Aboveground biomass and seasonal patterns of aboveground net primary productivity in five bamboo species in northern Laos

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Running title;

Net primary productivity of bamboos in Laos

Abstract

Aims

Accurate estimates of bamboo biomass and net primary productivity (NPP) are required to evaluate the carbon sequestration potential of bamboo forests. However, relevant data, which are important for climate change mitigation, have rarely been collected in regions outside of East Asia and India. Information on seasonal patterns of NPP and its components will enable the quantification of factors that influence the carbon balance in bamboo forests. In this study, we quantified the aboveground biomass (AGB) and aboveground NPP of five major bamboo species in northern Laos using monthly data collected over a 12-month period.

Methods

All live culms in 10, 2 × 2 m plots (for one monopodial bamboo species: *Indosasa sinica*) and 30 clumps per species (for four sympodial bamboo species: *Bambusa tulda*, *Cephalostachyum virgatum*, *Dendrocalamus membranaceus*, and *Gigantochloa* sp.) were numbered and measured at breast height. We set 10 or 20 litter traps per species to collect litterfall. Censuses of dead and recruited culms and litterfall collection were performed once per month for 12 months.

Important Findings

The AGB was highest in *I. sinica* (59.87 Mg ha^{-1}) and lowest in *C. virgatum* (11.54 Mg ha^{-1}), and was mostly below the plausible global range for bamboos (32−256 Mg ha^{-1}). The sympatric distribution of multiple bamboo species at the study sites may have suppressed the AGB in four of the five studied species. The aboveground NPP estimates were between 3.43 and 14.25 Mg ha^{-1} yr^{-1}; those for *D. membranaceus* (8.20 Mg ha^{-1} yr^{-1}) and *I. sinica* (14.25 Mg ha^{-1} yr^{-1}) were comparable to mean global estimates for temperate evergreen forests (8.78 Mg ha^{-1} yr^{-1}) and tropical moist forests (10.56 Mg ha^{-1} yr^{-1}). High culm recruitment rates (15.20−23.39% yr^{-1}) were major contributors to aboveground NPP estimates. Seasonal patterns of aboveground NPP were largely influenced by the phenology of the new culms. In the four sympodial bamboo species, new culms began to emerge following the onset of persistent rainfall, mainly in July and August. However, the sprouting of new culms in the monopodial species *I. sinica* followed a trend of increasing temperatures, mainly in March and April. Thus, our results indicate that bamboos have considerable potential for sequestering carbon in northern Laos, but that this potential may be impacted by climate change.

Keywords: carbon sequestration, culm dynamics, litterfall, seasonality

INTRODUCTION

The carbon storage potential of bamboo forests have recently been the focus of attention in climate change mitigation efforts, because bamboos have vigorous culm growth and a wide distribution range in tropical and temperate regions (Nath *et al*. 2015; Yuen *et al*. 2017). However, potential carbon sequestration rates of bamboo remain unclear (Zachariah *et al*. 2016), even though the carbon stocks of diverse bamboo stands have been calculated (Yuen *et al*. 2017). Estimates of carbon sequestration rates are few and mostly limited to stands in East Asia and India (Isagi *et al*. 1997; Lin *et al*. 2017; Nath *et al*. 2015). Even though 25% of the total bamboo area in Asia is located in mainland Southeast Asia, there is limited bamboo related research beyond China and India (FAO 2010). Given that bamboo species differ among regions, information on the carbon balance in under-represented regions is urgently required to resolve uncertainty in the carbon sequestration function of bamboo forests.

Carbon balance has been calculated as net primary productivity (NPP) from field measurements of parameters such as biomass increment and litterfall production (Clark *et al*. 2001; Luyssaert *et al*. 2007). Since radial growth does not occur in bamboos, the aboveground biomass (AGB) increment is a function of new culm recruitment, which is predicted to fluctuate temporally depending on the emergence timing of new bamboo shoots. Numerous studies have shown that seasonal variation in litterfall in tropical forests corresponds to the drought period (Zhang *et al*. 2014), but information on the seasonal pattern of bamboo litterfall is limited (Ge *et al*. 2014; Kuruvilla *et al*. 2016; Toledo-Bruno *et al*. 2017). Annual estimates of NPP and its seasonal fluctuations will promote understanding of the factors that influence potential carbon sequestration rates.

We aim to quantify the biomass and NPP of five major bamboo species in a bamboo dominated fallow forest in northern Laos. Bamboos tend to be found on relatively degraded land and they help to restore soil fertility and control soil erosion (Song *et al*. 2011; Sovu *et al*. 2009). We focused on dry weight of aboveground parts as a first step in examining whether bamboos make a significant contribution to carbon sequestration in the study area. Although AGB and NPP in a carbon base are typically determined by multiplying those dry-weight estimates by 50%, species- and organ-specific differences in the carbon content have been reported. Carbon content was highest in culms (49.5%) and lowest in litter (41.8%) of *Phyllostachys pubescens* (Lin *et al*. 2017) and carbon content in culms was slightly higher in *Bambusa balcooa* (51.72−52.28%) than *Bambusa cacharensis* (48.86−51.23%; Nath *et al*. 2009). Our specific objectives were to (1) estimate the AGB and aboveground NPP, (2) determine culm dynamics (i.e., mortality, recruitment rate, and phenology of dead/new culms), and (3) describe monthly variation in aboveground NPP and its components.

