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Carbon stocks in bamboo ecosystems worldwide: Estimates and uncertainties

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ABSTRACT

From a review of 184 studies on bamboo biomass for 70 species (22 genera) we estimate plausible ranges for above-ground carbon (AGC) biomass (16–128 Mg C/ha), below-ground carbon (BGC) biomass (8–64 Mg C/ha), soil organic carbon (SOC; 70–200 Mg C/ha), and total ecosystem carbon (TEC; 94–392 Mg C/ha). The total ecosystem carbon range is below that for most types of forests, on par with that of rubber plantations and tree orchards, but greater than agroforests, oil palm, various types of swidden fallows, grasslands, shrublands, and pastures. High carbon biomass was associated with many *Phyllostachys* spp., including Moso (*P. edulis*) in China, Japan, Taiwan, and Korea, as well as other "giant" bamboo species of genera *Bambusa*, *Dendrocalamus*, *Gigantochloa*, and *Guadua*. The low end of the TEC range for mature bamboo typically included various species of dwarf bamboo, understory species, and stands stressed by climatic factors (temperature, rainfall), soil conditions, and management practices. Limited research and uncertainties associated with determinations prevent a robust assessment of carbon stocks for most species. Moso bamboo was by far the most studied species (>40% of the reported values), as it is commonly grown in plantations for commercial use. Similarly, a review of available allometric equations revealed that more work is needed to develop equations for predicting carbon biomass for most species. Most allometry equations exist for AGC for China, where 33 species have been studied. Allometric equations for BGC are rare, with all work conducted in China (15 species) and India (2). Root:shoot ratio estimate for most groups of species and genera were less than one, with the exception of *Phyllostachys* spp (however, some individual species with small sample size were greater than one).

Estimated annual carbon accumulation rates were on the order of 8–14 Mg C/ha, relaxing to $\leq$4 Mg C/ha after selective harvesting of stands commences following maturation–but the timing of this rate change could not be reliably ascertained. The high standing carbon stocks and high annual accumulation rates point to the possibility of successful carbon farming using bamboo, if stands are managed efficiently (sufficient water, adequate nutrients, appropriate thinning/harvesting). Key in long-term carbon sequestration of bamboo is making sure harvested bamboo are turned into durable products (e.g., permanent construction materials, furniture, art). While our review demonstrated the potential of bamboo as an efficient and effective carbon sink, further research is needed to reduce uncertainties in the underlying data, resulting from a lack of standardization of methods, a lack of research for many bamboo species, and limited research of below-ground and soil organic carbon. Another priority is obtaining more carbon estimates for under-represented regions such as Central America, South America and Africa. Finally, we conducted a case study in northern Thailand that demonstrated the difficulty in sampling above- and below-ground components of total ecosystem carbon, as well as the threat of drastic bamboo biomass loss associated with instances of gregarious flowering. Overall, we recommend that instead of being seen as an invasive species with low utility, bamboo should be given greater recognition in policy and management for its value as a carbon sink, critical in mitigating the effects of climate change, and for its ability to provide key ecosystem services for humans, such as stabilizing hillslopes from accelerated soil erosion, improving soil fertility, and providing food and construction materials.

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Contents

1. Introduction

Bamboo is a woody-stemmed grass that belongs to the Bambusoideae subfamily and the Gramineae (or Poaceae) family (Scurlock et al., 2000). Worldwide, there are approximately 1250–1500 species of bamboo comprising approximately 75–107 genera (Ohrnberger, 1999; Scurlock et al., 2000; Zhu, 2001). They are distributed across approximately 31.5 million ha of land, the equivalent of 0.8% of the world's total "forested" area (FAO, 2010; Song et al., 2011). A large proportion of bamboo is concentrated in China and India. China is home to about 500–534 species that occupy approximately 4.84–5.71 million ha (Chen et al., 2009b; Li and Kobayashi, 2004; FAO, 2010; Song et al., 2011), mostly in the south (Chen et al., 2009b; Song et al., 2011). India has about 128 species distributed over approximately 5.48 million ha (Tewari, 1992; Seethalakshmi and Mutesh Kumar, 1998). Approximately 80% of the bamboo forests are found in the Asia-Pacific Region (Lobovikov et al., 2012).

The wide tolerance of bamboo to climatic and edaphic conditions means that it persists in tropical and subtropical areas between 46°N and 47°S (Song et al., 2011). In addition, some bamboo species have high (culm) growth rates that peak at approximately 7.5–100 cm per day (Buckingham et al., 2011). Rapid growth rates favor the accumulation of organic carbon by photosynthesis, in aboveground culms, the culm branches with their sheaths and leaves, and an underground network of roots and persistent rhizomes (Düking et al., 2011; Lobovikov et al., 2012). Given the large areal distribution of bamboo relative to other plant species and their high growth rates, it would appear that bamboo land covers can sequester substantial quantities of carbon, thereby helping to mitigate the effects of climate change (Nath et al., 2015). For example, the fast growth of a Moso bamboo (*Phyllostachys edulis*) forest in China resulted in 5.10 Mg C ha^{-1} of carbon sequestered during a single year – a rate that is 33% higher than a tropical mountain rainforest and 41% higher than a 5-yr old stand of *Cunninghamia lanceolata*, a fast-growing Chinese fir (Zhou and Jiang, 2004; Kuehl et al., 2013). More generally, the carbon storage in bamboo forests in China has been estimated to be 169–259 Mg C ha^{-1}, much higher than mean estimates for forests in China and globally, which are 39 and 86 Mg C ha^{-1}, respectively (Song et al., 2011).

In addition, Nath et al. (2015) report biomass carbon sequestration rates as high as 13–24 Mg C ha^{-1} y^{-1} for various types of bamboo worldwide. The highest rate (24 Mg C ha^{-1} y^{-1}) was associated with a sympodial (root growth pattern) *Bambusa bambos* plantation in India (Shanmughavel and Francis, 1996), whereas the next highest rate (16 Mg C ha^{-1} y^{-1}) was for a sympodial *Bambusa oldhamii* plantation in Mexico (Castañeda-Mendoza et al., 2005). The highest carbon sequestration rate (13 Mg C ha^{-1} y^{-1}) for a monopodial species was associated with a *Phyllostachys bambusoides* plantation in Japan (Isagi et al., 1993). Other sympodial species with high sequestration rates include *Bambusa pallida* and *Dendrocalamus strictus*, both growing in plantations in India (Singh and Kochhar, 2005; Singh and Singh, 1999).

Some authors have highlighted uncertainty over the carbon sequestration potential of bamboo. Liese (2009) and Düking et al. (2011) argue that the growth of new culms is merely a reallocation of carbohydrates from one part of the plant to another. According to them, culm growth is not driven by its own photosynthesis, but is derived from energy that was produced previously by an older culm. In addition, the relatively short lifespan of individual culms (7–10 years) means that stored carbon will be potentially released into the atmosphere relatively quickly, compared with the wood biomass of longer-lived tree species. However, harvested bamboo is now often used to produce durable products such as furniture and construction materials, which equate to long-term storage of carbon, offsetting the short lifespan of bamboo culms (Huang et al., 2014). In addition, bamboo can produce phytolith-occluded carbon, a stable form of carbon resulting from decomposing vegetation that remains in the soil for several thousand years (Huang et al., 2014). Parr et al. (2010) estimated that the bio-sequestration of phytolith-occluded carbon by bamboo worldwide is equivalent to 11% of the current increase in atmospheric carbon dioxide.

A recent study by Zachariah et al. (2016) has also raised uncertainty over the sequestration potential of bamboo. The authors measured gas exchange at the surface of a six-month old and a one-year old *Bambusa vulgaris* culm, and estimated that loss of carbon via emission of CO_2 could actually exceed the amount of carbon sequestered via growth. However, the results from this study must be viewed as preliminary, given that only two bamboo culms were studied and the emission rates measured were simply assumed to hold across the whole lifetime of a bamboo and across bamboo individuals in a stand. There is also the issue that if bamboo were net emitters of carbon, the source of the carbon needed to make up the balance is unclear. In contrast, by estimating production and respiration from a stand of *Phyllostachys pubescens* bamboo in Kyoto Prefecture, Japan, Isagi et al. (1997) found a positive net carbon production of 8.5 t ha^{-1} yr^{-1}, a rate that is comparable to values for forests in Japan with similar climates.

On balance, although there is uncertainty over how effectively bamboo stores carbon, there is enough evidence to suggest that the carbon storage potential is sufficient enough to include bamboo in debates on how land-cover transitions/manipulations influence climate change (cf. Lou et al., 2010; Wang et al., 2013; Nath et al., 2015). However, to date, bamboo has not been included in policy agreements related to feedbacks between land-use change and climate change. For example, the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Marrakech Accords do not refer to bamboo (Lobovikov et al., 2012). The omission may be originally related to bamboo's botanical classification as a grass (Buckingham et al., 2011; Lobovikov et al., 2012). It may also be related to views that bamboo is an invasive or emergent species growing opportunistically on degraded lands or is simply part of other types of recognized land covers (cf. Christanty et al., 1996; Buckingham et al., 2011; Kuehl et al., 2013). For example, the presence of bamboo has been noted on marginal degraded lands and swidden fallows, which have been historically criminalized and increasingly discouraged (Schmidt-Vogt, 1998; Ziegler et al., 2009). But even in these systems, bamboo may be important in land recovery, as Christanty et al. (1996) found in their compelling assessment of land recovery in the bamboo *talun-kebun* rotation swidden system in West Java, Indonesia.

We posit that bamboo has been overlooked in attempts to simplify the variables involved in contemporary carbon calculus. The neglect of bamboo in policy agreements is inopportune not only because of its potential to sequester carbon, but also because of its purported ecological and socioeconomic benefits. Bamboo has been cultivated and used by humans for at least 6000 years (Song et al., 2011), and it is now used by billions of people every day (Lobovikov et al., 2007). Bamboo is particularly important for rural livelihoods (Lobovikov et al., 2012). In addition, young bamboo shoots from 56 species are edible, while the sturdy culms of dozens of species can be used to produce furniture or construction material (Li and Kobayashi, 2004). Bamboo can also be used as firewood (Li and Kobayashi, 2004; Liese, 2009). Furthermore, as an alternative to wood, 18 species of bamboo can be used to make pulp and paper (Li and Kobayashi, 2004). There is little wastage in producing bamboo products – nearly 100% of harvested bamboo can be used in the manufacturing of commercial products, compared with about 20% for trees (Muladi, 1996; Lobovikov et al., 2012). With approximately 1500 commercial applications (Scurlock et al., 2000), bamboo has resulted in products with an estimated global market value of US $7 billion (Lobovikov et al., 2012).

From the perspective of ecosystem functioning, the extensive fibrous rhizome and root systems of bamboo can decrease surface soil erosion, lower the risk of shallow landslides, and stabilize river banks (Song et al., 2011). For example, a single bamboo plant can bind up to 6 m^3 of soil (Zhou et al., 2005) and the leafy mulch that is common around bamboo clumps protects the topsoil from erosion by the direct impact of rain (Liese, 2009; Zhou et al., 2005; Song et al., 2011). Furthermore, bamboo's presence on degraded lands helps rehabilitate soils via recycling of nutrients sequestered in deeper horizons of the soil profile (Christanty et al., 1996). The slow decomposition of silica-rich litter and high concentration of fine roots also contributes to the restoration of physical and chemical properties of soil (Christanty et al., 1996).

In this review paper, we attempt to provide a rigorous assessment of carbon sequestration potential of bamboo to inform management aimed at mitigating the effects of global climate change. By doing so, we also improve understanding of the importance of carbon sequestration by bamboo relative to other known ecological and socioeconomic benefits. In Part I of this paper, we review studies reporting aboveground (AGC), belowground (BGC) and soil organic carbon (SOC) stocks in ecosystems with significant amounts of bamboo (hereafter "bamboo ecosystems"), from around the world. Afterwards, we compare the carbon stocks of these ecosystems in Southeast Asia with those of the other major land covers in the region. Southeast Asia is the region where bamboo originated (Song et al., 2011) and for which estimates of carbon stocks for major land covers are most readily available (Yuen et al., 2013, 2016; Yuen, 2015). Apart from bamboo, these land covers encompass forest (FOR), logged-over forest (LOF), orchard and tree plantation (OTP), rubber plantation (RP), oil palm (OP), long-fallow swidden (LFS), intermediate-fallow swidden (IFS), short-fallow swidden (SFS), non-swidden agroforest (AGF) and grassland, pasture and shrubland (GPS; bamboo is excluded from this land cover type).

In Part II of the paper, we compile literature-reported allometric equations for calculating bamboo biomass, culm volume and culm height – quantities that are routinely used to estimate carbon stocks. The aim of this compilation is to provide a comprehensive overview of the equations available for estimating carbon storage in different bamboo ecosystems. This overview provides insight into the current capacity for carrying out these estimations in different geographical regions and facilitates use of the equations for the calculation and assessment of carbon storage in bamboo ecosystems worldwide. In our compilation (provided as Supplementary online material), we provide information on the taxonomy, age and location of the sampled bamboo used to derive the equations, because these are important factors influencing carbon storage.

Finally, in Part III of the paper we highlight the importance of bamboo as a carbon store in the context of land regeneration by presenting the results of a new case study in Thailand, which compares carbon stocks in a bamboo forest with those in an adjacent evergreen forest. This case study thus provides an explicit instantiation of the general conclusions that we derive from the analysis in Part I, which spans case studies from around the world. The case study also provides us with an arena to discuss the difficulties in undertaking carbon biomass determinations in these systems.

2. Part I: review of studies on AGC, BGC and SOC in bamboo ecosystems worldwide

2.1. Methods

We reviewed a total of 184 case studies reporting information on carbon stocks in bamboo ecosystems worldwide. Journal articles, book chapters, and scientific reports were identified in a comprehensive literature search carried out using Web of Science, Scopus, Google, Google Scholar, and individual journal databases, using permutations of keywords that include bamboo, aboveground, below-ground, roots, root:shoot ratio, allometry, allometric equations, carbon, biomass, tropics. The remaining keywords consisted of individual country and region names if bamboo is commonly found within the locations (Sharma, 1987): Africa, China, India, Indonesia, Japan, Laos, Malaysia, Myanmar, Philippines, South America, Southeast Asia, Taiwan, Thailand, and Vietnam. In addition, bibliographies of reviewed articles were used to find obscure and older articles. Furthermore, gray literature sources were examined. Relevant non-English articles (e.g. Chinese, Japanese, Korean and Thai) were translated into English by the first author.

We focused on AGC, BGC and SOC stocks as they largely comprise the total ecosystem carbon (TEC) stocks of land-covers, similar to our prior analyses (Ziegler et al., 2012; Yuen et al., 2013, 2016). In most studies the aboveground biomass estimates typically consisted of the bamboo culms, branches and leaves, while below-ground estimates typically included the underground stump, rhizome and roots. However, we did not exclude data if calculation methods varied or we were unsure of the exact components comprising AGC and BGC estimates. Because only a handful of studies reported carbon values (a percentage of the vegetative biomass), we typically determined AGC and BGC values by multiplying the biomass estimates by 50% (following Smith et al., 2010). In some cases, studies reported root:shoot ratios (RSR), which are the ratios of below-ground to above-ground biomass. In other cases, we determined them as BGC/AGC. Thus, our approach was to be as comprehensive as possible in our data collection, including values that were likely associated with immature stands or that were determined with non-standardized methods.

From the 184 case studies in our review, AGC data for 70 species from 22 genera were collated for bamboo ecosystems worldwide, resulting in a total of 543 AGC values (Table 1). The most common genera were *Bambusa* (16 species, sometimes mixed together at a study site), *Phyllostachys* (11), *Dendrocalamus* (7 species), *Gigantochloa* (6 species, sometimes mixed), and *Sasa* (5). The remaining genera were represented by one to three species. The countries with information on bamboo biomass stocks included Bangladesh, Bolivia, Brazil, Chile, China, Colombia, Ecuador, Ethiopia, India, Japan, Kenya, Laos, Malaysia, Mexico, Myanmar, Philippines, South Korea, Taiwan, Thailand and Vietnam (Table 1). The most data originated from China, where information on 35 species was found. The remaining countries provided data for one to seven species. In comparison, fewer data were available for BGC data: 303 values from 51 species from 19 genera around the world (Tables 1 and S1). Thus, a similar number of values (301) were collated for AGC + BGC and RSR. Carbon estimates, sampling and calculation methods, and other relevant characteristics of each reviewed case study are listed by country in Supplementary Table S1.

