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The impact of human activity on the biomass allocation of a medicinal herbaceous species in an agroforestry system of Southwest China

J. Zhang · T. Shen · Y. L. Zhao · H. Jin · L. H. Wu · H. G. Liu · Y. Z. Wang

Abstract Human activity has a greater influence on plants than on any of the other components of the environment. We used material from cultivated and wild *Coptis teeta* populations in the Hengduan Mountains to test the null hypothesis that there is no effect of human activity on the biomass allocation of an herbaceous understory species in a forest ecosystem. At the plot level, an isometric relationship existed in most of the significant relationships. However, at the individual level, an allometric relationship existed in most of the log–log relationships. Human activity could significantly affect the slope of the linear relationship of leaf versus total biomass; and also the intercepts of the relationships of root biomass versus total biomass, plant height versus total biomass and reproductive versus vegetative biomass. At any given plant body size, wild *C. teeta* has higher biomass in the leaf and less in root than cultivated counterpart. But the trajectories of log rhizome biomass versus log total biomass were the same for both cultivated and wild individuals. Thus, we conclude that (1) the allometric trajectories change at different scales and (2) *C. teeta*-based agroforestry system could ensure sustainable use of this medicinal plant because of the stable biomass allocation to the salable rhizome organs.

Keywords Allometry · Medicinal plant · Non-timber forest products · Understory species

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Introduction

It is commonly believed that human activity has a greater influence on plants than on any of the other components of the environment (Corlett 2014; Goudie 2013), and can negatively affect the vegetative cover which causes changes to the natural habitat in forest ecosystems (Wang et al. 2011). Studies have focused on the impact of human activity on herbaceous understory species (Bernatchez et al. 2013; Naud et al. 2010).

The herbaceous understory plants could change their biomass allocation in response to environment (Weiner 2004; Newton et al. 2011). If the allocation pattern of underdeveloped plants is not consistent with optimal foraging behaviour, plants will have to adjust

their development in response to environmental stress conditions (Semchenko and Zobel 2005; Ge and Xing 2012). The environmental factors govern plant biomass allocation to roots and leaves (Xie et al. 2012). For instance, fraction of total plant biomass allocated to leaves would increase if the plants are grown at lower light availability (King 1991; Meekins and McCarthy 2000; Pooter et al. 2012; Craine and Dybzinski 2013).

Allometry is the study of size and its biological consequences, which has fascinated biologists for centuries (Niklas 2004). Plant allometry related to plant architecture and biomass allocation strongly affects a plant's ability to grow in forest understory (Cao and Ohkubo 1998). Allometry of understory species in environments with different light conditions has been known for many years (Menges 1987; Geng et al. 2007). As understory species is one of the most important livelihood resources to support agriculture in mountainous regions (Chamberlain et al. 2013), the research on allometry of herbaceous understory plants could provide useful information for cultivation and management of these species (Zhang et al. 2013). In maple forests in Canada, light condition that favors the growth of medicinal plants also favors their total yield in active components (Naud et al. 2010).

Here, we collected cultivated and wild populations of *Coptis teeta* to test the null hypothesis that there is no effect of human activity on the biomass allocation of an understory species in a forest ecosystem.

Methods

Species selection

Coptis teeta Wall. (Ranunculaceae) is an endemic perennial herb naturally distributed in southwest China (mainly in northwest Yunnan province) and northeast India (Pandit and Babu 2000). The cultivation history of *C. teeta* in agroforestry system in northwest Yunnan has been more than 130 years (Huang et al. 2005). The rhizome of *C. teeta*, known as "goldthread", has been used as an anti-inflammatory and antibacterial medicine for a long time (Chueh and Lin 2012). It also provides a stable economic return, as a non-timber forest product to local forest communities (Huang et al. 2005). Sexual reproduction does not contribute significantly towards population increase in

this species (Pandit and Babu 2003). *Coptis teeta* was found to have highly specific microsite requirements. So in situ conservation measure, *C. teeta*-based agroforestry system, would be the best strategy for the continuing survival of this species (Pandit and Babu 1998). Therefore, it is an ideal plant for studying the biomass allocation response to human activity.

Study area and site selection

The study area was situated in the Hengduan Mountains, Southwest China. The vegetation is classified as subtropical wet forest. The average annual temperature is 7.5–12 °C, average annual precipitation is 1,600–2,300 mm, and altitude ranges are 1,900–3,100 m (Zhang et al. 2008). There are two seasons, rainy (May–November) and dry (December–April). We selected four sites for wild *C. teeta* population from natural habitat in which the cover of understory species (except *C. teeta*) is about 70 %, and four sites for cultivated one from the *C. teeta*-based agroforestry system (Supplementary Table S1). In the agroforestry system, local farmers tend the young *C. teeta* by weeding without using any pesticide and chemical fertilizer, so the cover of other understory species is below 30 %.

