Ecoregional variations of aboveground biomass and stand structure in evergreen broadleaved forests

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Abstract Biotic and abiotic factors control aboveground biomass (AGB) and the structure of forest ecosystems. This study analyses the variation of AGB and stand structure of evergreen broadleaved forests among six ecoregions of Vietnam. A data set of 173 1-ha plots from 52 locations in undisturbed old-growth forests was developed. The results indicate that basal area and AGB are closely correlated

with annual precipitation, but not with annual temperature, evaporation or hours of sunshine. Basal area and AGB are positively correlated with trees > 30 cm DBH. Most areas surveyed (52.6%) in these old-growth forests had AGB of 100–200 Mg ha⁻¹; 5.2% had AGB of 400–500 Mg ha⁻¹, and 0.6% had AGB of > 800 Mg ha⁻¹. Seventy percent of the areas surveyed had stand densities of 300–600 ind. ha⁻¹, and 64% had basal areas of 20–40 m² ha⁻¹. Precipitation is an important factor influencing the AGB of old-growth, evergreen broadleaved forests in Vietnam. Disturbances causing the loss of large-diameter trees (e.g., > 100 cm DBH) affects AGB but may not seriously affect stand density.

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Introduction

The importance of forest structure to ecosystem function and biodiversity is well-recognized (Reilly and Spies 2015), however, variation in structure at a regional scale is poorly understood. Ecoregions are large areas that contain a number of ecosystems. They are geographical zones that represent groups or associations of similarly functioning ecosystems (Bailey 1983). The differences in biotic and

abiotic factors lead to differences in ecosystem structures and functions.

Forests account for 80% of the earth's plant biomass (Kindermann et al. 2008), and contain more carbon in biomass and soils than in the atmosphere CO₂ (Pan et al. 2011). The aboveground biomass (AGB) integrates the processes of plant growth, recruitment and mortality, as well as succession and disturbance. It is influenced by climate, edaphic conditions, species composition, and topography (Muller-Landau et al. 2006; Urquiza-Haas et al. 2007). The AGB of tropical forests is a key property of ecosystems which plays an important role in the global carbon cycle, accounting for a significant fraction of the total carbon pool and nutrient stocks (Brown et al. 1995; Phillips et al. 1998; Chapin et al. 2002; Fahey and Knapp 2007). Because the AGB varies across landscapes and forest types (Saatchi et al. 2007; Houghton et al. 2009), estimating local and regional aboveground biomass provides data for understanding the forest carbon cycle (Urquiza-Haas et al. 2007; Houghton et al. 2009; Loarie et al. 2009).

Low-latitude forests are estimated to contain approximately 60% of the AGB in the world forests (Dixon et al. 1994). Nevertheless, there is still uncertainty about the AGB of tropical forests (Brown 1997; Zheng et al. 2016). A better understanding of tropical aboveground biomass distribution is of theoretical and practical interest (Schimel 1995). Because AGB is determined by the size and frequency distribution of species, opportunities for improving estimates of carbon stocks is to further our understanding of factors causing variations in forest structure. Structure and AGB of tropical forests reflect edaphic conditions (Pires and Prance 1985; Tuomisto et al. 1995; Laurance et al. 1999; Lee et al. 2018), climate (Holdridge 1979; Gentry 1982; Pandian and Parthasarathy 2016), disturbance regimes (Lugo and Scatena 1996), successional status (Saldarriaga et al. 1988), and human impacts (Laurance et al. 1997). However, the degree to which the structure of old-growth tropical forests vary across large scale landscapes (ecoregions) is not fully understood.

The aboveground biomass is an important part of carbon storage in forests (Sierra et al. 2007; Malhi et al. 2009). In tropical forests worldwide, about 50% carbon is stored in AGB (Dixon et al. 1994). However, there are significant differences among sites. For example, a moist tropical forest in Africa has more than three times as much carbon in the aboveground biomass than in the soil (Djomo et al. 2011); a tropical forest in Peru has twice the amount of carbon stored in the soil as in the AGB (Gibbon et al. 2010). A selectively-logged, lowland dipterocarp forest in Malaysia contains twice as much carbon in AGB as in the soil (Saner et al. 2012), and a secondary forest in the

Philippines contains 50% more carbon in aboveground biomass than in the soil (Lasco et al. 2004).