The most data were for *Phyllostachys edulis:* 217 AGC and 127 BGC values (Table 1). In deriving these numbers from Table 1, we considered *Phyllostachys pubescens*, *Phyllostachys pubescens* Mazel ex H. de Lehaire, and *Phyllostachys heterocycla* to be synonyms of *P. edulis*, following http://www.theplantlist.org/tpl1.1/search?q=phyllostachys and http://www.plantnames.unimelb.edu.au/Sorting/Phyllostachys.html. Commonly referred to as "Moso" bamboo, *P. edulis is* mostly found in China where it originated; however, data were also available for Japan, South Korea, and Taiwan (Tables 1 and S1). Of the other four genera with giant bamboos, the most data was available for *Dendrocalamus* spp. (43 AGC and 23 BGC values) from China, India, Myanmar, Philippines, Taiwan, and Vietnam (Table 1). *Bambusa* spp. had 67 AGC and 28 BGC values originating from work in China, Bangladesh, India, Mexico, Myanmar, the Philippines and Taiwan. Fewer than 10 AGC and

Table 1

Summary of data on aboveground carbon (AGC), below-ground carbon (BGC), and root:shoot ratio (BGC/AGC) of the various types of bamboos in the meta-analysis (in Mg C/ha).

Name	Location	AGC				BGC				AGC + BGC				RSR
		n	Mean	Stdev	Max	n	Mean	Stdev	Max	n	Mean	Stdev	Max	Mean
Acidosasa edulis	China	1	5.1	–	5.1	1	1.9	–	1.9	1	7.0	–	7.0	0.38
Arundianaria fargesii	China	1	23.7	–	23.7	1	10.9	–	10.9	1	34.6	–	34.6	0.46
Arundinaria alpina	Ethiopia, Kenya	3	68.4	18.8	89.9	1	12.8	–	12.8	1	67.7	–	67.7	0.23
Arundinaria pusilla	Thailand	4	2.1	0.5	2.6	2	13.1	0.3	13.3	2	14.9	0.5	15.2	7.78
Bamboo in fallow	India, Laos, Myanmar	35	14.7	14.1	56.4	15	4.1	3.1	11.9	15	20.9	17.5	68.3	0.27
Bamboo in forest	China, Laos, Myanmar, Thailand, Vietnam	24	27.5	43.1	162.0	7	13.6	21.8	50.4	7	55.0	78.1	193.7	0.17
Bambusa arudinacea	India	6	23.5	17.9	50.9	–	–	–	–	–	–	–	–	–
Bambusa bambos	India	13	81.1	46.0	143.3	9	5.3	4.0	12.2	9	76.5	54.3	148.9	0.17
Bambusa bulmeana	Philippines	3	57.1	13.0	71.5	1	21.5	–	21.5	1	93.0	–	93.0	0.30
Bambusa burmanica	China	1	23.4	–	23.4	1	7.4	–	7.4	1	30.8	–	30.8	0.32
Bambusa chungii	China	1	29.5	–	29.5	1	8.2	–	8.2	1	37.7	–	37.7	0.28
Bambusa dolichomerithalla	China	2	32.8	19.0	46.3	2	2.0	1.1	2.8	2	34.8	20.1	49.1	0.06
Bambusa oldhami	China, Mexico	9	25.7	27.7	71.6	8	4.6	5.5	16.7	8	27.0	29.9	74.4	0.47
Bambusa pachinensis	China	1	48.4	–	48.4	1	2.1	–	2.1	1	50.5	–	50.5	0.04
Bambusa polymorpha	Myanmar	13	15.3	9.1	31.8	–	–	–	–	–	–	–	–	–
Bambusa rigida	China	1	35.7	–	35.7	1	5.8	–	5.8	1	41.5	–	41.5	0.16
Bambusa spp.	India	3	25.5	30.8	61.1	–	–	–	–	–	–	–	–	–
Bambusa stenostachya	Taiwan	2	70.7	62.0	114.5	1	159.4	–	159.4	1	273.9	–	273.9	1.39
Bambusa textilis	China	1	21.7	–	21.7	1	4.5	–	4.5	1	26.2	–	26.2	0.21
Bambusa tulda	Bangladesh, India, Myanmar, Philippines	11	23.5	17.0	53.0	2	9.2	9.5	15.9	2	60.9	11.3	68.9	0.17
Bashania fangiana	China	1	2.1	–	2.1	1	3.4	–	3.4	1	5.5	–	5.5	1.63
Bashania fargesii	China	3	2.6	1.7	3.7	3	0.6	0.4	0.9	3	3.2	2.1	4.5	0.25
Chimonobambusa quadrangularis	China	1	5.0	–	5.0	1	6.1	–	6.1	1	11.1	–	11.1	1.22
Chusquea culeou	Chile	1	80.8	–	80.8	–	–	–	–	–	–	–	–	–
Chusquea tenuiflora	Chile	1	6.5	–	6.5	–	–	–	–	–	–	–	–	–
Dendrocalamopsis vario-strata	China	2	28.8	2.5	30.6	1	11.6	–	11.6	1	38.7	–	38.7	0.43
Dendrocalamus asper	Philippines, Taiwan	3	74.5	30.0	108.1	–	–	–	–	–	–	–	–	–
Dendrocalamus barbatus	Vietnam	2	26.6	25.4	44.6	–	–	–	–	–	–	–	–	–
Dendrocalamus giganteus	China, Taiwan	6	33.6	36.4	77.9	4	3.9	5.7	12.4	4	15.5	21.9	47.8	0.31
Dendrocalamus hamiltonii	China	1	53.1	–	53.1	1	17.7	–	17.7	1	70.8	–	70.8	0.33
Dendrocalamus latiflorus	China, Taiwan	22	15.3	15.7	57.0	12	5.4	7.1	19.8	12	14.2	11.7	40.8	1.00

Table 1 (*continued*)

Name	Location	AGC				BGC				AGC + BGC				RSR
		n	Mean	Stdev	Max	n	Mean	Stdev	Max	n	Mean	Stdev	Max	Mean
Dendrocalamus membranaceus	China	1	21.3	–	21.3	1	2.5	–	2.5	1	23.8	–	23.8	0.12
Dendrocalamus strictus	India, Myanmar	8	20.7	15.5	49.1	5	7.4	3.4	12.1	5	21.9	11.8	36.7	0.86
Fargesia denudata	China	8	33.5	22.9	69.2	8	26.5	13.6	44.3	8	60.0	35.7	113.5	0.90
Fargesia scabrida	China	1	4.4	–	4.4	–	–	–	–	–	–	–	–	–
Fargesia spathacea	China	1	10.9	–	10.9	–	–	–	–	–	–	–	–	–
Gelidocalamus stellatus	China	5	1.9	1.8	4.8	5	1.3	1.2	3.2	5	3.2	2.9	8.0	0.76
Gigantochloa apus	Indonesia	2	17.3	17.4	29.7	2	2.2	2.2	3.8	2	19.5	19.7	33.5	0.13
Gigantochloa levis	Philippines	1	73.4	–	73.4	–	–	–	–	–	–	–	–	–
Gigantochloa scortechinii	Malaysia, Myanmar	3	20.9	13.8	36.0	–	–	–	–	–	–	–	–	–
Gigantochloa spp.	Indonesia, Thailand	4	23.0	15.3	43.7	2	10.5	7.3	15.7	2	25.3	18.2	38.2	0.72
Guadua angustifolia	Bolivia, Colombia, Ecuador	8	69.9	41.3	155.5	6	7.5	2.7	10.8	6	57.7	17.4	80.0	0.15
Guadua weberbaueri	Brazil	1	5.1	–	5.1	–	–	–	–	–	–	–	–	–
Neosinocalamus affinis	China	9	29.9	19.5	62.2	8	6.3	5.4	16.0	8	33.5	24.1	78.2	0.21
Oligostachyum oedognatum	China	6	10.4	5.6	18.3	6	8.2	5.8	17.1	6	18.6	9.8	35.4	0.89
Phyllostachys atroviginata	China	1	56.0	–	56.0	1	92.2	–	92.2	1	148.3	–	148.3	1.65
Phyllostachys bambusoides	Japan, South Korea	4	31.2	20.5	52.3	2	13.4	10.4	20.8	2	45.7	38.7	73.1	0.44
Phyllostachys edulis	China, Japan, Korea, Taiwan	217	33.2	23.9	169.4	127	14.8	17.4	116.7	125	46.0	39.8	286.1	0.55
Phyllostachys heteroclada	China	14	20.0	6.5	32.6	5	35.6	6.0	45.2	5	55.7	11.6	69.0	1.97
Phyllostachys makinoi	Taiwan	16	24.7	11.0	49.8	7	69.2	29.1	90.1	7	92.7	37.9	128.2	2.79
Phyllostachys meyeri	China	1	42.2	–	42.2	1	59.0	–	59.0	1	101.2	–	101.2	1.40
Phyllostachys nidularia	China	2	14.5	12.1	23.1	2	12.2	16.5	23.9	2	26.7	28.6	47.0	0.56
Phyllostachys nigra	South Korea	1	28.2	–	28.2	1	15.1	–	15.1	1	43.2	–	43.2	0.53
Phyllostachys praecox	China	2	6.8	0.8	7.4	2	3.0	2.5	4.7	2	9.8	3.3	12.1	0.42
Phyllostachys rutila	China	1	68.1	–	68.1	1	117.1	–	117.1	1	185.2	–	185.2	1.72
Phyllostachys viridis	China	1	16.0	–	16.0	1	41.5	–	41.5	1	57.4	–	57.4	2.60
Pleioblastus amarus	China	18	17.3	16.0	63.5	13	11.6	20.4	76.8	13	27.0	37.6	140.3	0.65
Pseudosasa amabilis	China	8	20.0	11.2	35.2	4	7.8	0.5	8.4	4	17.9	2.5	20.3	0.78
Pseudosasa usawai	Taiwan	3	32.4	11.4	42.4	3	34.4	15.8	52.6	3	66.8	20.6	87.5	1.13
Qiongzhuea tumidinoda	China	1	13.3	–	13.3	1	10.8	–	10.8	1	24.1	–	24.1	0.82
Sasa kurilensis	Japan	2	40.0	1.9	41.3	2	15.5	0.8	16.1	2	55.5	2.7	57.4	0.39
Sasa nikkoensis	Japan	2	9.5	0.0	9.5	2	6.5	0.1	6.6	2	16.0	0.2	16.1	0.69
Sasa nipponica	Japan	2	4.1	0.5	4.4	2	3.7	0.6	4.1	2	7.8	1.0	8.5	0.91
Sasa oseana	Japan	2	8.3	1.8	9.5	2	5.7	1.2	6.6	2	14.0	3.0	16.1	0.69
Sasa senanensis	Japan	2	9.0	4.5	12.2	3	7.4	5.5	13.5	2	18.8	9.8	25.7	1.06
Schizostachyum lumampao	Philippines	2	31.1	2.8	33.0	1	9.9	–	9.9	1	42.9	–	42.9	0.30
Sinarundinaria fangiana	China	1	3.7	–	3.7	–	–	–	–	–	–	–	–	–
Thyrsostachys siamensis	Thailand	4	17.0	9.0	26.9	–	–	–	–	–	–	–	–	–

Bambusa oldhami includes *Dendrocalamopsis oldhami*, *Dendrocalamus oldhami*, *and Bambusa atrovirens*.

Phyllostachys pubescens, *P. heterocycla*, and *P. pubescens* Mazel ex H. de Lehaire are all synonyms of *Phyllostachys edulis*.

Bambusa spp. includes *B. cacharensis*, *B. balcooa*, *B. vulgaris*.

Gigantochloa spp. includes *G. ater*, *G. verticilata*, *G. apus*.

Data are from the following 167 studies: Abe and Shibata (2009), An et al. (2009), Castañeda-Mendoza et al. (2005), Chaiyo et al. (2012), Chan et al. (2013, 2016), Chandrashekara (1996), Chen et al. (1998, 2000, 2002, 2004, 2009a, 2012a, 2012b, 2012c, 2013, 2014), Christanty et al. (1996), Dang et al. (2012), Das and Chaturvedi (2006), Descloux et al. (2011), Ding et al. (2011), Dong et al. (2002), Du et al. (2010a, 2010b), Embaye et al. (2005), Fan et al. (2009, 2011, 2012, 2013), Feng et al. (2010), Fu (2007), Fu et al. (2014), Fukushima et al. (2007, 2015), Fukuzawa et al. (2007, 2015), Geri et al. (2011), Guo et al. (2005), Han et al. (2013), Hao et al. (2010), He et al. (1999, 2003, 2007), Homchan et al. (2013), Huang et al. (1993), Isagi (1994), Isagi et al. (1993, 1997), Kao and Chang (1989), Kaushal et al. (2016), Kiyono et al. (2007), Kleinn and Morales-Hidalgo (2006), Kumar et al. (2005), Kumemura et al. (2009), Lan et al. (1999), Li and Liao (1998), Li and Lin (1993), Li et al. (1993, 2006a, 2010, 2016), Lin (2000, 2002, 2005), Lin et al. (1998a, 1998b, 2000, 2004), Liu and Hong (2011), Liu et al. (2010a, 2010b, 2012), Lou et al. (2010), Lü and Chen (1992), Luo et al. (1997), Ly et al. (2012), Majumdar et al. (2016), Nath and Das (2010), Nath et al. (2009), Nie (1994), Oshima (1961), Othman (1994), Park and Ryu (1996), Patricio and Dumago (2014), Peng et al. (2002), Petsri et al. (2007), Qi and Wang (2008), Qi et al. (2009, 2012), Qiu et al. (1992, 2004), Quiroga et al. (2013), Rao and Ramakrishnan (1989), Riaño et al. (2002), Roder et al. (1997), Ruangpanit (2000), Sabhasri (1978), Shanmughavel and Francis (1996), Shanmughavel et al. (2001), Shen et al. (2013), Singh and Singh (1999), Sohel et al. (2015), Su and Zhong (1991), Sujarwo (2016), Sun et al. (1986, 1987), Sun et al. (2009, 2013), Suwannapinunt (1983), Suzuki and Jacalne (1986), Tanaka et al. (2013), Tang et al. (2011, 2012, 2015), Taylor and Qin (1987), Teng et al. (2016), Tian et al. (2007), Tong (2007), Torezan and Silveira (2000), Tripathi and Singh (1994, 1996), Uchimura (1978), Veblen et al. (1980), Viriyabuncha et al. (1996), Wang and Wei (2007), Wang (2002, 2004, 2009), Wang et al. (2005, 2009b, 2009c, 2010a, 2011, 2012, 2013), Wen (1990), Wu (1983), Wu et al. (2002, 2009), Xiao et al. (2007, 2009), Xu et al. (2011, 2014), Yang et al. (2008), Yen and Lee (2011), Yen (2015), Yen et al. (2010), Yu et al. (2005, 2016), Zemek (2009), Zhang et al. (2014b), Zheng and Chen (1998), Zheng and Hong (1998), Zheng and Wang (2000), Zheng et al. (1997a, 1998a, 1998b, 1998c), Zhou and Fu (2008), Zhou and Jiang (2004), Zhou (1995, 2004), Zhou et al. (1999, 2011), Zhu et al. (2014), Zhuang et al. (2015).

10 BGC values were available for *Gigantochloa* spp. (Indonesia, Malaysia, Myanmar, Philippines, and Thailand) and *Guadua* spp. (Bolivia, Brazil, Ecuador, and Colombia).

Descriptive statistics for the SOC values that we found are listed in Table 2. The 147 SOC values pertain to various depths in bamboo stands associated with eight genera (*Bambusa*, *Cephalostachyum*, *Dendrocalamus*, *Fargesia*, *Guadua*, *Neosinocalamus*, *Phyllostachys*, *Pleioblastus)* in Bangladesh, China, Ecuador, India, Japan, Myanmar, and Vietnam (Table 2). Most data were available for *P. edulis*, derived from studies conducted in China and Japan (Table 2). Supplementary Table S1 lists the SOC estimates, sampling and calculation methods, and other relevant characteristics reported by the authors of each reviewed case study.

To facilitate further analysis, we established eight groups of bamboo, defined either as individual species, genera, or a mixture of species from different genera: (1) *Phyllostachys edulis* (including the synonyms identified above)*; (2) Other Phyllostachys* spp.; (3) *Dendrocalamus* spp.; (4) *Gigantochloa* spp.; (5) *Guadua* spp.; (6) *Bambusa* spp.; (7) bamboos in forests or fallows; and (8) other species. Groups (1) and (2) are separated because Moso bamboo has been the subject of extensive study. Bamboos in forest often involve a dominant bamboo species growing in either a timber

Table 2
Soil organic carbon (SOC) in soils surrounding various bamboo species (in Mg C/ha), where n is the number of estimates from the reviewed case studies.

