Species-specific Allometric Models for estimation of Aboveground Stem Biomass of Three Dominant tree Species at Satchari National Park

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A dissertation submitted to the Department of Forestry and Environmental Science, ShahJalal University of Science and Technology, Sylhet, Bangladesh for the partial fulfillment of the degree of professional M.Sc. in Forestry

Prepared and Submitted by

Reg. no. 2008621003

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Dedicated to

My Beloved Parents

Certification

This is to certify that Registration No. **2008621003**, Session: 2008-2009, has prepared this thesis paper entitled **“Species-specific Allometric Models for estimation of Aboveground Stem Biomass of Three Dominant tree Species at Satchari National Park”** under my direct supervision. This is for the Partial Fulfillment of MSc. in Forestry and submitted to the Department of Forestry and Environmental Science, Shahjalal University of Science and Technology, Sylhet 3114, Bangladesh. I do hereby approve the style and content of this project paper.

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Declaration

I do here by declare that this thesis paper entitled **"Species-specific Allometric Models for estimation of Aboveground Stem Biomass of Three Dominant tree Species at Satchari National Park"**has been prepared by me to submit as a requirement for the partial fulfillment of MSc. in Forestry. This paper has not been submitted in any application for a degree. This reported work exclusively executed by me unless otherwise stated.

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Abstract

Species specific allometric equations were developed to estimate the above ground stem biomass of three dominant tree species viz. *Artocarpus chaplasha*, *Tectona grandis* and *Acacia auriculifomis* at Satchari National Park, Sylhet. Dendrometric data were collected from the 101 individuals of each species from 50 circular plots of 15m radius through arbitrary random samlpling method. Eighteen set of allometric models were developed and tested separately for all the three species. Model 15 (Ln Y= $\alpha + \beta$ ln(DBH2.H. ρ) was found as the best fitted model for biomass estimation for *A. chaplasha* and *T. grandis*, because of high coefficient of determination (R^2=0.99 and 0.94). On the other hand, nonlinear model 16 was (Y = (α DBH2) β) was found as the best fitted model for *A. auriculifomis* (R^2=0.72). Study results also revealed that DBH and wood density influence mostly in developing best fitted models. The allometric models developed in the present study could be used for future estimation of above ground stem biomass of selected species in other forest of Bangladesh after model evaluation.

Keyword: Allometric equation; Stem biomass; Wood density; *Artocarpus chaplasha*; *Tectona grandis*; *Acacia auriculifomis*; Satchari National Park.

Acronym

AGB	Aboveground Biomass
AGSB	Aboveground Stem Biomass
AIC	Akaike Information Criterion
BFRI	Bangladesh Forest research Institute
CO_2	Carbon-dioxide
DBH	Diameter at Breast Height
FAO	Food and Agricultural Organization
FD	Forest Department
FIA	Forest Inventory and Analysis
H	Tree height
IPCC	Intergovernmental Panel on Climate Change
IRG	International Resource Group
Mg	Mega grams
NAST	National Assessment Synthesis Team
Pg	Peta grams
R^2	The Co-efficient of determination
RSE	Residual Standard Error
SNP	Satchari national park
ρ	Wood density

List of tables

List of figures

CHAPTER ONE: INTRODUCTION

1.1. Introduction

It is well established that global climate is changing day by day as a result of global warming and anthropogenic causes. Tropical deforestation is estimated to have released of the order of 1–2 billion tonnes of carbon per year during the 1990s, roughly 15–25% of annual global greenhouse gas emissions (Malhi and Grace 2000, Fearnside and Laurance 2003; 2004, Houghton 2005b). Increasing carbon emission is one of today's major concerns, which was well addressed in Kyoto Protocol (Ravindranath et al. 1997) because it is the main causal factor for global warming (Lal 2001). IPCC (2007) reported that the amount of carbon dioxide in the atmosphere has increased from 280 ppm in the pre-industrial era (1750) to 379 ppm in 2005, and is increasing by 1.5 ppm per year. Current global circulation models from NAST (2000) predict that average annual global surface air temperatures may increase by approximately 2.5^{o}C by the end of this century.