Plant sampling

In April 2007, we randomly selected six plots (1 m × 1 m) within each site and then 11–12 individuals within each plot (up to 70 individuals for one site). Individual plants were divided into rhizome, root, leaves and fruit. Samples were dried to constant mass and weighted for individual-level biomass determination. The remaining individuals in each plot were also collected and combined to one composite. The plant materials within each plot were also separated into rhizome, root, leaf and fruit. Samples were dried to constant mass and weighted. The numbers of individuals in each plot were counted and expressed as density. The height of each individual was also measured.

Data analysis

The 70 selected individual data plus the remaining ones in each plot were the data for each population. Data of individuals or populations were log-transformed to

homogenize variances. We used regression models of the form

$$\log y = \alpha \log x + \log \beta$$

to determine the parameters α and β for the allometric relationships defined as log y and log x, where logβ is the intercept and α is the slope (Warton et al. 2006). The plants in each plot didn't develop at the same time, but the results may still be interpretable. Because zero values were not included for the allometric analyses, phenology had little impact in this case (Weiner et al. 2009a).

We estimated the slopes and intercepts of the log–log relationships by Standardized Major Axis (SMA) regression, using the R software package 'smatr' version 3.3 (Warton et al. 2012). For all regression lines, the 95 % confidence intervals for the slopes and intercepts were calculated.

To test the effect of plant form and elevation on the slope and intercept, we used a two way ANCOVA which was modified from Guo et al. (2012), and in which plant form was treated as fixed factors and elevation as a covariate. The analysis of ANCOVA was conducted using SPSS 17.0 software (SPSS, Chicago, IL, USA).

To compare the lines between cultivated and wild forms, we performed the data anlysis using smatr. First, a test of heterogeneity in slopes among different plots (or between different forms) was run, using likelihood ratio statistic (Warton et al. 2006, 2012; Li et al. 2013). If $P >$ critical value, we assume the slopes are not different. Then, we tested for differences in intercept or shift along main axis with Wald statistics (Warton et al. 2006). All graphics were carried out using the program R 3.0.0 (R Development Core Team 2013).

Results

Plot level

The log–log (base 10) relationships yield the linear regressions. An isometric relationship exists in most of the significant relationships (Supplementary Table S2, Fig. 1). However, the relationships between reproductive and vegetative biomass in most of sites (plot 2–8) did not fit the allometric model ($P > 0.05$, Supplementary Table S2). The relationships between