Vietnam has a monsoon climate and stretches from 8°34' to 23°23'N and from 102°09' to 109°24'E with over 3000 km of coastline. North and South Vietnam are divided by the Hai Van Pass at 16°11'N. In the North, there are four seasons: spring, summer (a rainy season), autumn and winter (a dry season); and there are two seasons (rainy and dry) in the South. Differences of climate and topography created eight ecoregions in Vietnam (Fig. 1), the Northwest (NW), Northeast (NE), Red River Delta (RRD), North Central Coast (NCC), South Central Coast (SCC), Central Highland (CH), Southeast (SE), and the Mekong River Delta (MRD). The objective of this study was to analyze variations in stand density and aboveground biomass in the ecoregions of Vietnam.

Materials and methods

Old-growth forest inventory data

Tree inventory data on old-growth forests were selected showing that survey plots were undisturbed. The criteria to identify old-growth forests included: (1) there were no cut stumps found on the site; (2) it is difficult to access to the site; and, (3) there was a thick layer of organic matter. A data set of 173 1-ha plots was assembled which were surveyed in 52 locations distributed in six of eight

Fig. 1 Ecoregions of Vietnam and the location of sample plots

Table 1 Climate (annual mean $\pm$ SE) and main soil types in the ecoregions of Vietnam

Ecoregion	Annual temperature ($^{\circ}$ C)	Annual precipitation (mm)	Annual evaporation (mm)	Annual hours of sunshine	Main soil types
Northwest (NW)	18.1 $\pm$ 0.4 ^a	1768 $\pm$ 37.9 ^a	835 $\pm$ 14.8 ^a	1674 $\pm$ 24.8 ^a	Acrisols, Alisols, Ferralsols
Northeast (NE)	18.4 $\pm$ 0.3 ^a	1836 $\pm$ 41.1 ^a	828 $\pm$ 10.4 ^a	1400 $\pm$ 14.7 ^b	Acrisols, Calcisols, Ferralsols
North Central Coast (NCC)	20.1 $\pm$ 0.4 ^b	1964 $\pm$ 43.0 ^b	897 $\pm$ 11.1 ^b	1521 $\pm$ 20.5 ^c	Acrisols, Ferralsols, Gleysols, Leptosols
South Central Coast (SCC)	21.8 $\pm$ 0.6 ^b	2052 $\pm$ 93.4 ^b	1170 $\pm$ 33.5 ^c	2249 $\pm$ 34.9 ^d	Acrisols, Ferralsols, Gleysols, Leptosols
Central Highland (CH)	18.9 $\pm$ 0.5 ^a	1924 $\pm$ 79.4 ^{ab}	972 $\pm$ 34.3 ^b	2061 $\pm$ 53.7 ^c	Acrisols, Ferralsols, Leptosols, Solochats
Southeast (SE)	21.9 $\pm$ 1.1 ^b	1804 $\pm$ 72.1 ^a	1233 $\pm$ 25.0 ^c	2375 $\pm$ 51.3 ^f	Acrisols, Ferralsols, Fluvisol, Solochats

ANOVA (single factor) analysis: annual temperature, $F_{(5, 75)} = 2.8$ and $p < 0.05$ indicate significant difference among ecological regions; annual precipitation, $F_{(5, 75)} = 2.9$ and $p < 0.01$ indicate significant difference among ecological regions; annual evaporation, $F_{(5, 75)} = 3.8$ and $p < 0.005$ indicate significant difference among ecological regions; annual hours of sunshine $F_{(5, 75)} = 11.1$ and $p < 0.001$ indicate significant difference among ecological regions. Different letters ^{a, b, c} in each column indicate significant difference of means by Tukey post hoc test at $p = 0.05$

ecoregions, excluding RRD and MRD which did not have old-growth forests (Fig. 1). Annual temperatures and precipitation, and main soil types of each ecoregion are indicated in Table 1. All locations were located in national parks, natural preserve areas, biodiversity protection areas, or community forests which are protected for spirits. In each surveyed plot, data collected included the list of all trees, and DBH (only trees with diameter at breast height ≥ 10 cm).

Aboveground biomass determination

Dry AGB was based on DBH as follows (Bao et al. 2016):

$$\text{AGB} = 0.12843\text{DBH}^{2.409074} \quad (1)$$

The sum of AGB of all trees is the AGB of the plot.

Climate data

Annual temperatures ($^{\circ}$ C), precipitation (mm), evaporation (mm), and hours of sunshine were recorded from 109 climate monitoring stations distributed around sample locations for 2001–2014 (Table 1) (MARD 2014). The recorded data were used to estimate daily values, monthly values, and annual values step by step. The average annual values for the 14-year period were calculated for each ecological region (Table 1).

Data analysis

ANOVA (single factor) analysis examined the differences of means of stem density, basal area, and AGB among ecoregions; Tukey's post hoc test compared ecoregions.