Forest inventories have often been used as starting points for the estimation of biomass and carbon storage in natural forests in Brazilian Amazon (Brown and Lugo 1992) and Europe (Kauppi et al. 1992). Often, biomass equations have been developed on the basis of forest inventory data (stand tables) (e.g., Brown 1997, Brown et al. 1989). In some cases, equations are constructed from individual tree measurements (e.g., Brown and Iverson 1992). Studies on biomass of forest vegetation are essential for determining storage of the carbon in the dominant tree component because the dominant tree species greatly influence the magnitude and pattern of energy flow that is stored in trunks, branches, leaves and roots in the form of various organic substances and material remained in continuous circulation between biotic and abiotic components of the ecosystem. IPCC (2003) suggests that inventory-based methods can be done either by directly applying allometric models that can predict tree biomass components based on field measurements of individual trees (like diameter at 1.30 m or tree height), or using multiplication factors that allow to convert or expand stem volume to the tree biomass component wanted. This involves the development of site-specific allometric equations requiring tree harvesting and weighting in the field, which is expensive and time-consuming. Yet, accurate estimates of above ground biomass in many tropical regions are lacking, due to difficulties in obtaining field data for converting tree measurements to aboveground biomass estimates of individual trees in species-rich ecosystems (Chave et al. 2005).

Biomass estimation can be done in a direct way, by cutting and weighing all the plants in sample areas. This requires considerable effort and time, destroys the vegetation in these areas and, in some situations, is not desirable or may even be illegal. Therefore, several methods have been devised to estimate biomass; the most frequently used being based on allometric relationships of biomass and plant measurements, such as stem diameter, plant height, and wood specific gravity (WSG) (TerMikaelian and Korzukhin 1997; Zianis and Mencuccini 2004; Chave et al. 2005) because once the equations have been developed, disturbance such as destruction of the forest stand is avoided and it is possible to investigate large study areas (Brown 1997; Chambers et al. 2001; Chave et al. 2005). Moreover, the adequacy of estimation using the equations is usually high, even when there are many tree species within the same forest stand (Kira and Shidei 1967). Different types of regression equations (linear, logarithmic, exponential and power) are used to estimate biomass indirectly. Several generalized biomass prediction equations have been developed for tropical species (Stromgaard 1985; Brown et al. 1989; Overman et al. 1994; Chave et al. 2005; Cole and Ewel 2006) on the basis of the easily measured attributes of trees. The use of these equations for consistent forest biomass estimation for all species is however troublesome because there are many gaps among species, tree sizes, and geographic areas not covered by the equations (Navar 2009b). Many factors can influence the accuracy of biomass estimations and are known to vary with environmental factors (e.g. soil type, soil nutrients, climate, disturbance regime, successional status, and topographic position), wood specific density, and genetic variation. Therefore biomass equations tailored to estimate biomass of a particular species in a given biome can provide more accurate estimates (Cole and Ewel 2006; Litton and Kauffman 2008) than generalized biomass equations.

1.2. Justification

Bangladesh is a low-carbon emitting country because of its low level of industrialization but its vulnerability to climate changes is very high as a sea rise of 1-2 meter would inundate a substantial area and thereby affecting a large coastal population. In Bangladesh the per capita carbon dioxide (CO2) emission is estimated to be as 0.2 ton/year which is much lower when compared to 1.6 ton/year in other developing countries and 20 ton/year in USA (Enayetullah et al, 2004). In the global trends of forestry business, carbon sequestration has been emerged as a potential profitable business, which is oriented to socio-economic development and environmental amelioration. Estimates of carbon stocks and stock changes in tree biomass (above- and belowground) are required for reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and will be required for Kyoto Protocol reporting (Green et al. 2007). In Bangladesh some sporadic works was done to estimate organic carbon in the plantation by Miah (2001; 2002) and Miah et.al (2002). Alamgir and Amin (2008) quantified the organic carbon stock in the hill forest of Chittagong Hill Tracts (CHT) Bangladesh developing allometric model to get a clear picture of organic carbon storage. Another carbon inventory was conducted by Forest Department (FD) and Bangladesh Forest Research Institute (BFRI) in the Chunoti Wildlife Sanctuary of Bangladesh in 2008. All these studies were conducted on the all types of vegetation of the respective forest not species-specific. To the best of my knowledge so far no biomass estimation and/or carbon inventory has been conducted on *Artocarpus chaplasha, Tectona grandis* and *Acacia auriculiformis* by developing allometric models of Satchari National Park in Bangladesh. These species are the most dominant tree species of Bangladesh that is why it is necessary to know the amount of biomass in these dominant species. The purpose of this study is to contribute the understanding of woody biomass by developing species specific allometric model from the perspective of carbon sequestration for the country.