Species	Geographic location	n	min	max	Average	Median
Bambusa polymorpha	Myanmar	3	12	14	13	13
Bambusa tulda Roxb.	Myanmar	2	18	20	19	19
Bambusa vulgaris	Bangladesh	1	–	–	25	–
Cephalostachyum pergracile	Myanmar	1	–	–	15	–
Dendrocalamus barbatus	Vietnam	1	–	–	92	–
Dendrocalamus latiflorus	China	8	76	144	109	115
Dendrocalamus strictus	India	2	48	53	51	51
Fargesia denudata	China	5	86	125	103	102
Guadua angustifolia	Ecuador	6	61	123	79	74
Neosinocalamus affinis	China	1	–	–	74	–
Phyllostachys edulis	China, Japan	107	35	269	120	107
Phyllostachys praecox	China	8	70	317	142	100
Pleioblastus amaraus	China	2	87	133	110	110

Data are from the following 52 studies: Chen et al. (2016), Christanty et al. (1996), Du et al. (2010c), Fan et al. (2012), Fu et al. (2014), Fukushima et al. (2007, 2015), Guan et al. (2015), Guo et al. (2005), Hu et al. (2011), Huang (2001), Huang et al. (2014), Isagi (1994), Isagi et al. (1997), Li et al. (2006a, 2006b, 2010, 2013, 2015), Liu et al. (2010b, 2013a, 2013b), Ly et al. (2012), Nath et al. (2009), Qi and Wang (2008), Qi et al. (2009, 2012, 2013), Roder et al. (1997), Shen et al. (2013), Sohel et al. (2015), Tang et al. (2012), Teng et al. (2016), Tian et al. (2007), Tripathi and Singh (1996), Wang and Wei (2007), Wang et al. (2009a, 2009c, 2011, 2012), Xiao et al. (2007, 2009, 2010), Xu et al. (2014), Yu et al. (2016), Zhang et al. (2013, 2014a, 2014b), Zhou and Jiang (2004), Zhou et al. (2009), Zhu et al. (2014), Zhuang et al. (2015).

plantation or a natural forest; in some cases the bamboos are understory species. Bamboos in fallow are of various ages and are often associated with swidden systems. A large number of data values for the "other species" group of bamboos stem from work in China, Ethiopia, Japan, Philippines, S. Korea, Taiwan, and Thailand (Table 1).

We related the carbon values that we found for the eight bamboo groups identified to rainfall, temperature, plant density, and age, in order to identify implausible outliers (usually values that were too low). This allowed us to identify plausible ranges of values for the carbon stocks of mature stands of bamboo, information that is useful for assessing the carbon sequestration potential of different types of bamboo. Because of our focus on mature stands, our analysis here was based only on data for bamboo plantations/-forests that were at least 3 years old, as we assume that younger plantation/forest data did not represent mature stands. Climate information (annual rainfall and mean temperature) reported in the studies was used for all but 33 locations; for the remaining 33 locations, climate information was extracted from the on-line source http://en.climate-data.org/.

2.2. Above- and below-ground carbon

Several of the studied bamboo species (or communities) have high carbon stocks in their vegetative components (AGC + BGC). Noticeable in Table 1 are the high values associated with *Phyllostachys edulis* (286 Mg C/ha), *Bambusa stenostachya* (274 Mg C/ha), *P. rutila* (185 Mg C/ha), *Bambusa bambos* (149 Mg C/ha), *P. atroviginata* (148 Mg C/ha), and *Pleioblastus amarus* (140 Mg C/ha). However, as several species have only been investigated only one time, including *B. stenostachya*, *P. rutila* and *P. atroviginata*, it is difficult to judge the representativeness of the sole carbon stock values for these species. For most species, the standard deviations are high relative to the mean values for any of AGC, BGC, or AGC + BGC (Table 1). Variability is expected as we did not restrict the data to a particular age, culm density, or environmental setting. For example, *P. edulis* had one of the highest maximum AGC values (169 Mg C/ha), yet the mean (±stdev) was 33 ± 24 Mg C/ha (i.e., a coefficient of variation >0.7). Also highly variable were reported root:shoot ratios (Table 1), with the means ranging from 0.04 to 7.78—the extremes (above 3 and below 0.10) are almost certainly outliers. The take away message from Table 1 is that it is likely that some species have high carbon stocks, but that it is probably best not to use the means and standard deviations from the limited data to define sensible ranges of plausible values.

In an attempt to define plausible ranges for AGC, BGC, and SOC in various types of bamboo, we plot reported values against annual rainfall, annual mean temperature, and culm densities reported in the studies (Figs. 1–3). Owing to limited data, these graphical analyses are performed on the eight groups defined above, each of which consists of more than one species except for the category with just *P. edulis*. For both AGC and BGC we define two thresholds that indicate the following: (1) values above the upper threshold are high (compared with those in other studies), and may only be plausible for the particular conditions of a site (PH, for "plausible, high"); and (2) values above the second threshold and below PH are the most plausible for a range of environmental and management conditions likely associated with healthy stands of various types of bamboo – thus, this threshold represents the lower limit of plausible carbon values (PL; "plausible, low"). The thresholds are based on consideration of all plots of carbon versus rainfall (Fig. 1), temperature (Fig. 2), and culm density (Fig. 3). Carbon values are plotted on a $\log_2$ scale to visualize the relationships clearly.

In the plot of AGC versus annual rainfall (Fig. 1a), the bulk of the data fall between the PL and PH thresholds of 16 and 128 Mg C/ha. The six values above 128 Mg C/ha are high (143–169 Mg C/ha), but may still be plausible for extreme conditions. Values below the threshold of 16 Mg C/ha are considered implausibly low for mature stands. These relationships relative to the defined thresholds are also visible in the plot of AGC versus temperature (Fig. 2a). The 6 AGC values that are above the PH threshold pertain to *P. edulis* in China ($n = 2$, but reported as *P. pubescens* and *P. heterocycla var. pubescens* by Wen (1990) and Zheng et al. (1997a), respectively), *Guadua augustifolia* in Colombia (Kleinn and Morales-Hidalgo, 2006), *B. bambos* in an irrigated and fertilized plantation in India (Shanmughavel et al., 2001), a 40-year managed bamboo forest in Vietnam with medium-sized trees present (Zemek, 2009), and a riparian forest in Laos with a high density of bamboos (Descloux et al., 2011). Another case of *B. bambos* having a relatively high AGC (125 Mg C/ha) near the upper threshold was reported for home gardens in India (Kumar et al., 2005). We consider the six high AGB values as plausible, given that most are associated with some type of giant bamboo, involve intense management, and/or occur in environmentally favorable conditions (e.g., riparian location).

Prominent features of Figs. 1a and 2a are the wide range of annual rainfall and temperature regimes where high carbon values for bamboo have been reported: (a) 1400–2800 mm of rainfall per year in locations with no irrigation; and (b) mean annual temperatures ranging from about 17 to 32 °C. In cool places, many high

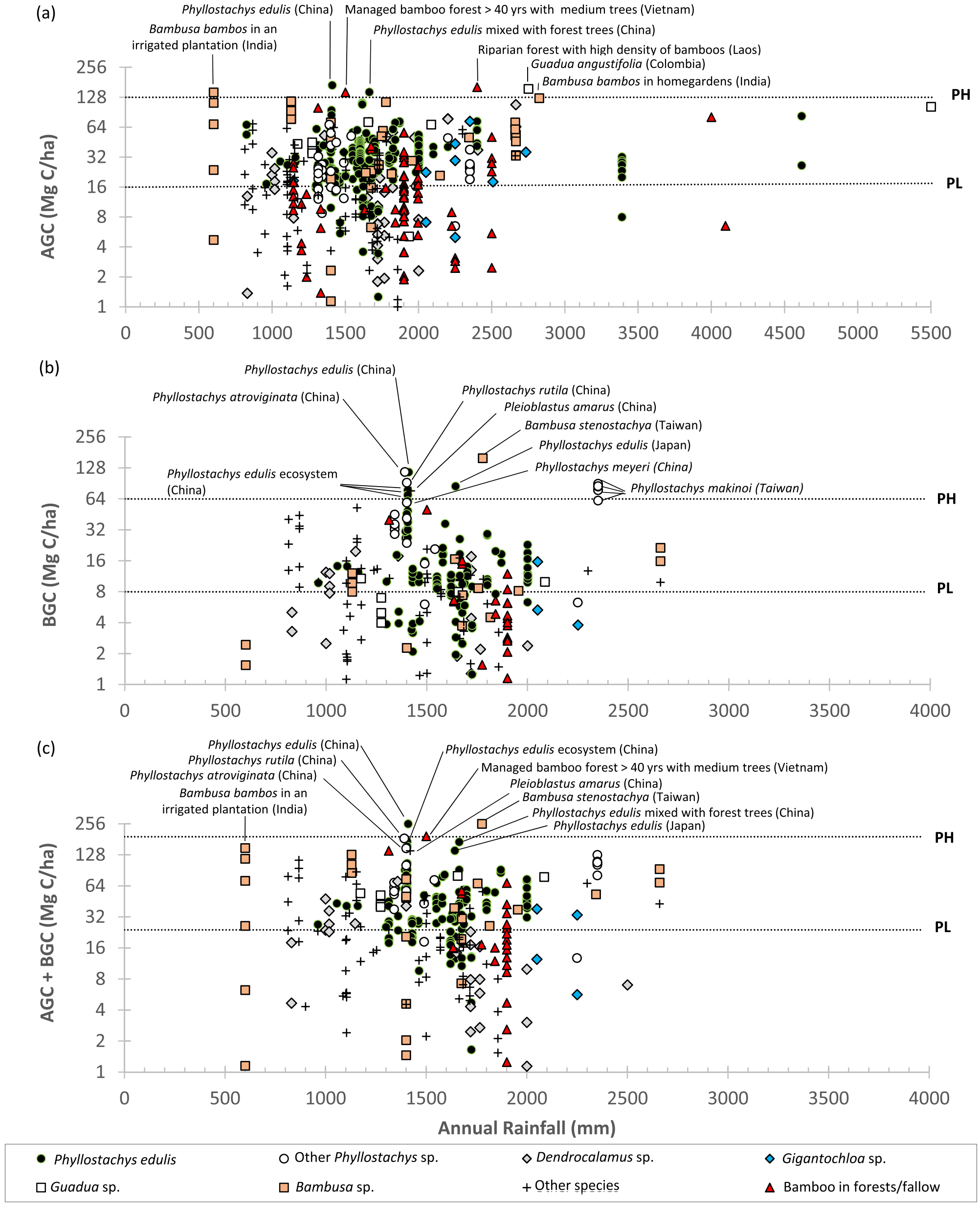

Fig. 1. Comparison of Above-ground Carbon (AGC) biomass (a), Below-ground Carbon (BGC) biomass (b), and AGC + BGC (c) with mean annual rainfall associated with the location where the values were determined. The most plausible values for any species or bamboo group fall between the two thresholds PH (plausible, high) and PL (plausible, low). The plotted values are from the review of 167 case studies.

values above about 50 Mg C/ha are associated with Moso bamboo (*P. edulis*) in China or Japan (Fig. 2a). Various bamboos growing in temperatures <15 °C have AGC values within the 16–128 Mg C/ha range, including *P. edulis* (China, Japan, Taiwan), *Chusquea culeou* (Chile), *Dendrocalamus asper* (Taiwan), *Pseudosasa usawai* (Taiwan), and *Sasa kurilensis* (Japan). In addition, a noticeable pattern is that for bamboos not associated with forests/fallows, most of the low AGC values occur in locations where annual rainfall is <2000 mm. A relatively small number of high AGC values (>50 Mg C/ha) have been recorded in sites with low rainfall ≤1200 mm. Little more can be gleaned from the temperature plot other than that most bamboos studied tend to grow in climates with annual mean temperatures between 13 and 27 °C.

The plots of BGC reveal the limited amount of reliable data available for determining plausible carbon stock thresholds for this underground component, compared with AGC. Based on the grouping of the data according to annual rainfall and temperature (Figs. 1b, and 2b), we define thresholds at 8 and 64 Mg C/ha. Below 8 Mg C/ha, the data are likely not representative of mature, healthy stands. The highest value (159 Mg C/ha) was determined for *Bambusa stenostachys* in Taiwan (Chen et al., 2012a). The value is about 40 Mg C/ha higher than the next two highest values that are associated with a site where high AGC was recorded: *P. edulis* and *P. rutila*. Both were reported for China by Wen (1990) and both were approximately 117 Mg C/ha. Two other high values were also reported by Wen (1990) for China (Figs. 1b, and 2b): *P. atroviginata* (92 Mg C/ha) and *Pleioblastus amarus* (77 Mg C/ha). Two more high BGC values (70, 78 Mg C/ha) originated from China for *P. edulis* ecosystems (Liu et al., 2012). Five other values ranging from 78 to 90 Mg C/ha were determined in *P. makinoi* plantations in Taiwan (Chen et al., 2009a). The remaining species with BGC above 64 Mg C/ha was *P. edulis* in Japan (Fukushima et al., 2015). Another

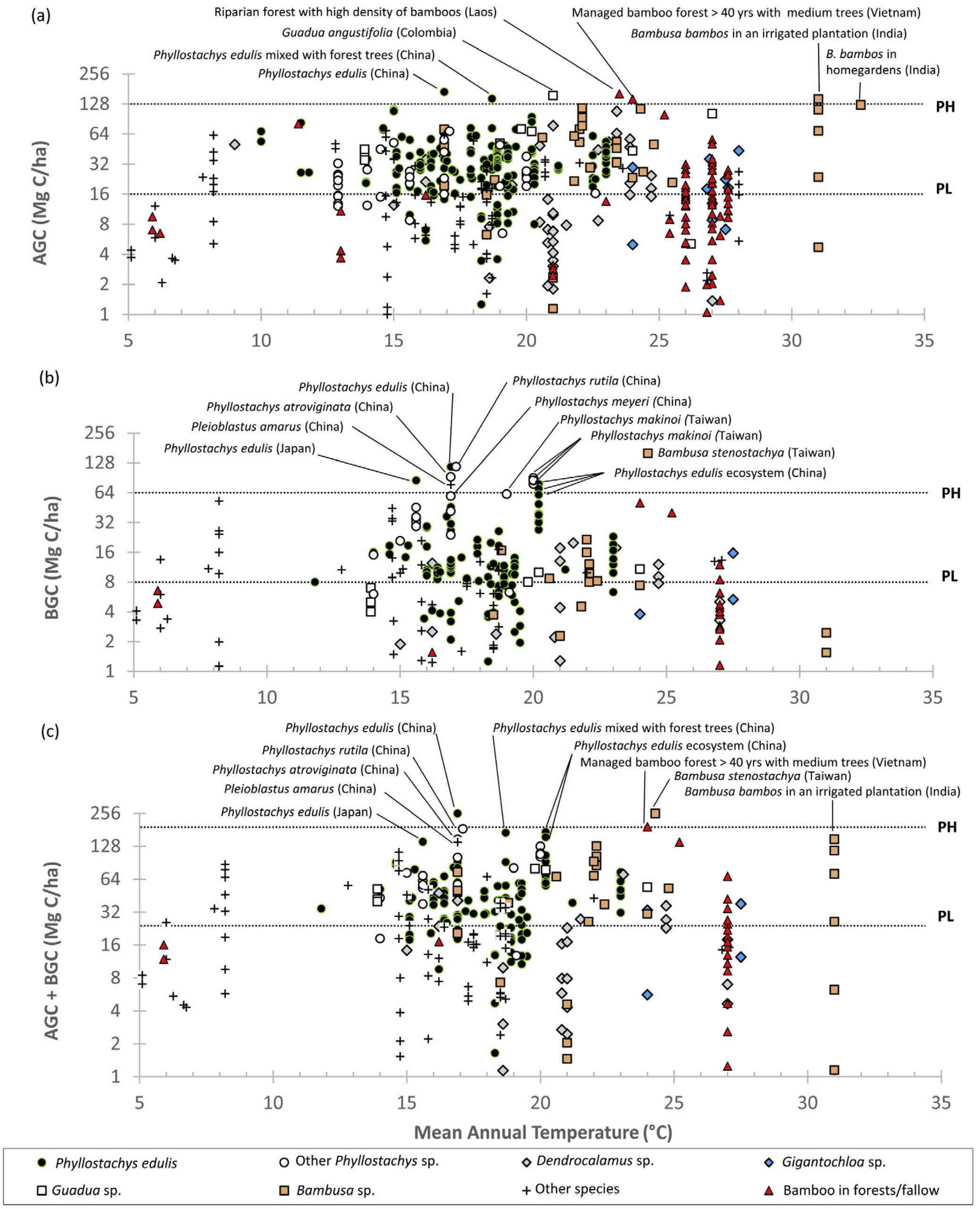

Fig. 2. Comparison of Above-ground Carbon (AGC) biomass (a), Below-ground Carbon (BGC) biomass (b), and AGC + BGC (c) with mean annual temperature associated with the location where the values were determined. The most plausible values for any species or bamboo group fall between the two thresholds PH (plausible, high) and PL (plausible, low). The plotted values are from the review of 167 case studies.