Best-fitted regression was used to show the relationship between temperature, precipitation, evaporation and hours of sunshine, and growth parameters (stem density, basal area and AGB). All data analyses used SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

Results

The lowest density was 210 ind. ha⁻¹ in the Central Highlands (CH) and the highest 1095 stems ha⁻¹ in the Northwest (NW). Basal area was lowest (11.6 m² ha⁻¹) in the Northeast (NE) and highest (87.2 m² ha⁻¹) in the South Central Coast (SCC). The highest AGB (910 Mg ha⁻¹) was found in the SCC and the lowest AGB (101 Mg ha⁻¹) in the CH. Ecoregions had significant effects on stem density, basal area, and AGB (Table 2). The mean stem densities in NW, SCC, and Southeast (SE) were significantly higher than that in NE and the North Central Coast (NCC). There were no significant differences in stem density in CH compared to other ecoregions (Table 2). There were three significant groups in terms of basal area, the highest was in SCC, a medium was in NW, NCC, SE and CH, and the lowest occurred in NE. There were three significant groups for AGB similar to that for basal area (Table 2). The country-wide average for density is 495 ind. ha⁻¹, 30.2 m² for basal area ha⁻¹, and 230.1 Mg ha⁻¹ AGB.

In all six ecoregions, more than 85% of trees, 45% of the basal area, and 33% of the AGB were distributed in the 10–40 cm DBH class (Figs. 2, 3, 4). Trees > 100 cm DBH were less than 1% of the density, 14% of the basal area, and 17% of the AGB. The general pattern was fewer trees

Table 2 Stand density, basal area and aboveground biomass (AGB) of evergreen broadleaved forests in ecoregions of Vietnam (mean $\pm$ SE)

Ecoregion	No. plot	Survey locations	Stem density (ind. ha ⁻¹)	Basal area (m ² ha ⁻¹)	AGB (Mg ha ⁻¹)
Northwest (NW)	10	6	629 $\pm$ 91 ^b	34.9 $\pm$ 3.8 ^a	260.9 $\pm$ 35.7 ^a
Northeast (NE)	17	8	471 $\pm$ 26 ^a	25.7 $\pm$ 2.0 ^b	199.0 $\pm$ 22.0 ^b
North Central Coast (NCC)	13	5	329 $\pm$ 35 ^a	31.1 $\pm$ 3.0 ^a	241.0 $\pm$ 26.4 ^a
South Central Coast (SCC)	21	5	542 $\pm$ 32 ^b	39.0 $\pm$ 4.7 ^c	320.2 $\pm$ 51.0 ^c
Central Highland (CH)	107	25	495 $\pm$ 11 ^{ab}	28.9 $\pm$ 0.9 ^a	214.9 $\pm$ 8.2 ^a
Southeast (SE)	5	3	533 $\pm$ 71 ^b	29.4 $\pm$ 6.8 ^a	224.4 $\pm$ 63.7 ^a
Mean			495 $\pm$ 11	30.2 $\pm$ 0.9	230.1 $\pm$ 8.6

ANOVA (single factor) analysis: stem density, $F_{(6, 166)} = 10.39$ and $p < 0.05$ indicate no difference among ecological regions; basal area, $F_{(6, 166)} = 16.88$ and $p < 0.01$ indicate significant difference among ecological regions; AGB, $F_{(6, 166)} = 14.91$ and $p < 0.05$ indicate significant difference among ecological regions. Different letters in each column indicate significant differences of means by Tukey's post hoc test at $p = 0.05$

Fig. 2 Tree distribution by DBH class in ecoregions (NW = Northwest, NE = Northeast, NCC = North Central Coast, SCC = South Central Coast, CH = Central Highland, and SE = Southeast). Bars indicate $\pm$ SE **Fig. 3** Basal area distribution by DBH class in ecoregions (NW = Northwest, NE = Northeast, NCC = North Central Coast, SCC = South Central Coast, CH = Central Highland, and SE = Southeast). Bars indicate $\pm$ SE

(Fig. 2) and lower basal area (Fig. 3) in larger DBH classes. The AGB in trees > 100 cm DBH in the NW, NE, and SCC ecoregions was higher than in the 70–100 cm DBH

class (Fig. 4); AGB in the 40–70 cm DBH class in NCC was much higher than that in other DBH classes.

Fig. 4 Aboveground biomass (AGB) distribution by DBH class in ecoregions (NW = Northwest, NE = Northeast, NCC = North Central Coast, SCC = South Central Coast, CH = Central Highland, and SE = Southeast). Bars indicate $\pm$ SE

Fig. 5 Frequency distribution in tree, basal area, and aboveground biomass (AGB) classes in ecoregions (NW = Northwest, NE = Northeast, NCC = North Central Coast, SCC = South Central Coast, CH = Central Highland, and SE = Southeast) and in all ecoregions combined (Mean)

Conversely, the reduction of AGB in larger DBH classes was found in CH and SE ecoregions (Fig. 4).