1.3. Objective of the Study

The main objective of this study is to develop species-specific statistical model to determine above ground stem biomass by using some dimensional variables such as tree diameter, height and wood density of three selected tree species at Satchari National Park

1.4. Research question

- What are the most influential variables in developing best fitted allometric model thus biomass estimation?
- Which allometric model is the best fitted model to estimate above ground stem biomass of the selected tree species?

CHAPTER TWO: LITERATURE REVIEW

2.1. Biomass, its components and types

Compared to other major types of ecosystems, tropical forests contain the greatest amount of plant material or plant biomass per area. Biomass is defined as the total mass of organisms (plants, animals, and others), both living and dead, in a given area or volume. Tropical forests have a high plant biomass because of high rainfall, warm temperatures, lack of extreme seasons, and sequences of plants at different heights starting at the forest floor. It is expressed in units such as grams per square meter or kilograms per hectare. Between different vegetation types, biomass ranges from around 100 kg/ha for deserts to 500,000 kg/ha for tropical rain forests. In the study of carbon budgets, biomass is important because it directly represents the amount of carbon stored in living plants. Biomass may be estimated in total for stands or portions of stands as noted, but information on biomass distribution by plant component is often needed. Above-ground biomass consists of all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. Below-ground biomass consists of all living roots excluding fine roots (less than 2mm in diameter). Biomass components may be divided as necessary for a given application, but often include categories such as stem wood, branch wood, foliage, bark, roots, etc., with more or fewer subdivisions as needed. A common constraint is that the sum of the component biomass estimates must equal the total biomass for the stands or portions of stands of interest. In many applications, only above ground biomass estimates are used. There are obviously belowground components to biomass (such as coarse roots, fine roots, etc.), but studies quantifying these values are difficult to conduct, are available for only a small number of species and ecosystems, and typically have low precision in the data.

2.2. Tropical forest biomass

Tropical forests cover a relatively small amount of the Earth's land surface (approximately 3.3%), of which 40% lies in the Amazon region (Kricher 2011; Buchmann et al. 1997; Verweij et al. 2009). They are considered as one of the most important terrestrial carbon sinks. To illustrate this, it has been estimated that the Amazonian forest stores approximately 86 ±17 petagrams of carbon (PgC) in biomass (Saatchi et al. 2007) with in addition 41-47 Pg C stored in its soil organic matter (Salimon et al. 2011).

However deforestation and forest degradation in the tropics are occurring at an alarming rate and are often driven by agricultural expansion and exploitation of forest resources (IPCC 2007). It has been estimated that deforestation is removing annually about 0.6% of total forest area in the tropics, adding up to an estimated cumulative loss of 8.3% of tropical forests from 1990 to 2005 (FAO 2006; Butler 2007; Myers 2007). As a result, tropical deforestation and forest degradation represent the second largest source of global greenhouse gas emissions, contributing to 12-20% of anthropogenic carbon emissions (Houghton 2005a; Ghazoul et al. 2010). Thus, there is a rising concern to include measures which aim to reduce deforestation of tropical forests in future policies towards combating climate change (Griffiths 2008). Furthermore, it is widely recognized that deforestation and forest degradation not only have a negative impact on carbon stocks but also on other essential environmental services such as biodiversity, hydrological cycles, erosion prevention or soil conservation (Salimon et al. 2011). Forest ecosystems cover about 30% of the Earth's land surface (Dale et al. 1991; Sedjo 1998 and Solomon et al. 1993). As trees grow, they sequester carbon from the atmosphere in their tissues, and as the amount of tree biomass increases within a forest or in forest products the increase in atmospheric CO_2 is mitigated (IPCC 1996 and Fearnside 1999). Forest biomass plays a key role in sustainable management and it has been identified as an important carbon sink (Brown 2002) the forest biomass contains approximately 80 % of all aboveground terrestrial carbon (Goodale et al. 2002). Thus, the knowledge about the development of aboveground biomass over the entire life cycle of a forest is required for an accurate quantification of biomass production and carbon pools.

Measuring tree biomass in the field is extremely time consuming and potentially limited to a small tree sample size, empirical relationships have been used to estimate total biomass from predictive biometric variables such as breast height diameter (D) or height (H) (Loetsch and Haller 1973; Wirth et al. 2004). In areas such as grasslands, all of the plants in a given area are clipped, then dried and weighed. At the stand level, biomass may be estimated for the over storey, shrubs, herbs, lichens, moss, etc. In forested situations, the over storey biomass usually dominates. There are cases where tree cover is low and over storey or tree biomass is smaller compared to that of other ecosystem components. The decision on which biomass components are necessary to consider is dependent on the ecosystems to be surveyed and the intended use of the resulting information.