Phyllostachys species (*P. meyeri*) has a high BGC value of 59 Mg C/ha (Wen, 1990). The high BGC values are associated with a more narrow range of rainfall (1400–1650 mm) and temperature (15–20 °C) than for the high AGC values.

We define the thresholds indicating the most plausible range of values for AGC + BGC by adding those for AGC and BGC (Figs. 1c, 2c), resulting in values of 192 and 24 Mg C/ha for PH and PL, respectively. This range is wider than the 30–121 Mg C/ha considered in a recent review of 17 case studies (Nath et al., 2015). In that review, the authors discounted two high values (144 and 160 Mg C/ha) as outliers (cf. Hunter and Wu, 2002). We however retain the values as they fall below the general threshold of plausibility. Only three values are above the upper threshold—the extremely high values for *P. edulis* for China (286 Mg C/ha) and *B. stenostachya* (274 Mg C/ha), as well as the 194 Mg C/ha for 40-year old managed bamboo within a tree forest in Vietnam (Figs. 1c and 2c). As the former two are nearly 100 Mg C/ha higher than the threshold, it is likely they are outliers, but they could be representative of ideal conditions for Moso bamboo in its native China, and irrigated plantation bamboo in Taiwan. The figures also show that most high AGC + BGC values occur at sites with a relatively narrow band of rainfall (1300–1700 mm) and warm temperatures (16–20 °C), with some forest-associated high-carbon bamboo growing at higher temperatures of 24–25 °C. In addition, some managed plantations with high carbon stocks were found in drier and warmer conditions (Figs. 1c, and 2c).

While some structure is apparent in the carbon versus rainfall and temperature data (Figs. 1 and 2), some of the observed variability probably results from differences in other environmental factors, management practices and biological characteristics, as

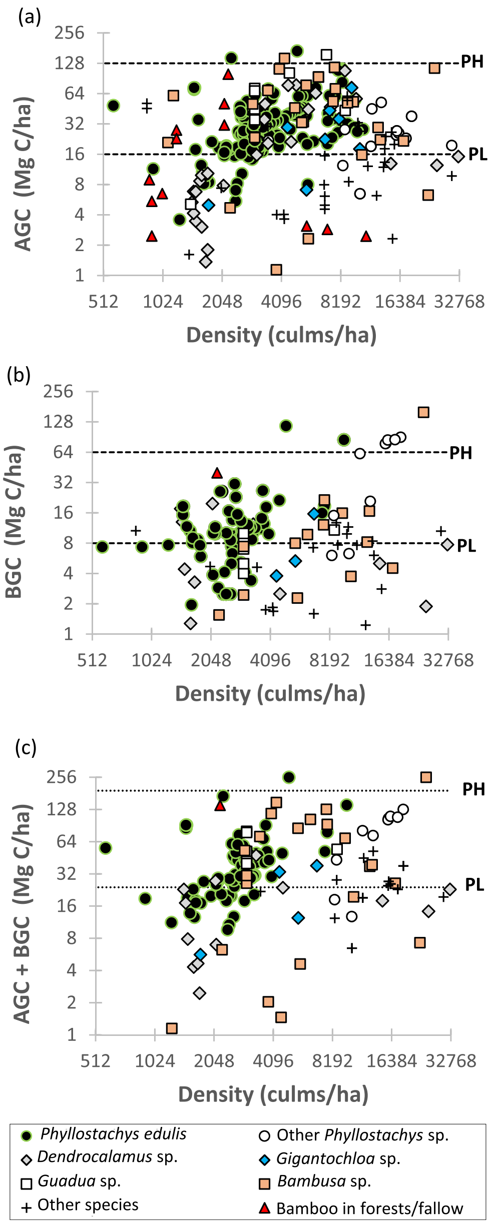

Fig. 3. Comparison of Above-ground Carbon (AGC) biomass (a), Below-ground Carbon (BGC) biomass (b), and AGC + BGC (c) with reported culm densities. The most plausible values for any species or bamboo group fall between the two thresholds PH (plausible, high) and PL (plausible, low). The plotted values are from the review of 167 case studies.

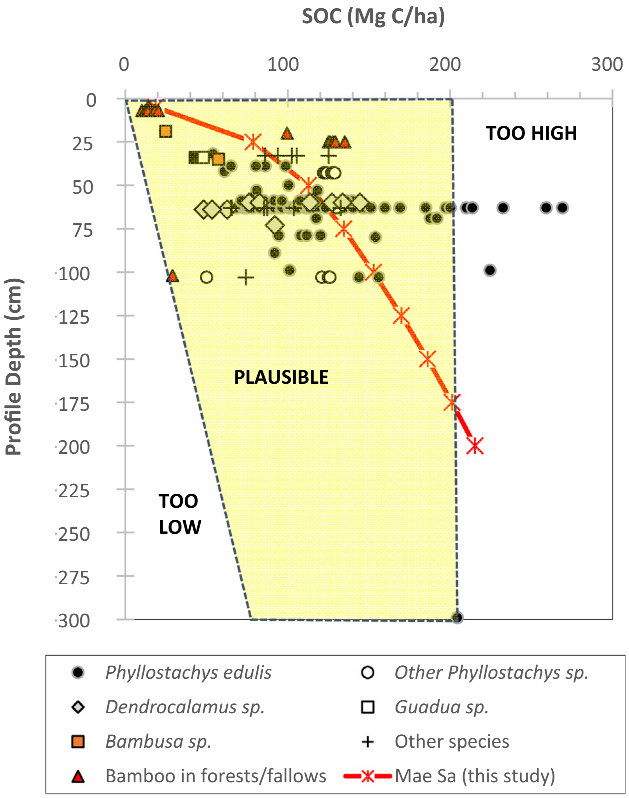

Fig. 4. Reported soil organic carbon (SOC), and respective depths of determination, for various types of bamboo. The range of values enclosed in the highlighted area represent the most plausible for all types of bamboo. The plotted SOC values are from the 52 studies reviewed in our synthesis, as well as the case study reported in section III.

well as measurement uncertainties. Culm density is potentially one of these biological characteristics and could be associated with biomass and hence carbon. However, Nath et al. (2015) did not find a strong association between culm density and biomass. In the larger dataset that we examined, considering all bamboo categories, the general pattern is for AGC to increase as density increases from about 1000 culms/ha to 7000–8000 culms/ha (Fig. 3). Thereafter, the limited data suggest a maximum point is reached, whereupon AGC decreases as very high culm densities are reached. Some studies reported data for densities exceeding 30,000 culms/ha, but we considered them to be extreme for mature stands and have not included them (some were based on conversion from culms/m^2). One difficulty in these comparisons is that high densities can occur for both young and old stands of low and high biomass. In contrast to AGC, BGC values do not show a clear trend with increasing culm density, although there is weak evidence of a decreasing trend as density exceeds about 8000 culms/ha. Similarly, total bamboo carbon biomass (AGC + BGC) has no clear trend with culm density (Figs. 3c and b).

Despite limited data, the relationships between carbon, rainfall, temperature, and culm density collectively allow plausible ranges of AGC (16–128 Mg C/ha), BGC (8–64 Mg C/ha), and AGC + BGC (24–192 Mg C/ha) to be derived for bamboo in general. In most cases, various giant bamboo species occupy the upper ranges, with *Phyllostachys* spp. dominating; some *Bambusa spp.* are also high. In agreement with Nath et al. (2015), AGC + BGC stocks >121 Mg C/ha are infrequent: only 13 instances (out of 546) in our analysis exceeded this value, mostly for *Phyllostachys* spp. in China. However, we consider values up to 192 Mg C/ha to be plausible.

2.3. Soil organic carbon

The 147 available SOC values are mostly for depths shallower than 1 m, typically ≤60 cm (Fig. 4). Ideally, soil layers that are 1–2 m thick and cover deeper profiles should be used for carbon stock estimates intended for comparison with other sites and vegetation. One major difficulty in comparing carbon stock differences among land covers is the differences in methods for determining SOC (Ziegler et al., 2012). The data nevertheless indicate a tendency for SOC per unit area to increase with depth. Most values for shallow profiles (≤50 cm) are in the range 80–160 Mg C/ha, whereas for deeper profiles of 60–75 cm, a wide range of values of 20–270 Mg C/ha have been reported. The upper limit for 1 m profiles is unexpectedly less (225 Mg C/ha, from a range of 70–225 Mg C/ha), but this decrease is related to limited data collected to this

Table 3
Estimated ranges of root:shoot ratio, aboveground carbon (AGC), below-ground carbon (BGC), soil organic carbon (upper 2 m; SOC), and total ecosystem carbon (TEC = AGC + BGC + SOC) for the several important vegetation types involved in on-going and projected land-cover conversions in SE Asia[a]. Data for bamboo land covers are from all studies considered in our review, whereas data for other land-cover types in SE Asia are from Yuen (2015). The unit for the carbon estimates is Mg C/ha.

Land-cover	Root:shoot ratio		AGC		BGC		SOC		TEC	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
PEAT	0.08	0.23	46	216	11	71	537	1612	594	1899
MAN	0.11	0.95	15	250	12	219	225	675	252	1144
FOR	0.08	0.35	40	400	11	74	75	225	126	699
LOF	0.09	0.33	30	210	5	26	68	205	103	441
OTP	0.11	0.39	15	200	5	33	65	196	85	429
BAM	0.14	1.72	16	128	8	64	70	200	94	392
RP	0.10	0.30	25	143	5	32	65	196	95	371
LFS	0.12	0.36	25	110	3	16	64	191	92	317
AGF	0.25	0.49	15	100	3	16	61	182	79	298
OP	0.18	0.41	17	69	4	22	65	196	86	287
IFS	0.12	0.36	4	50	3	16	62	187	69	253
GPS	0.48	1.92	2	35	2	4	66	198	70	237
SFS	0.12	0.36	2	22	3	16	59	178	64	216

[a] The land-covers considered are: peat forest (PEAT), mangrove forest (MAN), forest (FOR), logged-over forest (LOF), orchard and tree plantation (OTP), bamboo (BAM), rubber plantation (RP), long-fallow swidden (LFS), non-swidden agroforest (AGF), oil palm plantation (OP), intermediate-fallow swidden (IFS), grassland, pasture and shrubland (GPS) and short-fallow swidden (SFS).

depth, particularly in similar areas where the 60–75 cm SOC values were determined. The solid line represents the data determined in our accompanying case study (Part III), whereas the shaded area represents our best estimate of the range of plausible SOC values for depths extending down to 3 m, a depth for which there was only one data point reported in the literature. This wide plausible range (70–200 Mg C/ha) encompasses much of the reported data, allowing for the case of very high SOC in somewhat shallow horizons (200 Mg C/ha within a 1 m profile) to somewhat low values (70 Mg C/ha) in a 3 m profile.

2.4. Total ecosystem carbon

With the plausible ranges of AGC (16–128 Mg C/ha), BGC (8–64 Mg C/ha) and SOC (70–200 Mg/ha) identified above, we compare total ecosystem carbon of bamboo with that of other land covers, determined in earlier analyses for SE Asia (Table 3; Ziegler et al., 2012; Yuen et al., 2013; Yuen, 2015). Collectively, the ranges in Table 3 are representative of mature stands growing under a wide range of environmental conditions found in the tropics. The estimated TEC of bamboo land covers ranges from 94 to 392 Mg C/ha, which is slightly above that associated with rubber plantations (95–371 Mg C/ha), but lower than other types of tree plantations (85–429 Mg C/ha). These carbon stocks are lower than those determined for forest (126–699 Mg C/ha) and logged over forests (103–441 Mg C/ha). The highest values are for peat and mangrove forests, which grow in environments where bamboo is not typically found. These meta-analysis results highlight the variability expected for bamboo (and other land covers) in general, not just particular cases that may represent extreme or unique situations. In addition, the ranges reported in Table 3 are sufficiently wide that bamboo TEC may exceed that of a particular forest, although not all forests in general—again, our goal is to determine plausible ranges for TEC.

As in our prior works (Ziegler et al., 2012; Yuen et al., 2013; Yuen, 2015), we are unable to derive meaningful estimates of central tendency and confidence intervals for bamboo TEC. Total ecosystem carbon is composed of three components (AGC, BGC, and SOC) that are often not all determined together. In many cases, biomass is measured without determining carbon density. Of the three, above-ground carbon is the most frequently reported, yet the determination is not easy because it requires destructive sampling of living plants (partial for bamboo, total for most other types of vegetation). Below-ground biomass determinations are labor intensive, requiring excavation and collection of all root material that may be dispersed across a large spatial area, at various depths below the surface. Soil organic carbon determinations are often conducted at insufficient depths to provide data that are comparable across sites. In our approach, we considered all data that plausibly represented some stage of mature bamboo, regardless of knowing the exact age. By viewing the clustering of reported values with respect to rainfall, temperature, and culm density, we attempted to establish a plausible range for AGC, BGC, and the combination of the two. The final component, SOC, was associated with so much uncertainty that we chose a range that is not drastically different from what we have determined previously to be plausible for other tree-dominated land covers (Table 3).

Again, the range of TEC for bamboo represents carbon stocks that one could expect for bamboo in general for a wide range of environmental and management conditions. Collectively, the ranges for all land covers represent mature stands within the SE Asia region – and are therefore comparable for general assessments. The rankings must be weighed against the overlap of the ranges of several land covers—e.g., the TEC of some bamboo plantations may be higher than some forests, but not others. The 301 data points (AGC and BGC) are simply too few to compute specific values for nearly 70 species, occurring naturally and in plantations, across a range of climatic environments, soil conditions, and management scenarios. In general, however, we do have confidence that several *Phyllostachys* spp. have the highest reported carbon stocks (Figs 1 and 2), along with a few other types of giant bamboo, such as *Bambusa* spp. – particularly when managed efficiently. Lower carbon stocks are likely associated with various species of dwarf bamboo, understory species, bamboo stressed at high elevations, low temperatures, or low nutrient conditions. The limited data prevent us from concluding anything more specific about individual species than can be gleaned from Figs. 1–4. Nevertheless, we list the means and standard deviations for each species studied in Table 1 to provide readers with an estimate of central tendency. As above, we caution against using most of them for carbon comparisons because they are based on insufficient sample sizes.