density and total biomass in plot 1, 6 and 7 did not fit the allometric model ($P > 0.05$). The relationships between root and total biomass in plot 2 did not fit the allometric model ($P > 0.05$). Among all sites, the allometric slope and intercept showed different trends between cultivated and wild populations of *C. teeta* (Fig. 2). However, the effects of plant form, elevation, and a form × elevation interaction on the slope and intercept were not significant (Supplementary Table S3).
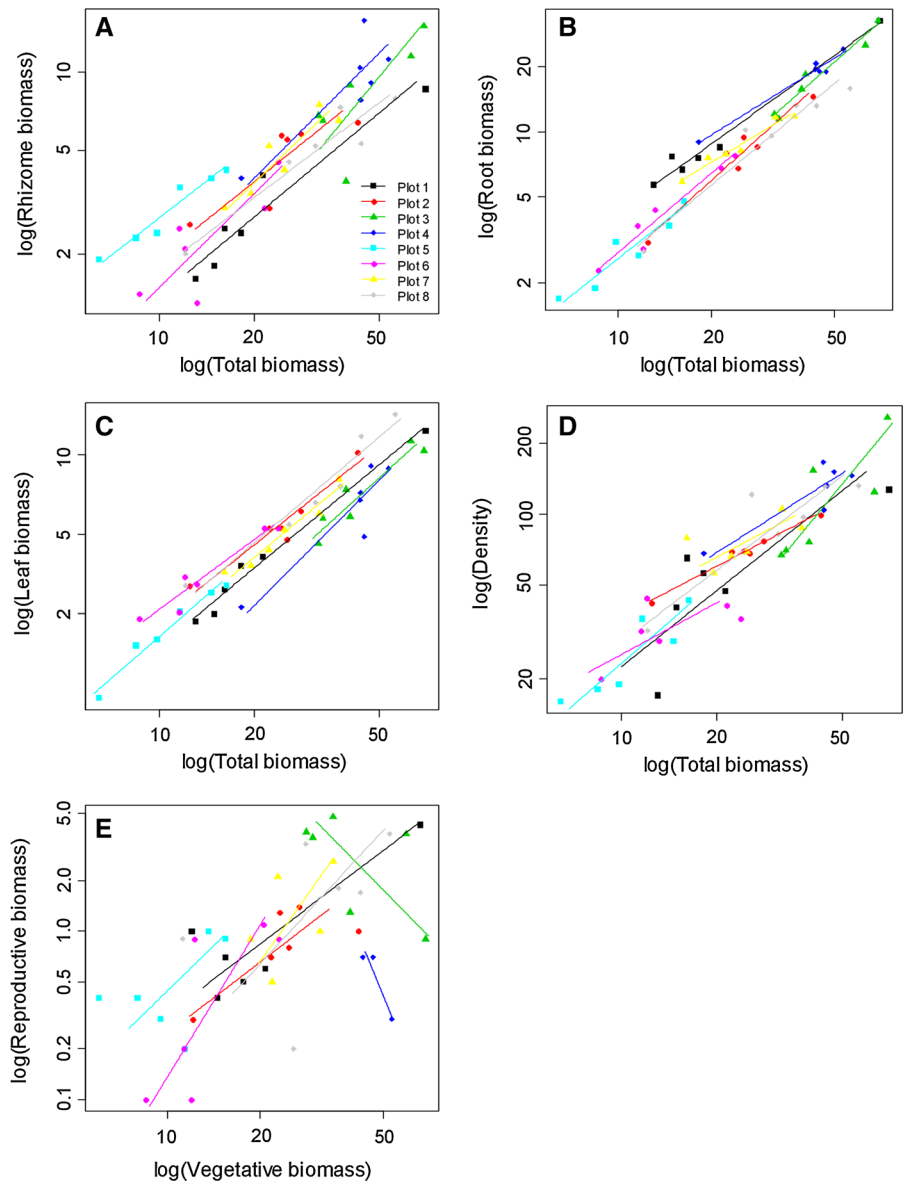
Individual level

With regard to the size dependence of individual growth, the log–log relationships yield the linear regressions, with the slopes differed from 1 ($P < 0.001$), except log leaf biomass versus log total biomass of wild *C. teeta* individuals ($P = 0.185$) (Supplementary Table S4, Fig. 3). The slope of the linear relationship between leaf biomass and total biomass at individual level differed significantly ($P = 0.008$) between wild and cultivated *C. teeta* (Supplementary Table S5, Fig. 3c).

The log rhizome biomass-log total biomass trajectories were the same for both cultivated and wild *C. teeta* individuals (Supplementary Table S5, Fig. 3a), which *C. teeta*-based agroforestry system could ensure sustainable use of this medicinal plant because of the stable biomass allocation to the salable rhizome organs. Human activity did not significantly affect the slopes of the allometric relationships of root biomass versus total biomass, plant height versus total biomass and reproductive biomass versus vegetative biomass. However, there were strong effects on the intercepts (Supplementary Table S5, Fig. 3b, d, e). At any given plant body size, wild *C. teeta* has higher biomass in the leaf and less in root than cultivated counterpart.

Discussion

In plant allometry theory, the roles of individual- and population-level processes have long been a topic of interest (Allen et al. 2008). The behavior of plant populations may be better understood if studied at the level of the individual (De Luis et al. 1998), while individual plant performance largely depends on the diversity of the surrounding community (Schmidtke

Fig. 1 Relationships of rhizome biomass (g m^{-2}), root biomass (g m^{-2}), leaf biomass (g m^{-2}) and density (ind. m^{-2}) to total biomass (g m^{-2}), and reproductive biomass (g m^{-2}) to vegetative biomass (g m^{-2}) for *Coptis teeta* at plot level

et al. 2010). As not all plant individuals in a certain population could reach the final development stage, developmental trajectories are not fixed in plant populations (Bonser and Aarssen 2009). In this study, the allometric trajectories changed at different scales. At plot level, the isometric relationship existed in most of the significant relationships. However, at individual level, the allometric relationship did exist. Herbaceous plants usually show a simple linear relationship (Weiner et al. 2009a). But the allometric correlation may not be significant if number of samples is

relatively small (Yan et al. 2012). This might be another reason to explain why some relationships at plot level did not fit the allometric model.