2.3. Importance of plant biomass estimation

Plant biomass assessment is important for many purposes (Parresol 1999). It is aimed at two major objectives: for resource use and for environmental management. It is important to determine how much fuel wood or timber is available for use. For this purpose, one needs to know how much biomass is available at one given time. It has been used for several purposes, including those related to wood production, net primary productivity, nutrient cycling and the recent interest in CO_2 dynamics and the greenhouse effect (Ter-Mikaelian and Korzukhin 1997; Nelson et al. 1999; Keller et al. 2001). In the light of environmental management, biomass assessment is important to assess the productivity and sustainability of the forest. Biomass is also an important indicator in carbon sequestration. For this purpose, one needs to know how much biomass is lost or accumulated over time.

2.3.1. Advantages of Estimating Plant Biomass

- Most biomass attributes are straight-forward, easy to interpret, and can be objectively measured.
- Biomass can be directly measured with little training, although, it is time consuming.
- Biomass can be measured for all types of vegetation and therefore comparisons can be made among different communities or ecosystems.
- Biomass can be easily measured and therefore the accuracy of estimation techniques can be easily tested. In contrast, cover is easy to estimate, but direct measures of cover are very difficult to make and therefore the accuracy of cover estimates are seldom examined.
- Biomass is considered a good measure of plant dominance on a site because it reflects the amount of sunlight, water and minerals a plant is able to capture and turn into biomass.

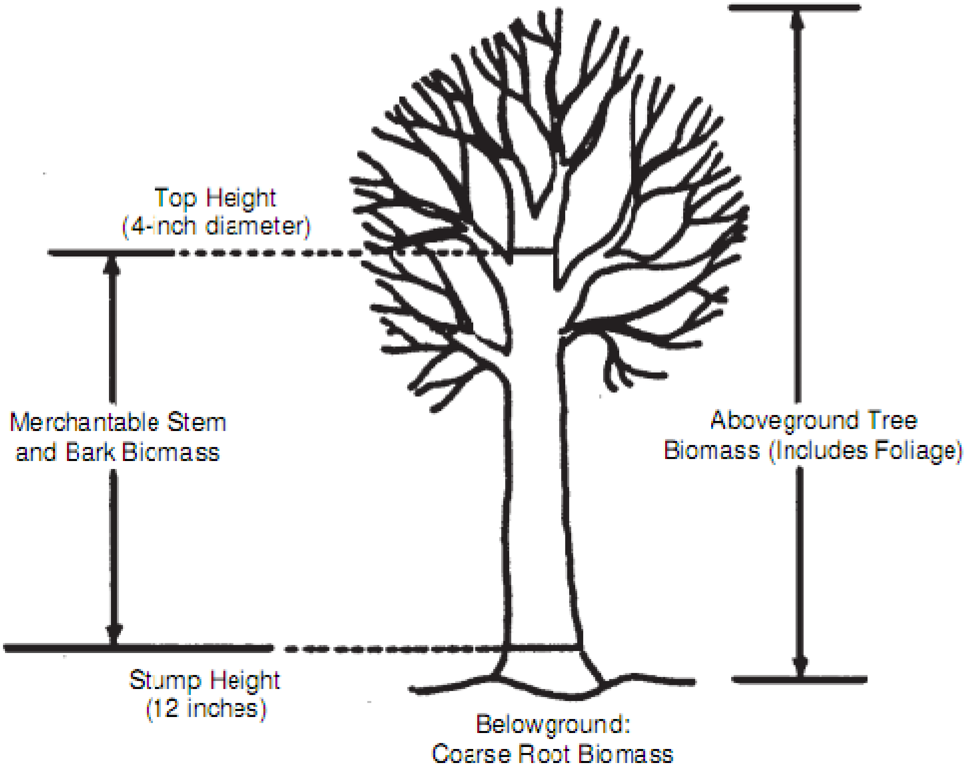


Figure 2.1. Tree component biomass **Source**: Jenkins et al. 2004

2.4. Biomass Equations

There are so many methods have been developed to estimate biomass but quantifying carbon stock through biomass estimation accurately is a challenging job since different methods have been developed to measure and monitor forest carbon stocks but there is no scientific consensus about which one is most accurate (Gibbs et al. 2007). Like volume equations, biomass equations usually express biomass as a function of tree dimensions (diameter and height) or stand-level variables such as basal area. Equations are usually developed for particular species or species groups, and may be developed with data collected from narrow geographic ranges. For trees, allometric approaches are used, where individual plants of varying size are cut down and weighed. Allometric relationships are developed between the readily made measurements of tree height and trunk diameter, and the harder to measure quantity of biomass. There are some equations developed by Brown et al. (1992); Brown and Iverson (1992); Brown (1997);