2.5. Root:Shoot relationships

To examine root:shoot ratios (RSRs) we plot BGC versus AGC for the eight groups of bamboo (Fig. 5). A few outliers where AGC >> BGC (RSR < 0.1) or BGC >> AGC (RSR > 3.33) were considered

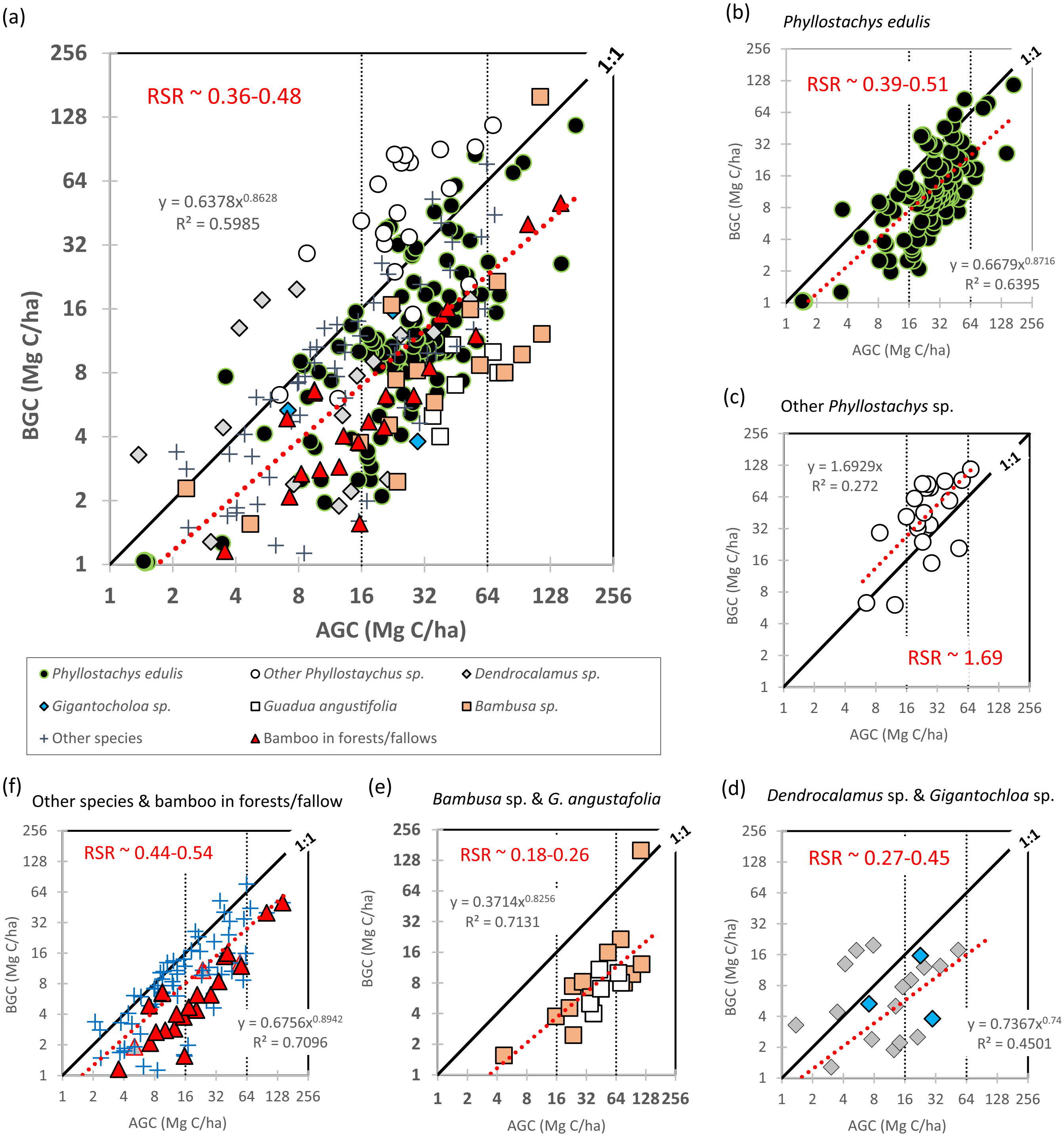

Fig. 5. The relationships between Above-ground carbon (AGC) biomass and Below-ground carbon (BGC) biomass for (a) all species/groups; (b) *Phyllostachys edulis* (Moso); (c) other *Phyllostachys* sp.; (d) *Dendrocalamus* sp. and *Gigantochloa* sp.; (e) *Bambusa* sp. and *Guadua angustifolia*; and (f) other species and bamboo in forests and fallows. Reported root:shoot ratios (RSR) are estimated from the fitted curves shown on the panels, determined at AGC values of 16 and 64 Mg C/ha. The 169 plotted values are from the review of 184 case studies.

unrealistic and excluded from the analysis. The bulk of the remaining data indicate bamboo BGC is usually less than AGC (i.e., points below the 1:1 line in Fig. 5). The main group for which BGC > AGC is “Other *Phyllostachys* spp.”, for which 16 of 20 BGC/AGC values are >1 (Fig. 5c). Included in this group are *P. viridis*, *P. heteroclada*, *P. rutila*, *P. atroviginata* and *P. meyeri*, for which only *P. heteroclada* and *P. makinoi* have more than two data points (Table 1). In comparison, a much smaller percentage of the *P. edulis* case studies reported have BGC > AGC (15 of 125 cases; Fig. 5a). Other cases of BGC > AGC include *Bashania fangiana*, *Chimonobambusa quadrangularis*, *Dendrocalamus latiflorus*, *Fargesia denudate*, *Gelidocalamus stellatus*, *Oligostachyum oedognatum*, *Pleioblastus amarus*, *Pseudosasa usawai*, and *Sasa senanensis* (the very high values >7 for *Arundinaria pusilla* are considered outliers, Table 1). Only in the case of *P. heteroclada* were BGC values consistently higher than AGC values (RSR ranges from 1.29 to 3.33); these values were associated with various percentages of rhizome capacity at locations in China (Sun et al., 1986).

A power function provided a better fit than a linear function for describing the relationship between BGC and AGC in most cases (Fig. 5). The exception was for the "Other *Phyllostachys* spp." category, for which a straight line was best (Fig. 5c). Coefficients of determination (R^2) in most cases ranged from 0.45 to 0.87, indicating fair to good fits for the power functions. Based on the best-fit functions, plausible RSR ranges were determined by calculating RSRs at AGC values of 8 and 64 Mg C/ha (the second value is lower than the 128 Mg C/ha upper threshold for AGC because many species with reported data for both AGC and BGC do not have such high carbon values). With the exception of the "Other *Phyllostachys* spp." group, the RSRs for the bamboo groups are less than 0.54, which is lower than the mean RSRs reported for a number of individual species (Table 1). The estimated RSR for "Other *Phyllostachys* spp." is 1.69. Here, we recognize the great uncertainty in determining mean RSR for groups (and even individual species), in part because of the difficulty in ensuring consistency in the way BGC values are estimated across case studies. Depending on the conditions at a particular site, the mean, minimum or maximum value from an RSR range may be more appropriate.

2.6. Carbon accumulation

Given recent attention on the carbon sequestration potential of bamboo (Lou et al., 2010; Song et al., 2011; Nath et al., 2015), we investigate carbon accumulation in above- and below-ground bamboo components over time, using data from studies reporting stand ages (Fig. 6). This data allowed us to estimate carbon sequestration beginning from an empty plot until eight years of bamboo growth, at which point the bamboo stand is assumed to be at maturity, but not necessarily at its maximum biomass. Considering all types of bamboo, the relationship between stand age and carbon biomass is not represented well by any one type of curve. Thus, we plot a series of lines that bound carbon accumulation rates at 25 Mg C/ha/year and 2.5 Mg C/ha/year (Fig. 6). Most values plot between 4 and 11 Mg C/ha/year, up to about 5–7 years. Other types of *Bambusa* sp. and "Other *Phyllostachys*" have reported carbon stocks equivalent to carbon accumulation rates on the order of 15–25 Mg C/ha/year. These carbon accumulation rates are similar to the range of 6–24 Mg C/ha/year reported in the review by Nath et al. (2015). Their high value of 24 Mg C/ha/year is associated with many of the high *Bambusa* sp. values shown in Fig. 6.

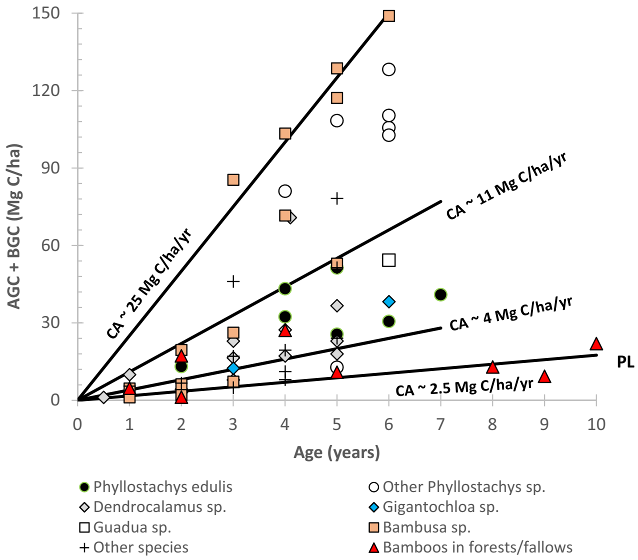

Fig. 6. The relationship between total vegetative carbon biomass (AGC + BGC) and age of a plantation/stand for all studies with sufficient data (total of 87 data pairs). Much of the data plot between lines indicating carbon accumulation (CA) rates of 4–11 Mg C/ha/yr. The rates associated with several *Bambusa* spp. and *Phyllostachys* spp. are much higher (∼15–25 Mg C/ha/yr). Bamboo growing in forests/fallows accumulate carbon more slowly (∼2.5 g Mg C/ha/yr). The lines are truncated because the indicated accumulation rates would surely stabilize upon stand maturity and commencement of harvesting.

Actual carbon accumulation rates at a particular site will depend on bamboo type, environmental conditions, and management practices (irrigation, weeding, thinning, harvesting intensity). Most of the data highlighted above are for giant bamboos with potential for high biomass, especially when growing in optimal environments. Some of the highest values are for intensely managed plantations, such as the irrigated *Bambusa* sp. plantation in India, whereas the other very high values are from an older study for which environmental conditions are unclear (Wen, 1990). The upper ranges we report are probably not achievable in most cases, and thus care is needed to avoid over-estimating the carbon accumulation rate at any one plantation or site. One caveat with this analysis is that the estimated rates are applicable up to maturity at 4–7 years, after which carbon accumulation rate should slow drastically (2–4 Mg C/ha/year), both naturally and in response to selective culm harvesting.

3. Part II: review of allometric equations for bamboo ecosystems worldwide

3.1. Method

We compiled allometric equations from 105 studies for calculating total biomass, aboveground biomass (AGB), below-ground biomass (BGB), culm volume and culm height. We also listed separate equations for the biomass of individual bamboo components (e.g., culm, branches, leaves, rhizomes, roots). The 105 case studies were extracted from the comprehensive literature search described in Section 2.1. Databases of allometric equations exist for several geographical regions (Yuen et al., 2016), but most focus on tree species with few or no entries for bamboo species. An exception is the GlobAllomeTree database (Henry et al., 2013), which is an international database for allometric equations that includes 65 biomass equations for six bamboo species (*Bambusa balcooa*, *B. bambos*, *B. cacharensis*, *B. procera*, *B. vulgaris*, *Indosasa angustata*) and one volume equation for *B. bambos*. These equations were developed in two countries, namely India and Vietnam.

The biomass equations provide a convenient means of estimating biomass of bamboo from easily measured or inferred physical properties such as diameter or height, without destructive sampling. Subsequently, the biomass estimates can be converted to carbon estimates using known conversion factors. Equations for culm volume and height are important for inferring values of physical properties that are used to estimate biomass. The equations were classified into four categories, depending on whether they were for multiple species or one species, and whether they were age-specific or not. To facilitate future use of the compiled equations, for each equation we included information on the species name, the plant component for which biomass was estimated, author-reported regression statistics, number of culms/clumps harvested, diameter range of the harvested culms, location of field site(s) and age of sampled culms. This information was presented both in Word and rdata formats, the latter of which should help automate future analyses.

3.2. Results

Table S2 shows the biomass equations and associated metadata compiled from the 105 case studies reviewed, whereas Tables S3 and S4 show the volume and height equations and associated metadata, respectively. A summary of the number of case studies with allometric equations for calculating the biomass of aboveground components, the biomass of below-ground components, culm volume and culm height in each of the four categories (multiple/single species and age/not age-specific) and in each country is provided in Table 4. In Table 4, the case studies were also grouped into four broader geographic regions: Northeast Asia, Central and South America, South Asia and Southeast Asia.

We found that there were many more case studies for estimating aboveground components than below-ground components–131 compared with 24. Most case studies for estimating biomass and height originated from China. In addition, China had biomass equations for the most number of species (33; forms and varieties of *Phyllostachys heterocycla* and *P. pubescens* are taken to be synonyms of *P. edulis*, following http://www.theplantlist.org/tpl1.1/search?q=phyllostachys). More than half (55%) of China's 56 case studies with above-ground biomass equations were species-specific but not age-specific. About 41% were both species- and age-specific and the remaining 4% were not age-specific and for multiple species. Case studies in China with biomass equations for estimating aboveground components were mostly for *Phyllostachys edulis* (15) and *Dendrocalamus latiflorus* (3); case studies in China with biomass equations for estimating belowground components were mostly for *P. edulis* (7). An example of an equation for estimating the culm biomass of *P. edulis* in China is found in the study of Nie (1994):

$$CB = 0.0925D^{2.081}, \tag{1}$$

where CB is the culm dry biomass in kg and D is diameter-at-breast-height (DBH) in cm. This equation was derived from an unspecified number of *P. edulis* culms from Dagangshan Experimental Centre in Jiangxi province, and has an R^2 value of 0.998 (Nie, 1994). An example of an equation for estimating the rhizome biomass of *P. edulis* in China is found in the study of Hao et al. (2010):

$$RB = -0.121D^2 + 2.320D - 10, \tag{2}$$

where RB is the rhizome dry biomass in kg. 20 culms of *P. edulis* from the Tianmu mountain national nature reserve in Zhejiang province were used to derive this equation, which has an R^2 value of 0.560 (Hao et al., 2010). It is noted that this equation is only positive and hence biologically meaningful for 6.55 cm < D < 12.63 cm.

Where information was available, we found that the number of culms sampled for Chinese biomass equations ranged from 1 to 3 *Sinocalamus oldhami* culms (Zheng et al., 1997b) to 368 *Sinocalamus oldhami* culms (Zheng et al., 1998c). Within Northeast Asia (China, Japan, South Korea and Taiwan), Taiwan had the second highest number of case studies with aboveground biomass equations: 18 case studies for five species. 17% were species-specific but not age-specific, 78% were age-specific/species-specific and the remaining 6% was non-age specific and for multiple species. Japan and Korea, the two remaining countries with aboveground biomass equations in northeast Asia, had five case studies for one species (*Phyllostachys edulis*) and three case studies for three species (*P. bambusoides*, *P. edulis*, *P. nigra var. henonsis*), respectively. All equations were species- and age-specific. Biomass equations for estimating below-ground components in Northeast Asia originated exclusively from China, with 21 species-specific case studies for 15 species. Of these 21, 8 (38%) were age-specific (Tables 4 and S2).

A total of six case studies with aboveground biomass equations for five species were found from Central and South America, originating from Bolivia, Brazil, Chile, Colombia and Mexico. All but one equation were species- and age-specific. However, no below-ground biomass equations from this region were found (Tables 4 and S2). The species represented include *B. oldhami* Munro, *Chusquea culeou*, *Chusquea tenuiflora*, *Guadua angustifolia and Guadua weberbaueri*. The number of culms sampled range from 12 for *C. tenuiflora* (Veblen et al., 1980) to 88 for *B. oldhami* (Castañeda-Mendoza et al., 2005). An example equation for estimating the culm dry biomass of adult *G. weberbaueri* culms is:

$$CB = 4.969D + 0.225H - 20.171, \tag{3}$$

where H is culm height in m (Torezan and Silveira, 2000). This equation was derived from a sample of 20 culms from Southeast Acre state in the Southwestern Amazon, and has an R^2 value of 0.748 (Torezan and Silveira, 2000). It is noted that this equation is only positive and hence biologically meaningful for $4.969D + 0.225H > 20.171$.

Of the 14 aboveground biomass case studies from South Asia, 11 were from India and three were from Nepal. The most common species *B. bambos* originated from three studies. All but four case studies had species- and age-specific equations. In total, equations for estimating the biomass of aboveground components were available from this region for nine different bamboo species. In addition, three case studies were found for estimating the biomass of below-ground components of two species (one-to-six year old *B. bambos* and three-to-five year old *D. strictus*), both species- and age-specific and originated from India. Between 15 (Singh and Singh, 1999) and 118 (Tripathi and Singh, 1996) culms were harvested for biomass equations from South Asia, with the extremes of both pertaining to *D. strictus*. Example equations for estimating the culm and rhizome dry biomasses of *B. bambos* in India are

$$CB = 0.287D^{3.524} \tag{4}$$

and

$$RB = 0.781D^{0.708} \tag{5}$$

These two equations by Shanmughavel and Francis (1996) were derived from the exponential of the original equations and obtained from a sample of 90 one-to-six year old *B. bambos* culms from Kallipatty in Tamil Nadu state. They have R^2 values of 0.938 and 0.554 respectively.

For Southeast Asia, field-work for development of biomass equations was completed in Laos, Malaysia, Myanmar, Philippines, Thailand and Vietnam. These six Southeast Asian countries each had between two to seven studies with aboveground biomass equations. The seven case studies from Vietnam covered six species; four studies from Thailand were for six bamboo species. Except for two multi-species studies, one from Laos (bamboo in Nakai Plateau, Descloux et al., 2011) and the other from Thailand (bamboo in Kanchanaburi, Viriyabuncha et al., 1996), all aboveground biomass equations from the various case studies were species-specific. Between five *Gigantochloa nigrociliata* (Chan et al., 2013) and 131 *D. barbatus* culms (Ly et al., 2012) were sampled for the species-specific equations. For the two multi-species studies, nine individuals were sampled for one equation (Viriyabuncha et al., 1996) and nine culms per size class (number of size classes not stated) were sampled for the other (Descloux et al., 2011). No equations for estimating the biomass of below-ground components for bamboo were found in Southeast Asia (Tables 4 and S2). An example of an equation for estimating culm dry biomass from Vietnam is:

$$CB = 0.113D^{2.102}, \tag{6}$$

Table 4

Number of case studies with (1) not age-specific/multi-species, (2) age-specific/multi-species, (3) not age-specific/species-specific and (4) age-specific/species-specific allometric equations available for calculating the biomass of aboveground components, biomass of below-ground components, culm volume and culm height for countries in four geographic regions (Northeast Asia, Central and South America, South Asia and Southeast Asia).