Allometry is a by-product of competitive interactions (Weiner and Thomas 1992). Asymmetric competition for light is the cause of the allometric changes and of the increase in size variability due to competition (Weiner and Fishman 1994). Competition for light is important for the growth of relatively small plants (Easdale et al. 2012). The light environment experienced by plants in forest is strongly dependent
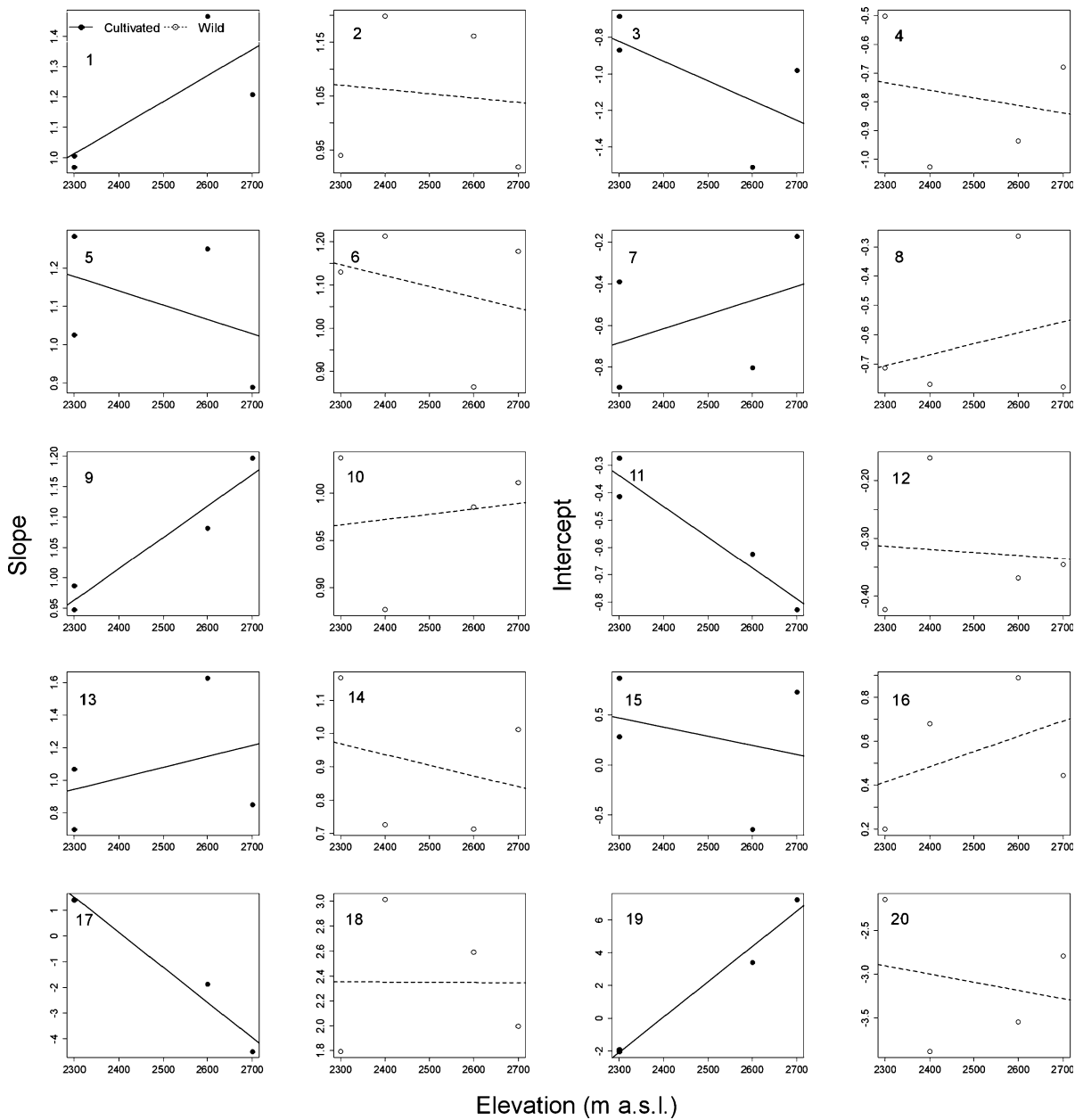
Fig. 2 Estimates of slope and intercept of the relationships between (*1–4*) rhizome and total biomass, (*5–8*) root and total biomass, (*9-12*) leaf and total biomass, (*13–16*) density and total biomass, and (*17–20*) reproductive and vegetative biomass in different plant forms of *Coptis teeta* along elevation gradients

upon interactions with their neighbors (Schmitt 1993). Competition for light will influence the variation around mean plant performance and may determine which species dominate (Kiær et al. 2013). In both European beech and Norway spruce seedlings, growth and biomass allocation to above and belowground plant components were affected by light availability (Schall et al. 2012). In this study, considering cultivated *C. teeta* is tended by weeding, wild *C. teeta* meets more interspecific competition for light, which pushes the plant to modify its biomass allocation to leaf.