MATERIALS AND METHODS

Study sites

The study sites were located in three villages, Huay Khot, Na Kok, and Phu Luang, in Luang Prabang Province in northern Laos (Table 1; Fig. 1). Fallow forests dominated by bamboos and early successional trees cover most of this area (Kameda and Nawata 2017; Roder *et al*. 1997). The region has a typical tropical monsoon climate with an approximately 6-month dry season extending from October to March. The annual rainfall over the study period (April 2017−March 2018) was 1,591.0 mm; reduced precipitation (monthly rainfall <100 mm) was recorded in September 2017 and during the period of November 2017 through February 2018 at the Luang Prabang meteorological station (19°53'N, 102°09'E; 304 m above sea level; Fig. 2; DMH 2018). The mean annual temperature over the study period was 25.9 °C, and monthly temperatures ranged from 20.9 °C in December 2017 to 29.1 °C in June 2017. Soils in the area were mainly Acrisols, with some Luvisols near the villages of Phu Luang and Na Kok and Alisols near the village of Huay Khot (district-based data; SSLCC 2010).

Field measurements

We studied five bamboo species that are widespread and common in northern Laos. These five species included four sympodial bamboos, *Bambusa tulda*, *Cephalostachyum virgatum, Dendrocalamus membranaceus*, and *Gigantochloa* sp., and one monopodial bamboo, *Indosasa sinica* (Table 1). Note that the binomial *Oxytenanthera parvifolia* in Hirota *et al*. (2008) has now been revised to *Gigantochloa* sp. (Xayalath *et al*. unpublished data). In March 2017, we randomly selected 30 clumps per species of sympodial bamboos that varied in size (i.e., number of culms per clump). Clumps that had been artificially or naturally damaged were avoided. We also established 10 plots (each 2 × 2 m) in a managed bamboo forest that contained the monopodial bamboo. Plots were placed >10 m apart. Although new bamboo shoots of *I. sinica* are harvested as a cash crop for sale at local markets, no harvesting or pruning was carried out within the plots during this study. All live culms were numbered and then measured to the nearest millimeter at breast height (DBH; 1.3 m above ground level). For each sympodial bamboo species, we counted the number of clumps within a 20 × 50 m area to calculate culm densities (mean culm number per clump multiplied by clump density). Monthly censuses of dead and recruited culms were performed between April 2017 and March 2018. The DBH of recruited culms were measured after new shoot sprouting had ended.

We set 10 or 20 litter traps, each with a surface area of 0.23 m^2, to collect litterfall (i) below the crowns of numbered clumps of each sympodial bamboo species and (ii) adjacent to each of the *I. sinica* plots. Litter traps were constructed from 1-mm nylon mesh and deployed *ca*. 1.0 m above ground level. Litterfall was collected once per month and oven-dried for 72 h at 80°C. We discarded the litter from trees and other bamboo species, and then sorted the litter of the study species into leaves, twigs, sheaths, and flowers. Each component was weighed to the nearest 0.01 g. Total litterfall was calculated as the summed dry weight of all components.

Culm dynamics

The annual culm mortality (m, % yr^{-1}) of each clump or plot was calculated as:

$$m = [\ln (N_0) - \ln (N_s)] \times 1/t \times 100$$

where N_0 is the initial number of culms per clump or plot, and N_s is the number of culms per clump or plot surviving through t year(s) (Sheil and May 1996). We also calculated the annual culm recruitment rate (r, % yr^{-1}) in each clump or plot as:

$$r = [\ln (N_t) - \ln (N_s)] \times 1/t \times 100$$

where N_t is the number of culms per clump or plot after t year(s). The value of t in our study was 1.0. Culm dynamics are expressed as means and 95% confidence intervals (CIs) of the mortality and recruitment rates for each bamboo species. CI calculations were performed using the bootstrap procedure in R version 3.0.2 (R Development Core Team 2013).

Biomass and NPP estimates

The AGB of each plant was estimated from its DBH using allometric equations for the sum of culms, branches, and leaves (Hirota *et al*. 2008; Xayalath *et al*. 2019; Table 1). As we used species-specific allometric equations developed in the same region of Laos with similar site conditions, the accuracy of the AGB estimates in this study is believed to be high. The AGB (Mg ha^{-1}) of each bamboo species was scaled up by multiplying mean plant biomass by the culm density.

Since the amount of biomass lost to herbivores is negligible (Clark *et al*. 2001), the aboveground NPP (Mg ha^{-1} yr^{-1}) was defined as the sum of the annual increment in AGB (ΔAGB) and total litterfall (Mg ha^{-1} yr^{-1}). Since no radial growth occurs in bamboos, ΔAGB was calculated by subtracting the biomass of dead culms from the biomass of recruited culms. Monthly aboveground NPP was also calculated using the same procedure. Five clumps of *C. virgatum* that bloomed and died during the study period were excluded from data analyses.

RESULTS

Biomass and culm dynamics

Culm density was highest in *I. sinica* (84,000 culms ha^{-1}) and lowest in *D. membranaceus* (2,336 culms ha^{-1}; Table 1), the largest study species. The AGB varied among bamboo species, ranging from 11.54 Mg ha^{-1} for *C. virgatum* to 59.87 Mg ha^{-1} for *I. sinica* (Table 2). The remaining three species had similar AGB values (21.21−25.85 Mg ha^{-1}), although they differed in size (3.38−5.21 cm in DBH) and culm density (2336−8908 culms ha^{-1}; Table 1).

The culm recruitment rate (15.01−23.39% yr^{-1}) exceeded the mortality rate (1.28−6.89% yr^{-1}) in all bamboo species (Table 3). The mortality rate of *C. virgatum* was significantly higher than those of other species, excluding *I. sinica*. The recruitment rate was significantly higher in *D. membranaceus* than in *B. tulda* and *Gigantochloa* sp.

Components of NPP

The lowest and highest total litterfalls were produced by *B. tulda* (1.46 Mg ha^{-1} yr^{-1}) and *I. sinica* (5.70 Mg ha^{-1} yr^{-1}), respectively; the remaining three species had similar total litterfalls (2.25−2.47 Mg ha^{-1} yr^{-1}; Table 2). Leaf litter was the major litter component in all bamboos, accounting for 56.1−71.1% of the total. The proportions of twig litter were broadly similar among species (16.5−21.0%), whereas the sheath litter proportions of *B. tulda* and *I. sinica* (7.9−13.7%) were smaller than those of the other three species (21.3−25.1%; Table 2).