	Northeast Asia				Central and South America					South Asia		Southeast Asia					
	China	Japan	South Korea	Taiwan	Bolivia	Brazil	Chile	Colombia	Mexico	India	Nepal	Laos	Malaysia	Myanmar	Philippines	Thailand	Vietnam
Aboveground																	
Total No. of case studies	56	5	3	18	1	1	2	1	1	11	3	2	5	7	4	4	7
No. of not-age specific/multi-species case studies	2 (4%)			1 (6%)								1 (50%)				1 (25%)	
No. of age-specific/multi-species case studies																	
No. of not age-specific/species-specific case studies	31 (55%)			3 (17%)	1 (100%)					1 (9%)	3 (100%)	1 (50%)	4 (80%)	7 (100%)	4 (100%)		5 (71%)
No. of age-specific/species-specific case studies	23 (41%)	5 (100%)	3 (100%)	14 (78%)		1 (100%)	2 (100%)	1 (100%)	1 (100%)	10 (91%)			1 (20%)			3 (75%)	2 (29%)
No. of species with equations	33	1	3	5	1	1	2	1	1	6	3	>1	3	5	4	6	6
Belowground																	
Total No. of case studies	21	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
No. of not-age specific/multi-species case studies																	
No. of age-specific/multi-species case studies																	
No. of not age-specific/species-specific case studies	13 (62%)																
No. of age-specific/species-specific case studies	8 (38%)									3 (100%)							
No. of species with equations	15									2							
Culm volume																	
Total No. of case studies	0	0	0	2	0	0	0	0	0	1	0	0	4	0	5	0	0
No. of not-age specific/multi-species case studies																	
No. of age-specific/multi-species case studies																	
No. of not age-specific/species-specific case studies										1 (100%)			4 (100%)		5 (100%)		
No. of age-specific/species-specific case studies				2 (100%)													
No. of species with equations				2						1			4		5		
Culm height																	
Total No. of case studies	5	3	0	1	0	0	0	0	0	0	0	0	5	0	2	3	4
No. of not-age specific/multi-species case studies																	
No. of age-specific/multi-species case studies																	
No. of not age-specific/species-specific case studies	3 (60%)	3 (100%)											4 (80%)		2 (100%)		3 (75%)
No. of age-specific/species-specific case studies	2 (40%)			1 (100%)									1 (20%)			3 (100%)	1 (25%)
No. of species with equations	3	2		1									3		2	1	4

Percentages in parentheses refer to percentages of the total number of case studies for a particular country.

Data are from the following 105 case studies: Abe and Shibata (2009), Azmy (1993), Azmy et al. (1991), Castañeda-Mendoza et al. (2005), Chan et al. (2013), Chandrashekara (1996), Chen et al. (1998, 2004, 2009a, 2012a, 2014), Das and Chaturvedi (2006), Descloux et al. (2011), Ding et al. (2011), Dong et al. (2002), Dung et al. (2012), Feng et al. (2010), Fukushima et al. (2007), Gao et al. (2015), Geri et al. (2011), Guo et al. (2009), Hao et al. (2010), Haripriya (2002), He et al. (1999, 2003, 2007), Huang et al. (2000, 2003), Hung et al. (2012a, 2012b, 2012c), Inoue et al. (2013), Isagi et al. (1993, 1997), Jin et al. (1999), Kao and Chang (1989), Kaushal et al. (2016), Kiyono et al. (2007), Kumar (2008), Kumar et al. (2005), Li et al. (2007, 2016), Liang and Cheng (1998), Liu and Kao (1988), Liu et al. (2010a), Lü and Chen (1992), Luo et al. (1997), Ly et al. (2012), Ma et al. (2009), Nath et al. (2009), Nie (1994), Oli (2003, 2005), Oli and Kandel (2005), Othman (1994), Park and Ryu (1996), Phuong et al. (2012), Qin et al. (1990), Quiroga et al. (2013), Riaño et al. (2002), Shanmughavel and Francis (1996), Singh and Singh (1999), Su and Zhong (1991), Su et al. (2006), Sun et al. (2013), Sun and Yen (2011), Sun et al. (1986, 2009, 2011), Suwannapinunt (1983), Suzuki and Jacalne (1986), Tandug and Torres (1987), Tang et al. (2011), Taylor and Qin (1987), Torezan and Silveira (2000), Tripathi and Singh (1996), Uchimura (1978), Veblen et al. (1980), Viriyabuncha et al. (1996), Wang (2009), Wang et al. (2004, 2009b, 2009c, 2010b, 2011), Wu (1983), Xu et al. (2004), Yang et al. (2008), Yang et al. (2011), Yen (2016), Yen and Lee (2011), Yen et al. (2010), You (2002), Zemek (2009), Zhang et al. (2009), Zheng et al. (1997b, 1998b, 1998c, 2000, 2001, 2003), Zhou et al. (1999, 2008, 2012, 2014), Zou (2011).

which was derived using a sample of 100 *D. barbatus* culms aged one year or over, in Con Cuong district in Nghe An province (Dung et al., 2012). The R^2 value for this equation is 0.883 (Dung et al., 2012).

A limited number of case studies were found for estimating culm volume and culm height. In total, 12 case studies were found with equations for estimating culm volume for 11 species; all but two case studies were species-specific and not age-specific (Tables 4 and S3). The remaining two studies had species- and age-specific equations for one- to five-year-old *P. makinoi* and *P. edulis* in Yunlin County, China (Wang, 2009). The number of culms sampled for developing volume equations ranged from 26 *B. blumeana* to 173 *G. scortechinii* culms (Azmy et al., 1991). In addition, we found 23 case studies with culm height equations for 15 different species. All culm height equations were species-specific but not age-specific, except for eight case studies that also had age-related information (Tables 4 and S4). The number of culms felled to develop culm height equations ranged from three to four for *P. edulis* (Huang et al., 2003) to 300 for *P. edulis* (Inoue et al., 2013).

In summary, our review of allometric equations for bamboo ecosystems worldwide reveals that most case studies derived equations for estimating the biomass of aboveground components, with a relatively small number of case studies with equations for estimating the biomass of below-ground components or culm height. Even fewer case studies exist with equations for estimating culm volume. Almost all equations are species-specific, although the equations span only a small fraction of the 1250–1500 species worldwide (Ohrnberger, 1999; Scurlock et al., 2000; Zhu, 2001). China has the most biomass equations for aboveground and below-ground components, but these only cover 33 and 15 species respectively, and no country has culm volume or culm height equations for more than five species. Geographically, most case studies come from Southeast Asia and Northeast Asia, which encompasses China. Given that India has approximately the same area of bamboo as China, there are surprisingly few case studies for India. Only a handful of equations exist for estimating the biomass of aboveground components for Central and South America, with no equations for estimating the biomass of below-ground components, culm volume or culm height.

4. Part III: case study of bamboo carbon stock estimation in Thailand

4.1. Study area

To highlight the potential importance of bamboo in storing and regenerating carbon stocks, we conducted fieldwork in June 2014 and June 2015 at the Pong Khrai Royal Forest Department Research Station, located in Mae Sa Catchment, Chiang Mai, northern Thailand (18°54′N, 098°48′E; Fig. 7). Chiang Mai has a monsoon climate with a rainy season from May to October and a dry season from November to April (Boonrodklab, 2007; Cheke et al., 1979). Annual rainfall ranges from 1200 to 2000 mm, with 80% falling in the rainy season. The lithology in the catchment is dominated by milled granite and gneiss (both ortho- and para-gneiss). Phyllite, limestone and marble can also be found. Soils in the area are mostly Ultisols, Alfisols and Inceptisols that overlie a variably deep

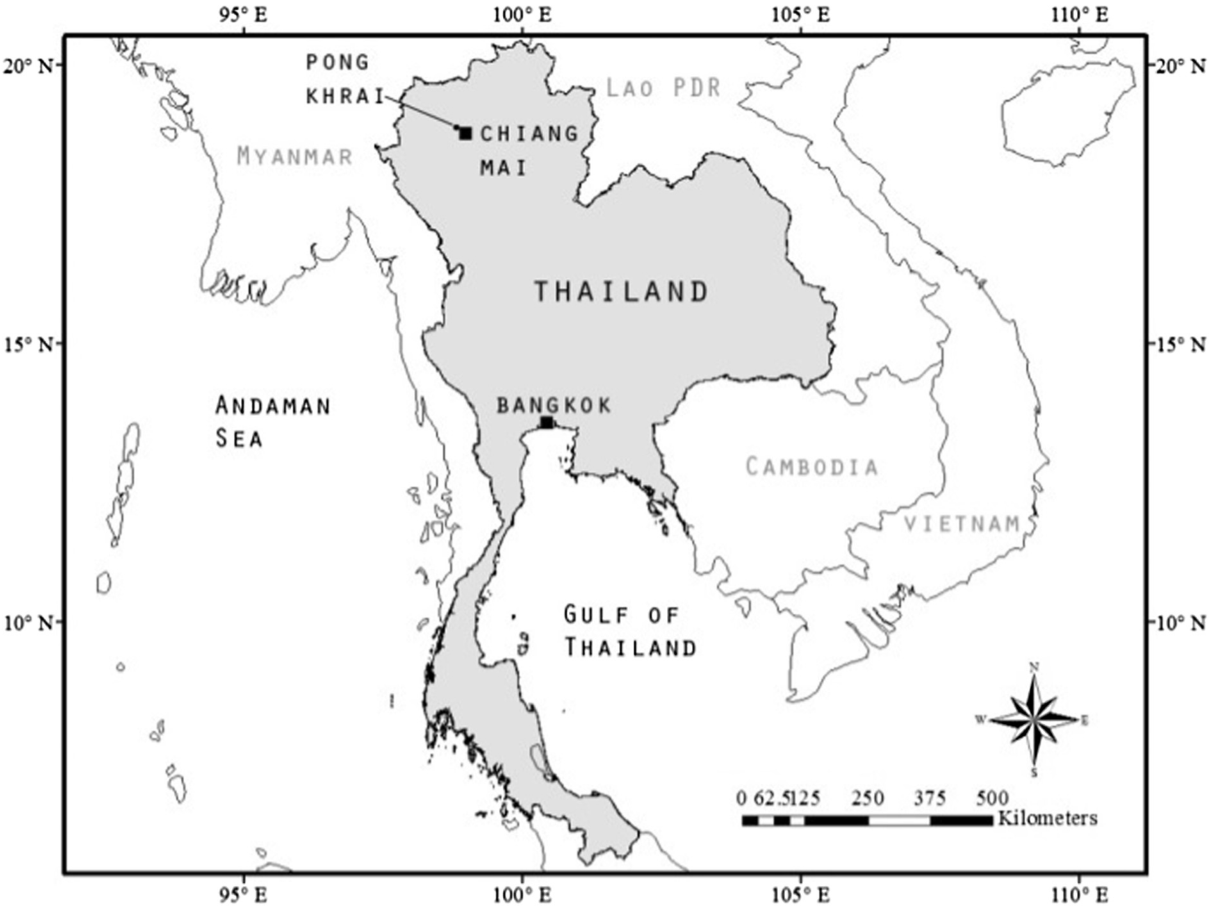

Fig. 7. Site for the case study of the potential importance of bamboo in storing and regenerating carbon stocks: Pong Khrai Royal Forest Department Research station, located in Mae Sa Catchment, Chiang Mai, Thailand (18°54′N and 098°48′E).

(1–20 m) weathered zone of iron-rich, orange-colored saprolite (Ziegler et al., 2014).

The objective of the field study was to compare the carbon stocks in a recovering forest containing a moderate density of bamboo (hereafter referred to as "bamboo forest") with those in a secondary forest with virtually no bamboo (hereafter referred to as "evergreen forest"). At the field site, the forests have been recovering under the protection of the Royal Thai Forestry Department for the last 25–30 years, following the abandonment of agriculture. In northern Thailand, swidden (or shifting) agriculture was commonly practiced in the mountainous regions, with different ethnic groups practicing alternative forms with different fallow periods and corresponding impacts on forest structure and composition (Funakawa et al., 1997; Schmidt-Vogt, 1998). More intense forms of swidden agriculture, partly driven by increasing populations and commercial trade, has increased in recent decades (Funakawa et al., 1997; Schmidt-Vogt, 1998; van Vliet et al., 2012). In most cases, swiddening in the region has been replaced by stationary, commercial agriculture, largely due to bans on tree cutting, cultivation on sloping lands, and burning (Ziegler et al., 2011).

The composition of recovering forests in Mae Sa often reflects the transition away from swiddening and opium cultivation several decades ago. Programs were developed to establish orchards (e.g. of lychee) or permanent crops (e.g., cabbage) on some swidden/opium lands; other lands were abandoned and allowed to regrow. Highly degraded lands were replanted with trees including *Pinus kesiya* and various *Eucalyptus* species. Recovering forests often lack a dominant native tree species, contain exotics, and are characterized by evergreen and deciduous tree species in the canopy layer with bamboo growing below (Larpkern et al., 2009, 2011). Our study site is representative of this type of secondary forest. Elsewhere throughout the catchment, other land covers include forests with various degrees of disturbance, cultivation and plantation agriculture on sloping lands, (peri)urbanized areas and greenhouse agriculture. The dominant bamboo species at the study site is *Bambusa nutans*, while *Pinus kesiya* is the dominant tree species. Other common species in the evergreen forest at our study site include *Croton roxburghii*, *Diospyros glandulosa*, *Erythrina subumbrans*, *Glochidion sphaerogymum*, *Hopea ferrea* and *Lagerstroemia villosa*.

4.2. Methods

We established three 20 × 20 m plots in each of the bamboo forest and the evergreen forest. The dominant bamboo species in the bamboo forest plots was *B. nutans*, while the dominant tree species in the evergreen forest plots include *Senna spectabilis*, *C. roxburghii*, *G. sphaerogymum* and *L. villosa*. In addition to *B. nutans*, there were 10–21 tree species in the three bamboo forest plots. The number of tree species in the three evergreen forest plots ranged from 10 to 16. Dominant species and key indicators of forest structure for the six study plots are summarized in Table 5.

In June 2014, all trees with ≥5 cm DBH (1.3 m) within each of the six 20 × 20 m plots were identified and their DBH measured. Wood cores were also collected with a tree increment borer having a diameter of 0.2 in. Wood density was determined using the wood cores following Dietz and Kuyah (2011). Aboveground biomass was then estimated using the DBH and wood density measurements and the equation of Chave et al. (2005) for dry forest stands in different locations around the world:

$$\mathrm{AGB} = \rho * \exp(-0.667 + 1.784 \ln D + 0.207 (\ln D)^2 - 0.0281 (\ln D)^3) \tag{7}$$

where AGB is the aboveground biomass in kg, ρ is the wood density in g/cm^3 and D is DBH in cm. Eq. (7) was chosen because it was derived together with AGB equations for other forest types by fitting to a comprehensive dataset of 2410 trees (Chave et al., 2005). The equation represents the best-fit model as determined by the Akaike Information Criterion (AIC), which is an estimate of the information (technically, the Kullback-Leibler information) lost when using a model to approximate the true model, relative to the information lost when using a reference model – the best-fit model out of a set of candidate models can therefore be interpreted as the one with the lowest AIC (Akaike, 1973; Burnham and Anderson, 2002). Heuristically, the AIC of a model measures the maximum probability of the model producing the observed data (the maximum likelihood of the model) whilst accounting for the complexity of the model, as measured by the number of parameters (Akaike, 1973; Burnham and Anderson, 2002). However, by definition the AIC does not measure the absolute goodness-of-fit of a model and therefore it is important to assess this using one or more other metrics (see Yuen et al. (2016) for more details on the construction and selection of allometric equations for estimation of tree biomass). As Eq. (7) has a high R^2 value of 0.996 (Chave et al., 2005), it is not only the best-fit model as determined by AIC, it also has a high absolute goodness-of-fit.

In the determination of aboveground carbon (AGC) for trees from aboveground biomass estimates, the dried wood cores used to estimate wood density were ground in a ball mill before being passed through a 125-μm sieve. Six mg of the <125-μm fraction were placed in a tin foil capsule and analyzed for organic carbon using the Elementar Vario TOC Cube (Hanau, Germany). Tree

Table 5
For the case study conducted in Pong Khrai Royal Forest Department Research Station located in Mae Sa Catchment, Chiang Mai (Thailand), comparison of key indicators of forest structure for the three study plots in each of two forest types, evergreen forest (FOR) and bamboo forest (BAM).