Fig. 3 Relationships of rhizome biomass (g), root biomass (g), leaf biomass (g) and plant height (cm) to total biomass (g), and reproductive biomass (g) to vegetative biomass (g) for *Coptis teeta* at individual level
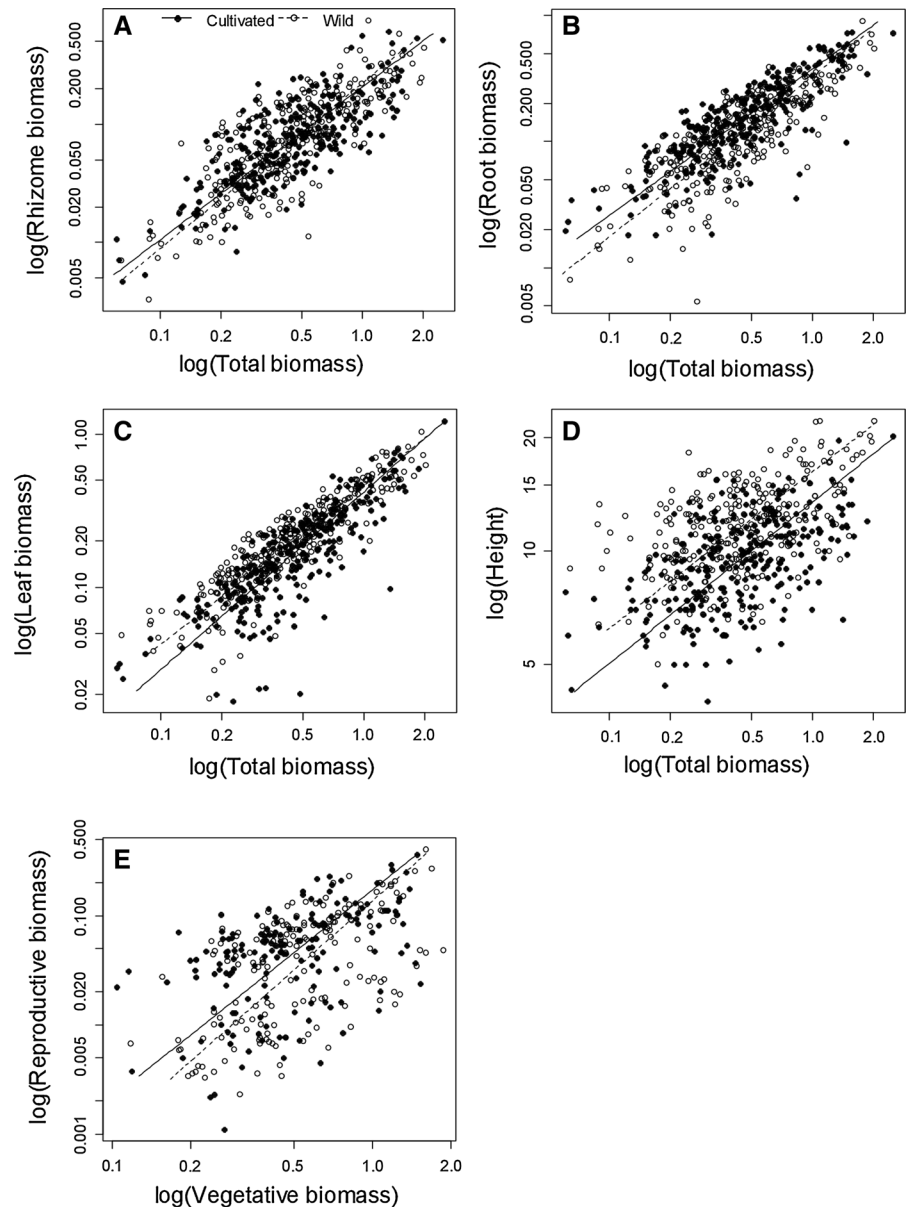
The relationship between reproductive and vegetative biomass is a fundamental aspect of a plant's reproductive strategy (Guo et al. 2012). Relative biomass allocation to reproductive structures generally decreases compared with vegetative allocation due to increasing plant competition (Dujardin et al. 2011). Changing environmental conditions will affect sexual reproduction of some understory plants with clonal growth (Grainger and Turkington 2013). In the study of *Senecio vulgaris*, the environment (i.e., competition) affected the intercept, not the slope of the allometric relationship between reproductive biomass and total plant biomass (Weiner et al. 2009b). In our study, human activity significantly affected the intercept of the allometric relationship between reproductive and vegetative allocation in *C. teeta*.

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