The ΔAGB ranged from 0.99 Mg ha^{-1} yr^{-1} for *C. virgatum* to 8.55 Mg ha^{-1} yr^{-1} for *I. sinica*. *D. membranaceus* had the second largest ΔAGB value (5.73 Mg ha^{-1} yr^{-1}). The aboveground NPP ranged from 3.43−14.25 Mg ha^{-1} yr^{-1} (Table 2). The order of aboveground NPP followed that of ΔAGB.

Monthly patterns

Monthly total litterfalls were generally highest toward the end of the dry season (February and March; Figs. 2, 3). However, the litterfall from *I. sinica* fluctuated greatly with no apparent seasonal pattern; the litterfall mass from this species mostly exceeded those of the others. New culm emergence patterns also differed between sympodial and monopodial bamboos (Fig. 4). In sympodial species, newly recruited culms were observed from June to September, peaking in July or August. New culms of *I. sinica* emerged from March to July, with peaks in March−April and in June. On the other hand, dead culms of all bamboo species were visible through the year. Thus, monthly NPP values peaked in July or August in the four sympodial bamboos, and values for *I. sinica* peaked in March−April and June (Fig. 5). Among the four sympodial species, peak of monthly NPP was highest in *D. membranaceus*, intermediate in *B. tulda* and *Gigantochloa* sp., and lowest in *C. virgatum*.

DISCUSSION

Aboveground biomass

We found large variations in the AGB among the five bamboo species. High AGB of *I. sinica* was likely a result of the high culm densities that were maintained in the managed bamboo forest. The large culm size of *D. membranaceus* appeared to counterbalance its low density. The mean DBH and culm density values of *C. virgatum* and *B. tulda* were similar, but the AGB of *C. virgatum* was lower, likely due to the thin culm thickness of this species.

The AGB values calculated in this study were mostly below the plausible range of global values for bamboos (32−256 Mg ha^{-1}; Yuen *et al*. 2017). Coexistence of multiple bamboo species and early successional trees at the study sites may cause the observed low AGB of the specific bamboo species. The AGB in *I. sinica*, which monopolized the plot in a managed bamboo forest, was within the plausible rage of global bamboo values. The previously reported AGB values of *B*. *tulda* and *D. membranaceus* in other Asian countries were roughly double what we observed in northern Laos: 25.85 Mg ha^{-1} for *B. tulda* in northern Laos *vs*. a mean of 47.0 Mg ha^{-1} in four other countries, and 25.17 Mg ha^{-1} for *D. membranaceus* in northern Laos *vs*. 42.6–44.6 Mg ha^{-1} in China (Xiang *et al*. 2016; Yuen *et al*. 2017). These discrepancies may also reflect the sympatric distribution of *B*. *tulda* and *D. membranaceus* at the study sites (Table 1). Compared to the AGB in dry tropical forests in South and Southeast Asia, the AGB of the five bamboo species was lower than the mean (82 Mg ha^{-1}; Brown *et al*. 1991). Previous studies have also reported a lower biomass in bamboo stands than in nearby forests (Lin *et al*. 2017; Yuen *et al*. 2017). The lower values for bamboo may be explained by the hollow culms in these plants, or by the effects of past cultivation in fallow forests (Chan *et al*. 2013).

Aboveground NPP and its components

Aboveground NPP varied among the five species. The low aboveground NPP value for *C. virgatum* reflected its low ΔAGB, which resulted in part from high culm mortality.

Adjacent bamboos sometimes flowered either earlier or later than the main mass-flowering (Hirota 2017). Although flowering and dead clumps were excluded from analyses, the reproductive phenology of *C. virgatum* may have affected the aboveground productivity estimates. The high culm density in *I. sinica* is likely a contributor to the large observed values for ΔAGB and total litterfall in this species, which resulted in a large aboveground NPP. Past management treatments such as the selective cutting of new shoots may have influenced productivity (Lin *et al*. 2017). In *D. membranaceus*, high culm recruitment rates and a large size (and resulting large biomass) likely accounted for the second largest ΔAGB and aboveground NPP estimates.

The total litterfall of these five species (1.46−5.70 Mg ha^{-1} yr^{-1}) was within the range for other bamboo species (0.45−10.22; Mg ha^{-1} yr^{-1}; Lin *et al*. 2017; Nath *et al*. 2009; Tripathi and Singh 1996; Xiang *et al*. 2016). However, *D. membranaceus* in northern Laos had twice as much total litterfall as that in China (0.90 Mg ha^{-1} yr^{-1}; Xiang *et al*. 2016), even though the AGB and the culm densities were lower in Laos. The annual litterfall of bamboos reportedly fluctuates over time (Ge *et al*. 2014; Toledo-Bruno *et al*. 2017). Irregular disturbances such as typhoons and droughts cause temporal fluctuations in litterfall input in subtropical forests (Beard *et al*. 2005; Lin *et al*.

2003). Long-term variability in litterfall production might not be fully captured by a limited length of monitoring (i.e., single 12-month period in northern Laos and China). In forest ecosystems worldwide, mean litterfall is within the range of 3−11 Mg ha^{-1} yr^{-1}; the mean litterfall in tropical seasonal forests is 7.0 Mg ha^{-1} yr^{-1} (Zhang *et al.* 2014). The bamboo litterfall production that we measured in northern Laos was comparable to the litterfall production in boreal needle-leaved forests.