Only the NW and CH had stand densities > 800 stems ha^{-1} , while only the SCC had basal area $> 80 \text{ m}^2 \text{ ha}^{-1}$. An $\text{AGB} > 700 \text{ Mg ha}^{-1}$ was found only in SCC (Fig. 5). Most plots (72%) were in the range of 300–600 stems ha^{-1} ; 7% of the plots had 200–300 stems ha^{-1} while 4% of the plots had > 800 ind. ha^{-1} (Fig. 5). Plots with basal areas of 20–40 $\text{m}^2 \text{ ha}^{-1}$ were 64% of the total number of plots, 18% of the plots with $< 20 \text{ m}^2 \text{ ha}^{-1}$ and 16% of the plots in the range of 40–60 $\text{m}^2 \text{ ha}^{-1}$ (Fig. 5). Eighty-one percent of the plots had 100–300 Mg ha^{-1} AGB (Fig. 5), 16% had 300–500 Mg ha^{-1} , and only 3% had $> 500 \text{ Mg ha}^{-1}$ AGB.

There was an exponential shape of the relationship between trees with $\text{DBH} > 30 \text{ cm}$ and basal area, and between trees with $\text{DBH} > 30 \text{ cm}$ and AGB. Basal area and AGB had a positive linear relationship (Fig. 6).

A linear relationship was best fitted for regression between climate variables (temperature, precipitation, evaporation, and hours of sunshine) and stand parameters (density, basal area, and AGB). However, regressions only existed between annual precipitation and basal area, and between annual precipitation and AGB (Fig. 7).

Discussion

Basal area and aboveground biomass are positively correlated with annual precipitation in this study (Fig. 7), which is consistent with other studies for tropical forests, for example, in Borneo (Slik et al. 2010), areas of Asia (Brown et al. 1993), the Amazon (Malhi et al. 2006; Saatchi et al. 2007), and African continent (Lewis et al. 2013). The AGB of tropical rain forests is controlled by environmental factors (Asner et al. 2009), as increased precipitation

Fig. 6 Aboveground biomass (AGB) plotted against stems and basal area (BA), and BA plotted against stems for 173 plots in tropical evergreen broadleaved forests

Fig. 7 Regression analysis between climate and stand parameters. Dots represent data of ecoregions

enhances net primary production (Quesada et al. 2012; Lewis et al. 2013). Average AGB in each ecoregion and over all Vietnam (Table 2) was much lower than in Borneo's tropical forest (457.1 Mg ha^{-1} , Slik et al. 2010), the Amazonian tropical forest (288.6 Mg ha^{-1} , Malhi et al. 2006), but was similar to AGB in Asian tropical forests (255 Mg ha^{-1} , Brown et al. 1993; Gibbs et al. 2007). Stand density for large trees ($\text{DBH} > 70 \text{ cm}$) accounted for 1.7% in this study, much lower than in Borneo (Slik et al. 2010). This is why the AGB of Vietnam's forests was much lower than in other studies as most AGB is stored in large-diameter trees (Slik et al. 2013). The importance of small-diameter trees in storing AGB in Vietnam is well-recognized, as there was linear regression between $\text{DBH} > 30 \text{ cm}$ stems and AGB. Trees with $\text{DBH} > 30 \text{ cm}$ accounted for 76% of the AGB (Fig. 6). In addition, the high AGB in Borneo's forest was due to dominance of large-diameter dipterocarp trees (Paoli et al. 2008; Slik et al. 2010). There are no large-diameter, dominant tree species in any ecoregions of Vietnam (Vo et al. 2010, Tran et al. 2016, 2017a, b). However, such findings should be treated cautiously because AGB is never measured directly (Tashi et al. 2017; Westfall and McRoberts 2017), but is rather estimated by using imperfect allometries.