Study plot	FOR 1	FOR 2	FOR 3	BAM 1	BAM 2	BAM 3
Vegetation type	Evergreen forest	Evergreen forest	Evergreen forest	Bamboo forest	Bamboo forest	Bamboo forest
Plot size	20 × 20 m	20 × 20 m	20 × 20 m	20 × 20 m	20 × 20 m	20 × 20 m
Total # of species	10	16	16	11	22	14
Dominant tree (for FOR) or bamboo (for BAM) species	*Senna spectabilis*	*Croton roxburghii*, *Glochidion sphaerogymum*, *Lagerstroemia villosa*	*Croton roxburghii*	*Bambusa nutans*	*Bambusa nutans*	*Bambusa nutans*
Shannon-Wiener diversity index	2.2	2.6	2.5	1.1	2.1	1.2
Stand basal area (m^2 ha^{-1})	49.7	21.3	17.8	29.0	15.4	14.5
Tree density (stems ha^{-1})	250.0	825.0	850.0	350.0	1000.0	650.0
Bamboo density (Culms ha^{-1})	0.0	350.0	250.0	10850.0	7850.0	5175.0
Range of tree DBH (cm)	7.5–105.0	5.5–30.3	5.5–32.7	5.4–109.5	5.0–24.7	5.1–43.0
Mean tree DBH (cm)	36.5	14.2	13.2	20.3	12.6	14.2
Range of bamboo DBH (cm)	NA	2.0–4.5	2.1–3.5	2.0–7.5	2.0–7.5	2.0–8.2
Mean bamboo DBH (cm)	NA	3.0	2.7	3.9	4.0	4.0

AGC was then calculated by multiplying AGB values estimated using Eq. (7) by the carbon percentages determined from the wood cores.

Within each of the six 20 × 20 m plots, the DBH of all bamboo culms with ≥2 cm DBH were measured. The condition of each culm was recorded (e.g. alive, dead, cut, broken, location of cut/breakage). A total of 65 bamboo culms were then felled to develop a site- and species-specific allometric equation. Of the 65 culms, 45 were felled in a separate patch of bamboo forest outside the 20 × 20 m plots, because the original patch of bamboo forest in the plots had undergone mass flowering and death in the second year of the study. This bamboo forest is considered to be similar to the bamboo forest at the original field site as the same species of bamboo was dominant and the bamboo clumps were interspersed by trees. Each culm was cut at the base and partitioned into smaller sections to facilitate the determination of its mass, with branches and leaves separated from the culm. Culm height was recorded first before the culm was cut into smaller sections according to natural partitions. Fresh masses of culm, branches and leaves were determined in the field. Three subsamples each of the culm main stem, branches and leaves were collected and then oven-dried at 65 °C for 5 days to determine moisture content. The fresh weight of each biomass component was multiplied by the dry:fresh mass ratio to obtain their dry weights.

Using the AGB and DBH measurements from the sample of 65 bamboo culms, an allometric equation for estimating bamboo AGB was developed. Specifically, a power-law relating AGB and DBH was fitted using ordinary least-squares (OLS) regression on a double log-scale. Normality of errors was assessed by graphically comparing the quantiles with that of a normal distribution, whereas homoscedasticity was assessed by graphically examining whether the residuals exhibited a trend with increasing DBH or not. The mean AGB was estimated as the exponential of the expression for the mean logarithmic AGB from the OLS regression multiplied by a correction factor $\exp(s^2/2)$, where s is the standard error of the residuals (Finney, 1941). In the correction factor, the terms with higher orders of s were omitted because they were <<1. DBH was chosen as the sole independent variable because it was the most easily measured variable and culm height was difficult to measure accurately within the dense canopy. We also chose not to estimate height using DBH because subsequent use of this estimated height together with DBH in deriving an allometric equation suffers from multicollinearity (Sileshi, 2014).

A power-law relation is one of the most common forms of allometric equations for calculating biomass (Banaticla et al., 2007; Chan et al., 2013). Allometry was originally conceived as the study of how properties of an organism vary with traits related to size (Huxley, 1932), and these relationships were commonly found to be described by power-laws (Sileshi, 2014). Goodness-of-fit of our bamboo allometric equation was assessed using the statistical significance of the slope on a double log-scale and also the R^2 value of the associated model. AIC was not used because there was only one independent variable (the minimum possible), such that there was no need to correct for the number of independent variables.

Bamboo AGC was calculated by multiplying the AGB estimated from the allometric equation by the mean carbon percentage of the culm, branches and leaves. To obtain the carbon percentages of the culm, branches and leaves, subsamples of the oven-dried culm, branches and leaves were cut into smaller pieces, ground in a ball mill and passed through a 125-μm sieve. A total of six mg of the <125-μm fraction of each component were then placed in tin foil capsules and analyzed for the percentage of organic carbon using the Elementar Vario TOC Cube.

To estimate below-ground biomass (BGB) for the bamboo forest and the evergreen forest, a 2 m soil pit was dug within each 20 × 20 m plot. In each pit, three 5-cm long cores (internal diame-

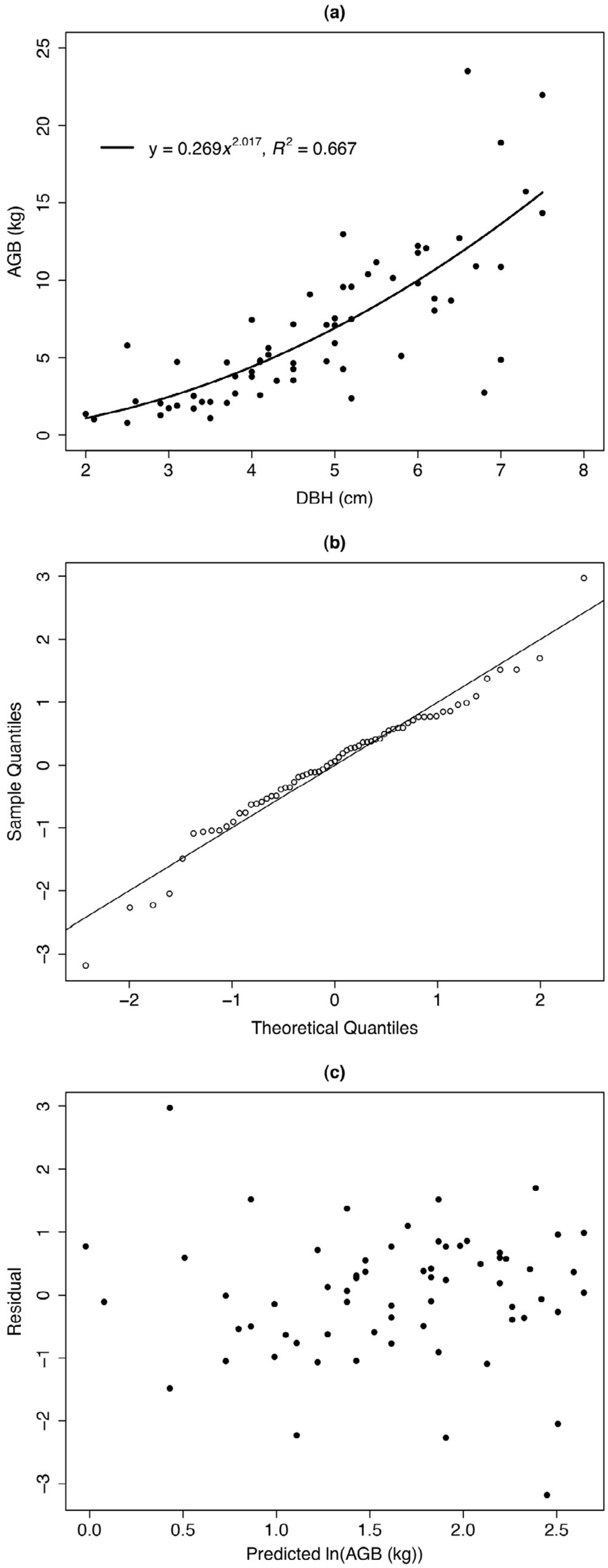

Fig. 8. Allometric equation relating the aboveground biomass (AGB) of the sampled bamboo in Chiang Mai (Thailand) to their DBH ($n = 65$), as fitted using OLS regression on a log-log scale. (a) Shows the fitted equation together with the data points, (b) compares the quantiles of the standardized residuals from the OLS regression with those of a standardized normal distribution, and (c) shows the residuals from the OLS regression against different values of the AGB predicted by the fitted equation, on a logarithmic scale.

ter 4.5 cm) were collected at 25-cm increments from just under the soil surface to a 2 m depth, resulting in nine depths from 0 to 2 m. Soil samples were first oven dried at 105 °C for 24 h to determine the bulk density. Following Yuen et al. (2013), roots were then separated from the soil by manual sorting, followed by washing and drying at 65 °C for 24 h. Finally the dry mass of the coarse and fine roots were determined by weighing. Where samples could not be taken due to rocks, a sample was taken at the same depth from a nearby road cut. Roots from all the cores were then amalgamated, ground in a ball mill and passed through a 125-µm sieve. For each sample, six mg of the <125-µm fraction was placed in a tin foil capsule and analyzed for organic carbon using the Elementar Vario TOC Cube. Below-ground carbon (BGC) was calculated by multiplying BGB by the percentage of carbon in the sampled roots.

The same cores that were used to measure BGB were used to measure SOC. Soils were first passed through a 2-mm sieve to remove rocks and other large particles. The <2 mm material was then ground in a ball mill. A total of 30 mg of soil was placed in a tin foil capsule and analyzed for organic carbon using the Elementar Vario TOC Cube. SOC (g C/cm^2) was then calculated using the following equation:

$$SOC = b * P * d \tag{8}$$

where b is the bulk density of the soil in g/cm^3, P is the percentage of organic carbon in the soil and d is the soil depth in cm. SOC in each soil core was calculated using Eq. (8), converted to units of Mg C/ha, and then summed over the entire 2 m depth to determine SOC in each study plot (Hairiah et al., 2010; Phang et al., 2015).

Total ecosystem C (TEC) for the bamboo forest or the evergreen forest was estimated as the sum of the estimated AGC of bamboo, AGC of trees, BGC and SOC. To capture uncertainty in TEC for each of the two forest types, 95% confidence intervals were estimated using 1000 bootstrapped samples of bamboo, trees and the soil. Specifically, for the three bamboo forest plots, the AGC values for the bamboo individuals (n = 434, 314 and 206 for the three plots) were resampled 1000 times, as were the AGC values for the tree individuals (n = 14, 42 and 27) and the values of BGB and SOC at each of the nine depths (three values of BGB and SOC at each depth). Then, the 1000 bootstrapped samples were used to calculate 1000 estimates of the TEC for each of the bamboo forest plots, thus allowing a corresponding 95% confidence interval to be derived for the median TEC. A 95% confidence interval for the median TEC of the three evergreen forest plots was calculated in the same way (n = 16 and 10 bamboo individuals for two of the plots, with no individuals for the remaining plot; n = 10, 42 and 41 tree individuals). If the 95% confidence intervals for the median TEC of the two forest types did not overlap, then we considered this to be a statistically significant difference. Similarly, we use the bootstrapped samples to estimate 95% confidence intervals for the components of TEC for the two forest types – bamboo AGC, tree AGC, BGC and SOC.

4.3. Results

4.3.1. Derivation of allometric equation for estimating bamboo AGB

Eq. (9) specifies the power-law that was fitted to the AGB and DBH values for the 65 destructively sampled bamboo individuals, using OLS regression on a double log-scale and incorporating a correction factor for converting to a linear scale:

$$\mathrm{AGB} = 0.269D^{2.017}(R^2 = 0.667) \tag{9}$$

where AGB is aboveground dry biomass in kg and D is culm DBH in cm. Culm DBH ranged from 2 to 7.5 cm. The standard error for the slope of the log-log regression line (exponent of the power-law) was 0.179, whereas that for the intercept was 0.277 (logarithm of the prefactor of the power-law, before multiplying by the correction factor of 1.11). The R^2 value of 0.667 indicates a reasonably good fit, with the presence of about seven "outliers" representing individuals that were particularly light or heavy given their DBH (Fig. 8). However, we did not remove these outliers because there was no reason to believe that they were not within the natural range – in general, outliers should not be removed purely to increase goodness-of-fit (Yuen et al., 2016). The OLS regression satisfied both the normality and homoscedasticity assumptions (Fig. 8). Both the slope and intercept were highly statistically significant ($p \ll 0.01$).

4.3.2. Results for TEC

The total ecosystem carbon (TEC = Tree AGC + Bamboo AGC + BGC + SOC) in the bamboo forest was 348 Mg C/ha (median over three plots; 95% confidence interval (CI) for median of 321–374 Mg C/ha) versus 337 Mg C/ha (median with 95% CI for median of 298–366 Mg C/ha) in the evergreen forest (Fig. 9). Differences in the TEC

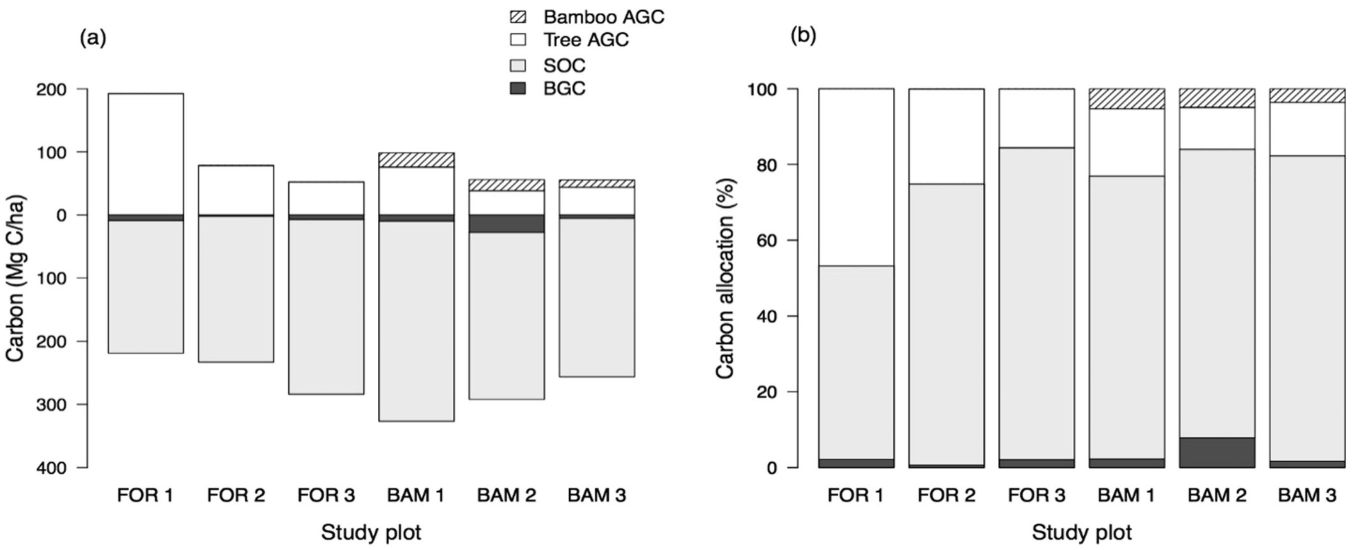

Fig. 9. (a) Estimated carbon stocks in the study plots in Chiang Mai (Thailand), apportioned between bamboo (Bamboo AGC), trees (tree AGC), soil (SOC) and below-ground roots (BGC). (b) is the same as (a) except that the carbon stocks of each component are expressed as percentages of the total in each plot. Soil samples were taken from 0 to 2 m depth in order to estimate SOC and BGC. FOR and BAM refer to the evergreen forest and bamboo forest plots, respectively.

for the two types of forest could not be distinguished statistically, suggesting that the bamboo forest, including the bamboo therein, was important for storing and regenerating carbon stocks. Soil organic carbon (SOC) contributed 76% (median with 95% CI for median of 71–86%) of TEC in the bamboo forest and 74% (68–83%) in the evergreen forest (Fig. 9). Thus, SOC was the largest carbon store in the two types of forest ecosystems. The second largest store of carbon was tree AGC (Fig. 9). Tree AGC in the evergreen forest plots constituted 25% (median with 95% CI for median of 15–31%) of TEC, while the corresponding value in the bamboo forest was less at 14% (8–20%). Bamboo AGC in the bamboo forest constituted 5% (median with 95% CI for median of 4–5%) of TEC, whereas bamboo AGC in the evergreen forest only constituted 0.07% (0.06–0.09%) of TEC.

The overall contribution of AGC to TEC in the bamboo forest was 18% (median with 95% CI for median of 12–24%), smaller than the 25% (15–31%) contribution of AGC in the evergreen forest, but nevertheless still substantial. BGC made up 2% (2–3%) of TEC in the bamboo forest and 2% (1–2%) of TEC in the evergreen forest. Both of these contributions are almost certainly underestimates because large roots and rhizomes could not be collected by the coring method employed. The SOC in the bamboo forest was 265 Mg C/ha (median with 95% CI of median of 251–282 Mg C/ha) versus 231 Mg C/ha (220–241 Mg C/ha) for the evergreen forest plots (Fig. 9), and thus the SOC values were broadly similar (Fig. 9).