The aboveground NPPs for *D. membranaceus* and *I. sinica* (8.20 and 14.25 Mg ha^{-1} yr^{-1}, respectively) were in the lower range of previously reported values for bamboo forests/plantations (7−48 Mg ha^{-1} yr^{-1}; Lin *et al.* 2017; Nath *et al.* 2015), however, surprisingly, comparable to mean global estimates for temperate evergreen forests (8.78 Mg ha^{-1} yr^{-1}) and tropical moist forests (10.56 Mg ha^{-1} yr^{-1}; Luyssaert *et al.* 2007). The high ΔAGB values for these two species (5.73−8.55 Mg ha^{-1} yr^{-1}) were generally within the upper range for tropical forests (0.6−7.6 Mg ha^{-1} yr^{-1}; Clark *et al.* 2001), likely due to high culm recruitment rates (>15 % yr^{-1}) and low culm mortality (<4 % yr^{-1}). High culm recruitment rates have also been reported for *Dendrocalamus strictus* plantations (18−36% yr^{-1}) in dry tropical regions of India (Singh and Singh 1999). These high aboveground NPP estimates and sympatric distribution of multiple bamboo species indicate that bamboos have an important role in sequestering carbon in the region.

Seasonal patterns

We detected moderate seasonality in total litterfall in the four sympodial bamboos. The major peak in total litterfall occurred in February or March, at the end of the dry period. The peak likely reflects a response to drought stress (Detto *et al*. 2018; Reich and Borchert 1984). Similar seasonal patterns in litterfall production have been reported in both bamboos and tropical forests in the tropical monsoon climate zone (Kuruvilla *et al*. 2016; Nath *et al*. 2004; Zhang *et al*. 2014). A deeper understanding of the drivers that influence the seasonal pattern of litterfall production in bamboos will require an extended dataset on the relationship between litterfall and climate.

The temporal pattern in culm recruitment that we observed differed between bamboo growth patterns. Rainfall is among the most important climatic factors thought to influence the timing of new culm production (Banik 2015); we found that new culms began to emerge in sympodial bamboos after the onset of persistent rainfall. New culm emergence has often been reported early in the rainy season in monsoonal tropics

(Banik 2015; Franklin 2005; Nath *et al*. 2004). In contrast, the sprouting of new culms in monopodial *I. sinica* occurred earlier than in sympodial bamboos, as air temperature began to increase. *I. sinica* is a temperate woody bamboo species (Triplett and Clark 2010), and new culms of temperate bamboos often emerge in spring (Gratani *et al*. 2008; Li *et al*. 1998b; Pearson *et al*. 1994); hence, the pattern of culm emergence in *I. sinica* in northern Laos is likely a response to temperature. As production of new culms seldom occurs in the dry season (Banik 2015), the shoots of *I. sinica* should provide important food and monetary income for local people in northern Laos during the dry season. Shoots of *I. sinica* are sometimes sold in local markets before March (Hirota personal communication); the seasonal pattern in culm recruitment may differ slightly among regions.

Since the monthly variation in culm productivity was larger than the variability in total litterfall for all study species, we suggest that the monthly pattern in aboveground NPP was most affected by the temporal pattern of new culm emergence. Inter-annual variation in NPP is also reportedly influenced by the rate of new shoot production in Moso bamboo (*Phyllostachys pubescens*; Li *et al*. 1998a; Lin *et al*. 2017). Therefore, successful culm recruitment is an essential element of aboveground NPP in bamboos. New shoot sprouting in Moso bamboo decreased when precipitation levels were low during the new culm growth period (Lin *et al*. 2017). Changes in precipitation patterns and the duration of drought periods may significantly impact the carbon sequestration rate in bamboos.

CONCLUSIONS

We calculated the AGB and aboveground NPP in five common bamboo species in northern Laos using monthly measurements collected over one year. The AGB, aboveground NPP, and seasonal variations in culm recruitment, litterfall, and NPP varied among species. Cross comparisons of aboveground NPP estimates between bamboo stands and forests, combined with the observed sympatric distribution of multiple bamboo species at the study sites, indicate that bamboos in this region may have marked carbon sequestration capabilities and that appropriate management such as cutting of new bamboo shoots may improve carbon sequestration rates. The dry-weight based estimates were used in this study, however, to precisely and directly assess carbon stocks and carbon dynamics of bamboos, further measurements of carbon content for each organ in each species will be needed. The high productivity of newly-emerged culms and the high recruitment rates were major contributors to high aboveground NPP estimates. Since new shoot recruitment seems to respond to changes in precipitation or air temperatures, future climate change such as global warming and prolonged drought period may affect the productivity of new culms. Hence, additional studies of the climatic and biotic factors that influence new culm emergence are required to improve the understanding of carbon dynamics in response to climate change and shifts in management protocols. It is important to note that bamboos often allocate considerable biomass to their underground organs (Yuen *et al*. 2017). The quantification of rhizome and root productivity will be needed to estimate the total NPP in bamboo forests.

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Table 1: five bamboo species studied in Luang Prabang Province, northern Laos.

Species	Local name	Growth pattern	Culm density (ha^{-1})	Mean DBH with range (cm)	Study site		Allometric equation for AGB (kg)
					Village	Altitude (m)	
Bambusa tulda	*Bong*	Sympodial	6059	3.38 (0.83−6.84)	Huay Khot	400−430	0.6062×DBH^1.559
Cephalostachyum virgatum	*Hia*	Sympodial	6527	3.45 (0.80−7.48)	Phu Luang	750−950	0.05671×DBH^2.607
Dendrocalamus membranaceus	*Sang*	Sympodial	2336	5.21 (0.59−9.33)	Huay Khot	400−450	0.3634×DBH^1.9938
Gigantochloa sp.	*Sot*	Sympodial	8908	3.67 (0.73−7.70)	Phu Luang	920−980	0.09265×DBH^2.374
Indosasa sinica	*No Khom*	Monopodial	84000	1.95 (0.75−3.41)	Na Kok	390−400	0.163×DBH^2.134

Table 2: aboveground biomass (AGB) and the components of net primary productivity (NPP) for the five bamboo species studied. The values in parentheses are the proportions of litterfall (%).