It is recognized that AGB in the Central Highland is highest among Vietnam's ecoregions (Le 1996; Vo et al. 2015). However, this study found that its AGB (241.9 Mg ha^{-1}) was among the middle class, where the highest AGB was in the South Central Coast (Table 2). This may be explained by high precipitation and temperatures (Table 1) and the long latitudinal distribution of this ecoregion may explain this, and results in a diversity of forest types and tree species in diverse climate, edaphic, and topographical conditions (Fig. 1). This ecoregion has a long coast line in the east and inland in the west and no winter, supporting a diverse growth of tree species. The lowest AGB in the Northeast ecoregion (Table 2) may be explained by low temperatures, precipitation, evaporation, and the lowest annual sunshine hours among the ecoregions (Table 1), and the difference in species composition (Tran et al. 2010; Vo et al. 2015). With only 1400 h of sunshine annually (Table 1), photosynthesis may be limited and with a winter season from November to March the growing season is limited to the summer months in the NE. However, the AGB in NE ecoregion was 260.0 Mg ha^{-1} , the second highest among the six ecoregions. Such differences in AGB between the NE and NW ecoregions may be explained by difference in species composition and edaphic factors (Tran et al. 2010, 2011). However, further studies are needed, especially on the effects of edaphic conditions on AGB and stem density.

Thirty-two percent of tropical forests in Asia (Chave et al. 2008; Slik et al. 2010) and 40% of African tropical

Fig. 8 Aboveground biomass (AGB) of global tropical forests. Data from Chave et al. (2008) and Slik et al. (2010) for Asia, Lewis et al. (2009) for Africa, Chave et al. (2008) and Malhi et al. (2006) for the Neotropics, and this study for Vietnam

forests (Lewis et al. 2009) had AGB of $400\text{--}500 \text{ Mg ha}^{-1}$ and 62% of Neotropical forests had AGB of $300\text{--}400 \text{ Mg ha}^{-1}$. However, 52.6% old-growth, evergreen broadleaved forests in Vietnam only had AGB of $100\text{--}200 \text{ Mg ha}^{-1}$ (Fig. 8). Tropical forests may have AGB as high as $800\text{--}900 \text{ Mg ha}^{-1}$. Studies report on the high variation of AGB among tropical forests and that biotic and abiotic factors influence different AGB (Muller-Landau et al. 2006; Urquiza-Haas et al. 2007). Even on a small-scale as in Vietnam, the AGB among ecoregions is variable (Table 2). Therefore, regional as well as local studies on AGB and forest structure are needed to fully understand the role of forests on carbon storage against global warming and climate changes.

Low stand density in evergreen broadleaved forests in the NE, NCC, and CH ecoregions of Vietnam (Table 2) was similar to that in some tropical African forests (426 ind. ha^{-1} , Lewis et al. 2013). However, higher stem density was also found in the NW, SCC, and SE ecoregions which was similar to that in Borneo (602 ind. ha^{-1} , Slik et al. 2010) and in the Amazon (592 ind. ha^{-1} , Lewis et al. 2004). These reflect the high variation of stem density among ecoregions of Vietnam which may be due to latitude (Fig. 1), resulting in seasonality between north and south, and from species differences. For example, there are no dominant species in any ecoregion (Tran et al. 2010; Vo et al. 2015) compared to Borneo forests dominated by dipterocarps (Slik et al. 2010) and central Africa forests dominated by *Gilbertiodendron dewevrei* (De Wild.) J. Leonard and *Cynometra alexandri* C.H. Wright (Lewis et al. 2013). Lewis et al. (2013) found the higher AGB of African forests near the equator, which is similar in this study where the highest AGB (320 Mg ha^{-1}) was found in SCC near the equator (Fig. 1), followed by NW (260 Mg ha^{-1}), and the lowest of 199 Mg ha^{-1} in NE furthest from the equator.

In the old-growth, evergreen broadleaved forests of Vietnam, trees in 10–100 cm DBH classes accounted for > 99% of the stand density (Fig. 2), > 85% of the basal area (Fig. 3), and > 78% of AGB (Fig. 4). Any natural or anthropogenic disturbances (Miles and Kapos 2008; Slik et al. 2010, 2013; Miller et al. 2011; Pearson et al. 2014; Vo et al. 2015) such as typhoons or illegal logging removing large-diameter trees (e.g., > 100 cm DBH) will significantly reduce carbon storage. Carbon loss in an ecosystem is increased by (1) removing carbon from the forest through timber removal, (2) disturbing soil that promotes organic matter decomposition, and (3) reducing forest cover leading to higher surface temperature which may promote higher soil microorganism activity, causing an increase in the rate of heterotrophic respiration.

In conclusion, the aboveground biomass of evergreen, broadleaved forests in Vietnam increased with higher annual precipitation but not with annual temperatures. There was no correlation between stand density, precipitation or annual temperatures. Correlations between aboveground biomass and edaphic conditions, and between stand density and edaphic conditions were not examined in this study because of data limitations. Such correlations should be conducted in the future to fully understand the effects of abiotic factors on aboveground biomass and stand structure of Vietnamese forests.

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