When compared with other estimates of TEC in Southeast Asia (Table 3), the TEC of the bamboo forest that we studied in Chiang Mai (median over three plots of 348 Mg C/ha, with 95% CI for median of 321–374 Mg C/ha) was within the range found for bamboo land covers reported for other sites (94–392 Mg C/ha). It was greater than the TEC in oil palm plantations (86–287 Mg C/ha), long-fallow swidden (92–317 Mg C/ha), intermediate-fallow swidden (69–253 Mg C/ha), short-fallow swidden (64–216 Mg C/ha) and grasslands, pastures and shrublands (70–237 Mg C/ha). The TEC of the evergreen forest that we studied in Chiang Mai (median over three plots of 337 Mg C/ha, with 95% CI for median of 298–366 Mg C/ha) was within the range of TEC values for other forests in Southeast Asia (126–699 Mg C/ha; Table 3).

Our TEC estimates for the bamboo and evergreen forest in Chiang Mai are similar to the mean of 358 Mg C/ha estimated for five forest plots in the Nam Hean Watershed Management Unit Area, Nan Province, northern Thailand (Pibumrung et al., 2008). There, bamboo was present in the five plots (*B. tulda*, *Gigantochloa albociliata*, *Thyrsostchys siamensis*), although the amount was not quantified (Pibumrung et al., 2008). We estimated that SOC contributed 76% and 74% of TEC in the bamboo and evergreen forest in Chiang Mai, which is substantially larger than the 55% for the five forest plots at Nam Hean (Pibumrung et al., 2008). The reason for the lower SOC estimates in the latter could be because soils were sampled to a depth of 1 m (Pibumrung et al., 2008), compared with our sampling to a depth of 2 m. In addition, our median estimate of 17.2 Mg C/ha (95% CI for median of 16.1–18.3 Mg C/ha) for bamboo AGC in the bamboo forest plots is within the range of means found for bamboo AGC in other forest plots in Thailand, which is 2.1–23.0 Mg C/ha (Table 1).

5. Discussion

5.1. Carbon sequestration potential of bamboo

Our review of bamboo ecosystems revealed that estimates of their aboveground carbon (AGC) and below-ground carbon (BGC) stocks are likely to be comparable to or exceed those for a number of other land-cover types associated with key land-cover changes occurring in SE Asia (Table 3). Notably, the AGC estimates are likely to exceed those for oil palm plantation; grassland, pasture and shrubland; and intermediate and short-length fallow swidden (Table 3). Bamboo AGC (16–128 Mg C/ha) is most comparable with non-swidden agroforest, rubber plantations, and oil palm plantations (ranging from 15–143 Mg C/ha). The BGC estimates for bamboo overlap with most of these other types of land-covers. In addition, the range of estimates of soil organic carbon (SOC) stocks for bamboo land covers is comparable to those for nine other major land-cover types that we considered. The range of estimates of the total ecosystem carbon stocks (TEC, which is sum of AGC, BGC and SOC) of bamboo land covers is intermediate of orchard and tree plantations and rubber plantations (Table 3), and higher than that for various types of swidden fallows, oil palm plantations, and grasslands, pasture and shrublands.

Thus, our review suggests that particular bamboo ecosystems can be as effective at sequestering carbon over time as particular low-to-moderate biomass forests or plantations. Yearly, carbon accumulation rates for some fast-growing species may be as high as 8–14 Mg C/ha, slowing after full stand maturation and harvesting commences (Fig. 6). Carbon estimates from our case study in Mae Sa Catchment in Chiang Mai, northern Thailand, are consistent with this suggestion: the median TEC in the three bamboo forest plots was estimated to fall within a 95% confidence interval of 321–374 Mg C/ha, which overlaps with the 95% confidence interval of 298–366 Mg C/ha for the median TEC estimated for three evergreen forest plots. However, we caution that our case study was only performed with samples from three bamboo forest plots and three evergreen forest plots. Therefore, if there is large variation in TEC among plots for a given forest type, the bootstrapping procedure would not be effective at capturing this variation. On the other hand, because 27 soil samples and at least 10 tree individuals were sampled at each plot and 10 bamboo individuals were sampled at each plot with bamboo, the sampling variation within plots was more robustly captured by the bootstrapping. Future studies at our study site should better quantify the variation between plots, to see whether it changes the conclusions that we have reached in our review.

In addition, the TEC estimates for our bamboo forest plots did not incorporate carbon in rhizomes because the soil cores we used were too small, and so the range of TEC estimates for bamboo forest plots in our case study is likely to be an underestimate. However, we also note that in the bamboo forest plots, the median proportion of TEC due to bamboo was estimated to fall within a 95% confidence interval of 4–5%, which is small. Therefore, our case study is not a direct comparison of carbon stocks in a bamboo-dominated forest and an evergreen forest. Also, we emphasize that we do not imply equivalence of the carbon storage potential of bamboo plantations and forests in general. From previous reviews (Ziegler et al., 2012; Yuen et al., 2013; Yuen, 2015), the range of TEC estimates for forests extend to values that are among the highest of all major land-cover types. A major contributing factor is the structural complexity of forest ecosystems, with the variety and stature of tree species present helping to fill empty space and increase biomass.

Our review thus highlights the considerable potential of bamboo to sequester carbon, but the extent to which this potential is realized depends on appropriate management of bamboo stands throughout their growth cycle. This dynamic aspect is not transparent from the estimates of carbon stocks in our review, which only provide snapshots at particular times. Using dynamic models of the growth and mortality of bamboo, Lou et al. (2010) demonstrated that a Moso bamboo (*Phyllostachys edulis*) plantation in subtropical southeast China can sequester approximately as much carbon as a plantation of fast-growing Chinese fir (*Cunninghamia lanceolata*), but only if the bamboo is regularly harvested. The harvests prevent culms from deteriorating due to age, which would release carbon stored in the culm back into the atmosphere. In an alternative scenario where the bamboo plantation is unmanaged, Lou et al. (2010) estimated that it sequesters only 30% of the total carbon sequestered by the Chinese fir plantation.

Ly et al. (2012), studying the cultivation of 'Luong' bamboo (*Dendrocalamus barbatus*) in the northwest uplands of Thanh Hoa province in Vietnam, found that AGC was highest under selective harvesting of mature bamboo culms. However, bamboo-derived products must be durable for effective long-term sequestration of carbon; such durable products include bamboo furniture, flooring and houses (Lou et al., 2010). Another issue is that many bamboo species, including Moso bamboo, exhibit gregarious flowering events that are followed by mass die-offs, with concomitant loss of carbon. These events typically occur on regular intervals on decadal timescales, which may have evolved from shorter intervals (Veller et al., 2015). At present, little is known about the determinants of these flowering events (Lou et al., 2010), and thus more research is required to mitigate loss of carbon from these events. Of note, such a flowering and dieback event occurred at our site for *Bambusa nutans* in 2015–2016, following our measurements.

5.2. Uncertainty in estimates of carbon in bamboo

While most of the reported bamboo AGC, BGC and SOC values in our review were from direct sampling of biomass and soils, there is often a lack of standardization of methods. Importantly, there were substantial variations in the number of replicates and the sampling depths for belowground biomass or soil organic carbon. In terms of sample size, some studies only sampled three to six bamboo individuals when deriving biomass allometric equations for aboveground components – these equations are used to estimate biomass of the components, which are then used to estimate the amount of carbon. For example, Huang et al. (2003) only used three to four culms in deriving their culm biomass equations for Moso bamboo in a forest farm in Chaohu City, China. In addition, Fukushima et al. (2007) and Chan et al. (2013) only sampled five or six culms for each of three bamboo species (*Bambusa tulda*, *Cephalostachyum pergracile*, *Gigantochloa nigrociliata*) to create corresponding biomass equations, in traditional Karen swidden cultivation systems in the Bago Mountains, Myanmar. In contrast, some studies sampled over a hundred bamboo individuals to construct biomass equations. Notable examples include the 365 and 368 bamboo individuals used by Zheng et al. (1998b,c) to create biomass equations for *Oligostachyum oedogonatum* and *Sinocalamus oldhami* in China, respectively. Also, in northwest Thanh Hoa Province in Vietnam, Ly et al. (2012) cut 131 culms of *D. barbatus* to construct an aboveground biomass (AGB) equation.

The wide range of sample sizes used in the reviewed studies raises the issue of sampling uncertainty. In this respect, the analysis by Roxburgh et al. (2015) of 23 AGB equations, for tree species in southeastern Australia, provides a useful guideline. The authors found that sample sizes of 17–95 were sufficient to achieve biomass predictions for an independent set of tree census data that had a low coefficient of variation (<5%), provided the diameter size-class distribution of the trees in the independent set is similar to that used to construct the equations (Roxburgh et al., 2015). When the distributions were dissimilar, the authors found that sample sizes of 26–166 were required. These results suggest that studies in our review with sample sizes below the low end of the range (<17) would likely have high sampling uncertainty.

The problem of small sample sizes is particularly acute when taking soil samples to estimate fine root mass and SOC (Yuen et al., 2013). For example, Isagi et al. (1997) and Nath et al. (2009) both took only three replicate soil samples at each depth examined. Ideally, sampling uncertainty for such studies would be incorporated into the parameter estimates for the equations, but standard errors and confidence intervals for these are rarely reported and incorporated into biomass estimates – for example, Huang et al. (2003), Fukushima et al. (2007) and Chan et al. (2013) did not do this. The sample size that we used to construct AGB equations for bamboo in Mae Sa Catchment in Chiang Mai, northern Thailand, was 65, which falls within the ranges suggested by Roxburgh et al. (2015). On the other hand, we estimated BGC and SOC using only three samples at each depth, and thus it was necessary that we captured the corresponding sampling uncertainty using bootstrapping.

Another source of uncertainty in estimates of BGC and SOC was the depth to which soil was sampled, which varies widely among the studies that we examined. For example, Fukushima et al. (2007) only sampled the top 0–5 cm of soil in a Karen swidden cultivation system in the Bago Mountains in Myanmar. Nath et al. (2009) collected soil samples up to 30 cm depth in bamboo stands in the Barak Valley region in northeast India. Tripathi and Singh (1996) took soil samples up to 60 cm depth in bamboo plantations in the Indian dry tropics. The aforementioned study Ly et al. (2012) sampled soil up to 70 cm depth. Finally, Isagi et al. (1997) took soil samples down to 100 cm depth among a Moso bamboo stand in Kyoto Prefecture in Japan. Overall, soil depths in the reviewed studies varied from 5 to 300 cm (however, all but one was from the upper 100 cm). Sampling only the upper layers of the soil results in substantial underestimation of carbon in the soil – although soil carbon tends to decrease with depth, a substantial percentage of soil carbon is located at depths > 50 cm, in particular for bamboo species with extensive rhizome and root networks. On a related note, in general, there is a need to develop more allometric equations for estimating below-ground biomass (BGB). Our review of allometric equations found only 24 case studies that developed equations for estimating components of BGB, which is an order of magnitude fewer than the number of case studies with equations for estimating components of AGB.

For the three bamboo forest plots in our case study in northern Thailand, SOC for depths 50–200 cm constituted a median of 48% of SOC up to 200 cm, whereas SOC for depths 100–200 cm constituted a median of 27%. Most studies in our review did not sample soils deeper than 100 cm, and thus there is scope in future studies to standardize SOC estimates by depth, if possible, to allow for meaningful comparisons between studies. Given the substantial contribution of soils deeper than 100 cm to bamboo SOC, together with evidence of tree roots extending down to 700 cm (Canadell et al., 1996), we recommend that future studies designed to estimate carbon stocks attempt to sample soils down to at least 200 cm, if logistically feasible.

Furthermore, for the vast majority of articles reviewed, a one-time snapshot of biomass or carbon stocks was provided for a particular site. While logistical and financial constraints might prevent researchers from doing repeated, long-term sampling, one should be aware of potential seasonal variations in biomass and carbon, which will not be reflected in a one-off sampling campaign. Tripathi and Singh (1996), working in a dry tropical bamboo savanna dominated by *D. strictus*, found that more live roots were recorded during the rainy season when temperature, water availability, and nutrient status favored growth. In bamboo plantations, temporal variations in bamboo biomass also occur in relation to periods when the bamboo is harvested, which depends on the particular management regime being used (Lou et al., 2010). Thus, one-time snapshots do not reveal the extent of variation in biomass and carbon stocks. Future studies should therefore aim to incorporate more than one sampling period.

The sources of uncertainty identified make it difficult to directly compare estimates of bamboo carbon stocks between different studies, especially when the uncertainty has not been adequately quantified. Therefore, effort should be expended to design more consistent methodologies between studies, ensuring sufficient replicates, sampling intervals and depth of soil sampling. Here, an analogy could be drawn with the Center for Tropical Forest Science-Forest Global Earth Observatory (CTFS-ForestGEO) network, which is a worldwide network of 59 long-term monitoring forest plots, with standardized protocols for collecting data on plants, animals and the physical environment (Anderson-Teixeira et al., 2015).

In addition, from our review of bamboo AGC, BGC and SOC, most research was done in China, India and Taiwan, with focus on a few bamboo species such as Moso bamboo. This species is commonly found in China, where its areal extent accounts for 70% of the total bamboo area in the country (SFAPRC, 2005). In comparison, studies in other countries, particularly for species other than Moso bamboo, are much fewer. Therefore, the range of carbon stock values for these other species are likely to be under-estimated, adding another source of uncertainty to comparisons between countries and regions. Thus, a priority for future research is obtaining more estimates for under-represented regions such as Central America, South America and Africa. Perhaps a closer examination of the gray literature from these regions might reveal useful sources of carbon stock estimates. For example, much of the bamboo research in China and Taiwan were written in Chinese (129/184 studies for our review were written in simplified or traditional Chinese), constituting a large body of gray literature which we were able to include in our review. In particular, more allometric equations need to be derived for these under-represented regions – our review found no equations for Africa and only six case studies with equations for estimating components of AGB for Central and South America.

6. Conclusion

We have collated and reviewed estimates of carbon stocks in bamboo ecosystems in different countries around the world, but mostly in Asia. By comparing these estimates with those for other types of land cover, we have demonstrated the value of bamboo as an efficient and effective carbon sink. This conclusion was further supported by our new case study, which compared estimates of carbon stocks in bamboo and evergreen forest plots in northern Thailand. We have also compiled and tabulated allometric equations for estimating biomass and hence carbon content of different components of bamboo, for different locations worldwide.

Given the potential for bamboo to act as an important carbon sink, there is a need for greater integration of bamboo into national and international policies and mechanisms aimed at managing the effects of global climate change. The most prominent international policy framework in this regard is the United Nations Framework Convention on Climate Change (UNFCCC), with its Clean Development Mechanism (CDM) that aims to reduce emissions via projects in developing countries. Although the Executive Board of the CDM recognized bamboo as equivalent to trees for reforestation and afforestation projects (UNFCCC, 2008), the Designated National Authorities in each country can over-ride this at their discretion (Lou et al., 2010). Moreover, as bamboo is technically a woody grass, it is not adequately recognized as part of a “forest” in major international policy instruments such as the Kyoto Protocol and the Marrakech Accords (Lou et al., 2010).

Besides benefits for carbon accounting, bamboo also provides a number of other ecosystem services. The presence of bamboo, with its extensive rhizome and root network and dense canopy, helps to reduce soil erosion, which reduces run-off and hence improves retention of nutrients and regulation of water flow in rivers and lakes (Li and Kobayashi, 2004; Song et al., 2011; Lobovikov et al., 2012). Furthermore, regrowth of bamboo during fallow periods in swidden systems has been documented to aid recovery of other vegetation (Fukushima et al., 2007). And harvested bamboo can be used to manufacture a variety of products that can be sold or kept for personal use, such as food and construction materials (Song et al., 2011). In this way, sustainable use of bamboo can help to supplement the livelihoods of millions of rural people, thus helping to decrease poverty and increase employment (Nath et al., 2009; Lou et al., 2010; Ly et al., 2012). On the other hand, the economic returns per area of bamboo can be up to eight times less than for crops such as cassava (Ly et al., 2012), and thus, cultivating bamboo as a cash crop alone may not be viable. There is also the risk of bamboo expanding quickly and threatening rare and endangered species, as occurred with Moso bamboo in China (Song et al., 2011). Thus, bamboo should be managed with an ecosystem perspective that explicitly considers the social-ecological interactions within which they are embedded. In this way, the potential of bamboo to sequester carbon can be effectively harnessed to mitigate and protect against the impending effects of future climate change, as well as to provide other key ecosystem services that help to sustain human livelihoods.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.01.017.

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