Species	AGB (Mg $\mathrm{ha^{-1}}$)	△AGB (Mg $\mathrm{ha^{-1}\ yr^{-1}}$)	Litterfall (Mg $\mathrm{ha^{-1}\ yr^{-1}}$)					NPP (Mg $\mathrm{ha^{-1}\ yr^{-1}}$)
			Leaf	Twig	Sheath	Flower	Total	
B. tulda	25.85	3.56	0.95 (68.5)	0.31 (17.8)	0.20 (13.7)	0.00	1.46	5.02
C. virgatum	11.54	0.99	1.37 (56.1)	0.44 (18.1)	0.59 (24.2)	0.039 (1.6)	2.44	3.43
D. membranaceus	25.17	5.73	1.45 (58.7)	0.40 (16.2)	0.62 (25.1)	0.00	2.47	8.20
Gigantochloa sp.	21.21	2.43	1.40 (62.2)	0.37 (16.5)	0.48 (21.3)	0.00	2.25	4.68
I. sinica	59.87	8.55	4.05 (71.1)	1.19 (21.0)	0.45 (7.9)	0.00	5.70	14.25

Table 3: culm dynamics for the five bamboo species studied.

Species	Mortality (% yr^{-1})	Recruitment rate (% yr^{-1})		
	Mean	95% CI	Mean	95% CI
B. tulda	1.28	0.34—2.72	15.20	10.24—18.76
C. virgatum	6.89	5.60—11.26	16.91	12.88—20.76
D. membranaceus	3.09	1.03—3.31	23.39	18.82—26.52
Gigantochloa sp.	3.55	1.67—4.02	15.01	11.22—16.33
I. sinica	3.48	1.80—5.82	17.61	12.76—21.41

Figure Legends

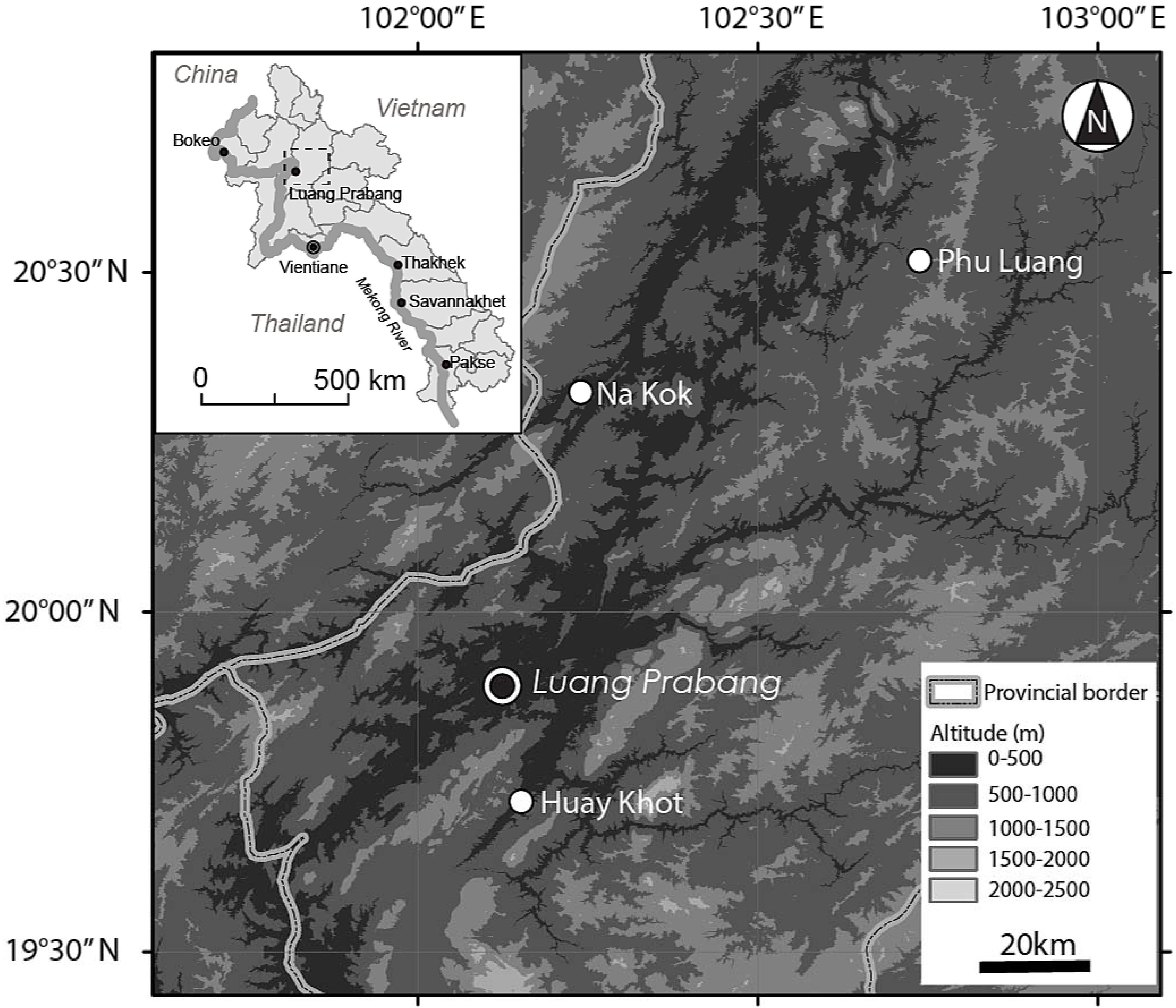
Figure 1: location of the study sites, Huay Khot, Na Kok, and Phu Luang villages, in Luang Prabang Province.

Figure 2: monthly mean air temperature and precipitation during the study period (April 2017−March 2018). Mean air temperature and precipitation from 2012 to 2016 are provided for comparison.

