vegetation carbon stocks

The ranges of BGC we have determined for some land covers are slightly different from those we reported in the prior meta-analysis of total ecosystem carbon (Ziegler et al., 2012), particularly, those for grasslands and non-swidden agroforests categories. Again, partial motivation of this review was to improve upon our prior assessment of carbon stock changes related to land-cover conversion. In our new estimation of TEC changes (Table 3), minimum and maximum values of AGC for most land covers were adopted from the prior assessment (Ziegler et al., 2012). The AGC values for mangrove and peat forests were determined from new data presented in Table S1, for which obvious outliers were removed (as per Ziegler et al., 2012).

The mangrove and peat forest calculations were complicated because soil profiles for these vegetation types can have very high organic contents extending down several meters. We estimate the range of SOC for mangrove forests and peat forest as 225-675 Mg C ha^{-1} and 537-1612 Mg C ha^{-1}, respectively. These values are estimates for a soil profile 2 m deep, in agreement with the idealized soil profiles for which the other land-cover SOC values are estimated (described in detail in Ziegler et al., 2012). The mangrove value is estimated as 3-fold that of forest—an assumption based on the data of Donato et al. (2012) showing mangrove SOC ranging from 13-15%, compared with values for upland soils that ranging from 0.4-5.5%. For the peat forest, the maximum value of 1612 Mg C ha^{-1} (for 2 m) is within the range of 1425 Mg C ha^{-1} (2.67 m depth) to 7889 Mg C ha^{-1} (12.07 m depth) reported by Warren et al (2012). It is estimated by a linear regression equation, determined by fitting the data in that study: 412.85 * 2 (m depth) + 786.41 (R^2 = 0.85; n =10). The minimum peat forest SOC value is about 2.4-fold that of the mangrove minimum (based on ratio of peat maximum to mangrove maximum)

The rationale of these new TEC estimates is to explore the plausible impacts of changes from one land cover to another in the region. Such comparisons are often the starting points in any proposal related to REDD+ or other carbon accounting endeavors. Ideally such studies would collect site-specific data, but this is not always the case. In absence of other more detailed data, it is evident from the values in Table 3 that conversion among several land covers could result in ambiguous outcomes in carbon stocks. The improved estimates of BGC give us more confidence in claiming that many projected land-cover/land-use transitions would produce uncertain or potentially neutral carbon outcomes: e.g. (a) transitions between short-fallow swidden systems and permanent croplands; (b) land-cover changes between/among long-fallow swidden, other agroforestry systems, and possibly rubber; and (c) land-cover changes between/among intermediate-fallow swiddening, grasslands, pastures, shrub lands, and oil palm plantations. These uncertainties are important to stress because many of these transitions are currently at the heart of REDD+ debates (cf. Ziegler et al. 2012). Also apparent in the estimates is the importance of forests, particularly peat and mangrove forests, as carbon sinks (cf. Donato et al., 2012). Conversions of these land covers almost invariably results in losses of carbon stocks.

5. Towards a better carbon database

Our analysis revealed that careful attention should be given to sampling to appropriate depths, obtaining sufficient replicates, and using appropriate sampling intervals to capture accurately heterogeneous root distribution, both vertically and laterally (cf. Moore and McCabe, 1999). Detailed information should also be presented to provide clarity and aid in interpretations. When applicable, roots should not be amalgamated into a single category, but partitioned into live and dead roots. Information on the distribution of root lengths and depths for species should also be recorded. Where indirect methods are to be used, information should be validated against direct methods as a form of quality control. In most cases, multiple methods should be used to substantiate common calculations and provide the most accurate calculation for particular root types (e.g., coarse versus fine). Long-term sampling to account for temporal variability in root dynamics at a given site should be considered. In general, time-average carbon stocks are preferential for comparing differences between land uses. These observations are in general agreement with published outlines of appropriate sampling protocols for determining BGC accurately (Vogt et al., 1998; Oliveira et al., 2000; Qureshi et al., 2012).

In most cases, the use of general allometric equations or RSRs is not as desirable as using one determined specifically for a location (cf. Chave et al., 2005; Kauffman and Donato, 2012). An important shortcoming of deriving such equations is that below-ground biomass components must be determined from direct sampling using destructive methods (Chave et al., 2004; Levillain et al., 2011; Mokany et al., 2006). Destructive sampling in forests, logging concessions, orchards, and plantations, however, is often not possible. In the latter three cases, root biomass determinations can be conducted between rotations. This would require researchers to develop working relationships with loggers and plantation owners (Laclau, 2003). Research in natural forests is complicated because most now fall under the protection or jurisdiction of government forest and/or conservation departments. Government conservation agencies should therefore be drawn into the forest carbon documentation process, whereby opportunistic events can be used to bolster the forest carbon inventory. One means of generating new data on protected trees is to align research with planned construction projects. In most countries road network, power line, and rural expansion requires the removal of trees for which limited or no BGC data exist. Allowing researchers to extract trees prior to removal would provide an avenue to bolster the forest carbon database. Likewise, partnerships with the mining industry to allow sampling of deep rooted vegetation in open-cut mines would be useful as well.

6. Conclusions

Uncertainty in below-ground root carbon stocks for eleven major land covers in twelve countries across SE Asia results in part from the limited amount of research that has been conducted to date and methodological inconsistencies between existing studies. Limited data exists for rubber and oil palm despite their importance as cash-generating crops in the region (Edwards et al., 2012; Fox et al., 2012; Koh and Wilcove, 2008; Ziegler et al., 2009; Ziegler et al., 2012). Furthermore, the paucity of data for swidden fallows is surprising given the historical criminalization of slash-and-burn agriculture and the uncertain role of this land cover in the future (cf. Mertz, 2009; Ziegler et al., 2011, 2012). The paucity of data strengthens our claim that great uncertainty exists with regard to carbon outcomes of transitions between many land covers. One implication of this uncertainty for policy-making is that reliable estimates of how any land-use changes will affect below-ground root carbon simply cannot be made with existing (published) above- or below-ground meta-analysis data (Ziegler et al., 2012). Some land-cover transitions are less affected by uncertainty: e.g., transitions to/from mature forests and other tree-based plantations to low biomass crops. However, the outcomes of changes in below-ground carbon regarding many non-forest changes are ambiguous. Furthermore, the time scale over which the BGC is lost to the atmosphere is very poorly understood. Root biomass may persist for decades, but breakdown rates and the fate of the root carbon are rarely studied.

New carbon stock assessment programs must include complementary site-specific, direct measurements of both above- and below-ground carbon. Unfortunately, new BGC measurements will require using destructive methods that quantify all biomass components (live or dead, coarse or fine) over time and space. Reliance on allometric relationships already determined for the region may not provide reliable estimates, although the inclusion of data determined outside SE Asia may be useful. Government agencies, private enterprises, and development agencies could play a role in developing a better forest carbon database by teaming with researchers to assess AGC and BGC prior to trees being removed for construction (road, dam, power lines), mining, or stand rotations (forestry, plantations). Achieving greater certainty in terrestrial carbon stock, while challenging, will allow improved assessments of stock losses associated with the rapid landscape changes now taking place in the region. This is particularly true at forest frontier areas where rapid conversion from traditional land covers to high value plantations (oil palm, rubber) is occurring at unprecedented rates (Ziegler et al., 2009; Fox et al.,2012).

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