Figure 3: monthly variation in total litterfall for the five bamboo species studied (mean ± SE).

Figure 4: monthly variation in the productivity of newly recruited and dead culms for the five bamboo species studied.

Figure 5: monthly variation in aboveground net primary productivity (NPP) for the five bamboo species studied.


102°00″ E
102°30″ E
103°00″ E
20°30″ N
20°00″ N
19°30″ N
China
Vietnam
Bokeo
Luang Prabang
Vientiane
Thakhek
Savannakhet
Mekong River
Thailand
Pakse
0
500 km
N
Phu Luang
Na Kok
Luang Prabang
Huay Khot
Provincial border
Altitude (m)
0-500
500-1000
1000-1500
1500-2000
2000-2500
20km

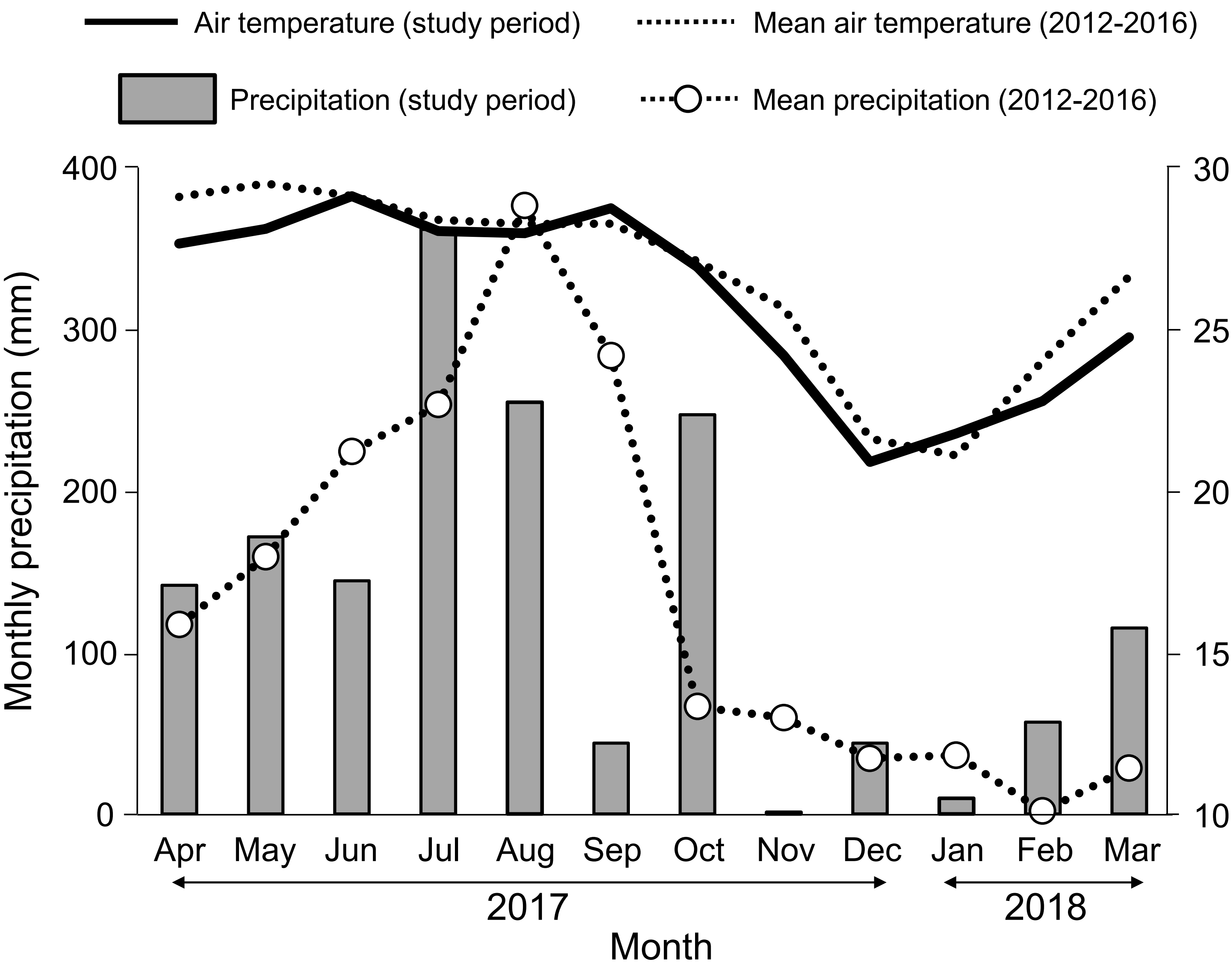
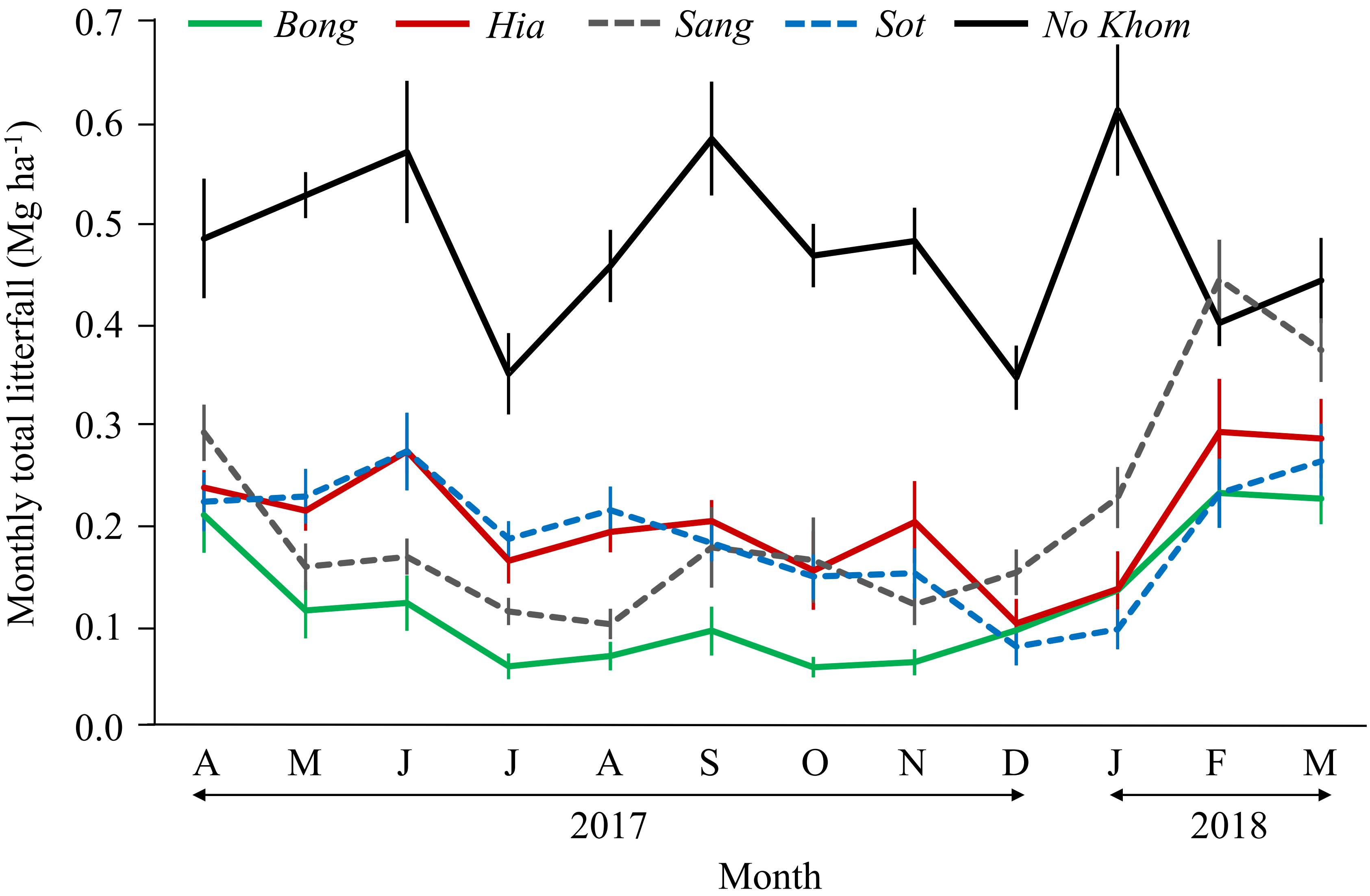

Air temperature (study period)
Mean air temperature (2012-2016)
Precipitation (study period)
Mean precipitation (2012-2016)
Monthly precipitation (mm)
400
300
200
100
0
Monthly mean air temperature (°C)
30
25
20
15
10
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
2017
2018
Month

Fig. 2



Bong
Hia
Sang
Sot
No Khom
Monthly total litterfall (Mg ha^{-1})
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
A
M
J
J
A
S
O
N
D
J
F
M
2017
2018
Month

Fig. 3

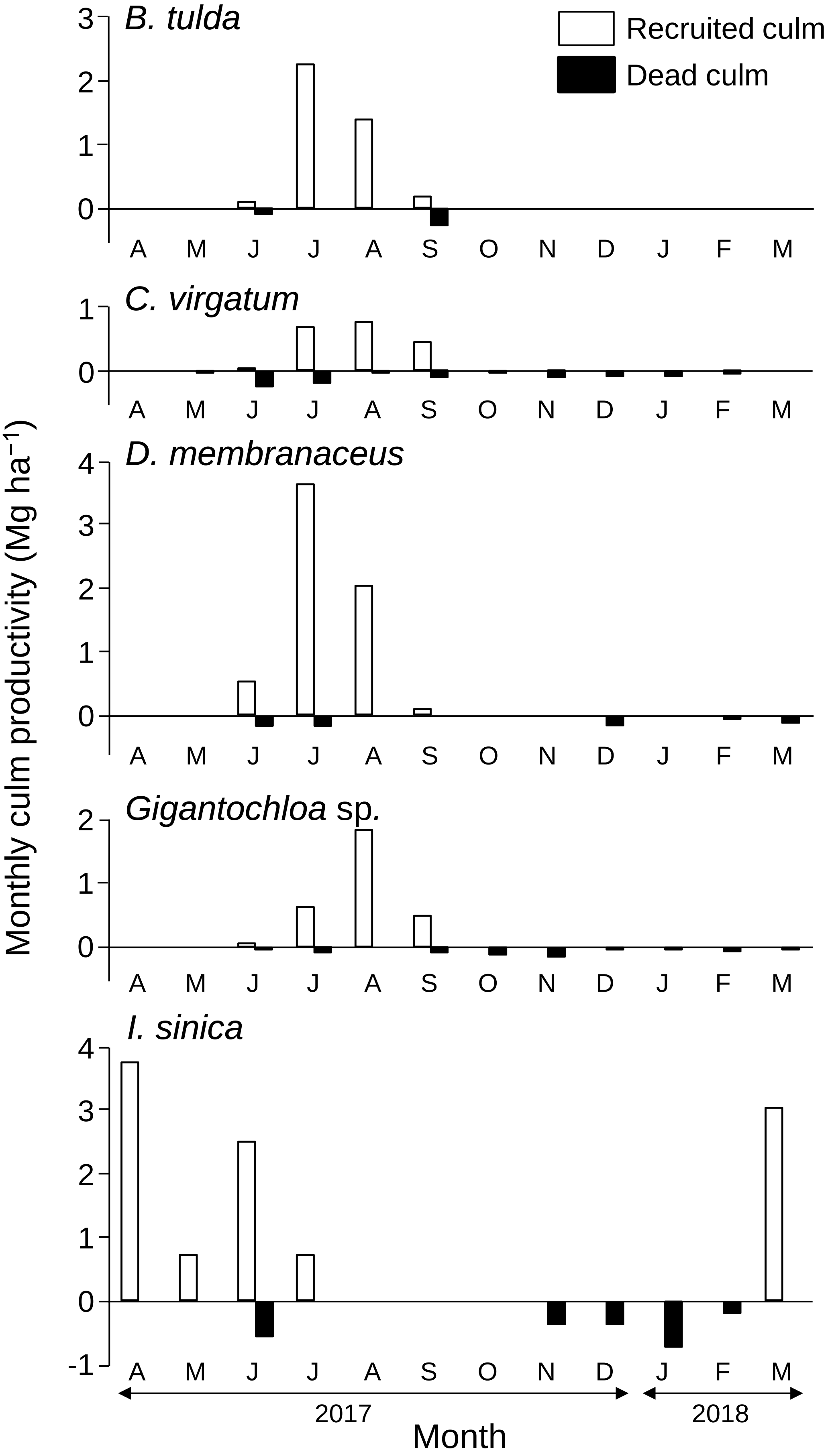

B. tulda
Recruited culm
Dead culm
C. virgatum
D. membranaceus
Gigantochloa sp.
I. sinica
Monthly culm productivity (Mg ha^{-1})
A M J J A S O N D J F M
-1
0
1
2
3
4
2017
2018
Month

Fig. 4

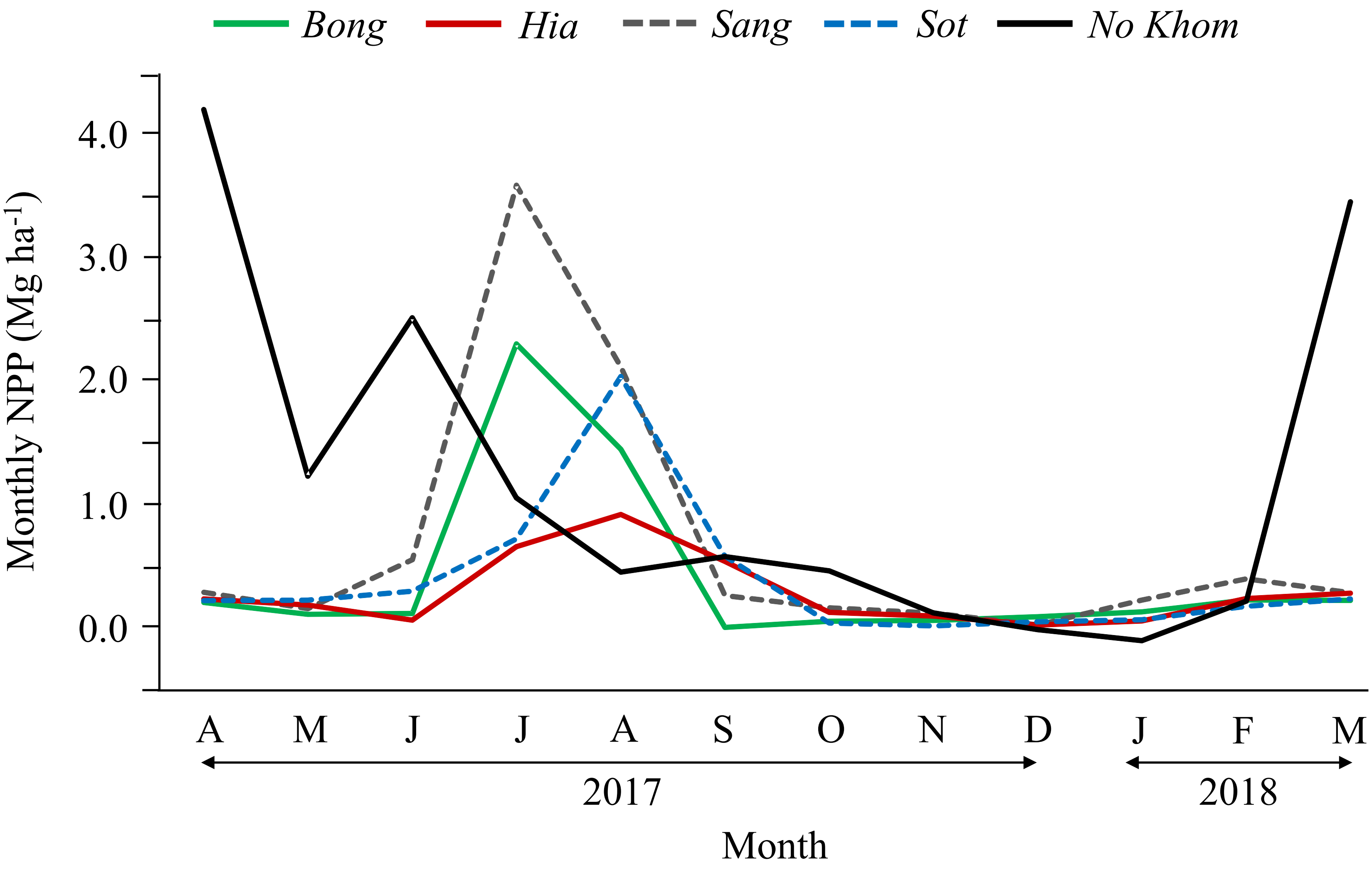

Bong
Hia
Sang
Sot
No Khom
Monthly NPP (Mg ha^{-1})
4.0
3.0
2.0
1.0
0.0
A
M
J
J
A
S
O
N
D
J
F
M
2017
2018
Month

Fig. 5