Chave et al. (2004; 2005); Chambers et al. (2001); Segura and Kanninen (2005). These equations are simple to apply since they use variables commonly obtained during field data collection, and are applied at the stand level rather than at the individual tree level. Brown (1997) presented allometric equations for individual trees in tropical forests. For broadleaved species, two equations are presented for tropical dry forests, two for tropical moist forests, and one for tropical wet forests. In addition, one equation is presented for palms and another for Tropical Conifer forests. All of these equations express individual tree biomass as a function of diameter and height, though different specific equation forms are used in different applications.

2.5. Methods for measuring above-ground biomass and carbon stocks

In the following paragraphs, three different methods for estimating above-ground biomass are described. In particular, the field-based method is discussed in more detail as this method will be used for this research project. First, the relation between above-ground biomass and carbon stocks is discussed.

2.5.1. Aboveground biomass (AGB) and carbon stocks

The majority of the carbon stored in tropical forest ecosystems is found in the living biomass of trees, woody debris, dead ground litter and soil organic matter. Among these different forest components, the above-ground biomass (AGB) of living trees contains the largest carbon pool and is the most directly affected by deforestation and degradation activities (Gibbs et al. 2007). Consequently, measurements of the carbon stored within the AGB of living trees provide the most representative estimate of the forest carbon stocks for REDD.

It has generally been assumed that the carbon content of the AGB of living trees consists of 50% of overall biomass (Clark et al. 2001; Lamlom and Savidge, 2003). However, other studies have argued that the carbon content of AGB can vary between 47% and 59% depending on the tree species (Ragland et al. 1991; Elias and Potvin, 2003; Lamlom and Savidge 2003). Species may differ in carbon content due to their unique chemical composition and anatomy, and therefore in specific wood density. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) decided to use a carbon fraction of 0.47 of biomass in its calculations (Gibbs et al. 2007). Due to the potential variation in the carbon content of the AGB of living trees, the results obtained in this study are not converted into carbon values but kept as initial AGB values. This decision also makes comparison with the results of other studies more straightforward because they are most commonly presented in this form.

2.5.2. The biome-average approach

The biome-average approach estimates forest carbon stocks by applying a specific representative value of forest carbon per unit area (i.e. tonnes of C per hectare) to large forest categories or biomes (Fearnside 2000; Gibbs et al. 2007). These biome averages are based on two main data sources. One source is the compilations of biomass harvest measurement data: all trees in a defined area are harvested, dried and weighed to measure their biomass. Although this approach produces very accurate results for a specific site, it is very time-consuming, expensive, destructive and highly biased for extrapolation over a larger spatial scale such as country level (Gibbs et al. 2007). The other source of data for the biome-average method makes use of forest inventory data gathered by the Food and Agriculture Organization (FAO) and others. However, the data from forest inventories are missing a lot of information for tropical forests and tend to be collected inadequately for conclusions to be made on a national level (FAO 2005; Gibbs et al. 2007).

Despite the limitations and uncertainties of the biome-average approach, it still remains a regularly used method for estimating forest carbon stocks because it is free, easily accessible and is considered as an important source for global carbon information (Gibbs et al. 2007). However, more recent methods are developing which may provide better estimates of forest carbon stocks across a larger spatial scale.

2.5.3. Field-based method and allometric equations

This method consists of following two methods. At first sampling plots are selected by adopting sampling method depending upon the purpose of the study. Then, data like as diameter at breast height, height, form factor, GPS location of the sampling plot is recorded and wood samples are collected from the individuals and after that from this data and samples allometric relationship for the whole tree is developed. Detailed description of this method is as follows:

2.5.3.1. Sampling method for collecting field data

The first step for the field-based approach is to collect field data using standardized sampling methods with appropriate plot size, shape and number in order to generate accurate biomass estimates. Adequate sampling of easily measured variables enables the extrapolation of plot data to regional biomass estimates. Any technique of spatial estimation of biomass at project, regional or continental scales, for example using remote sensing data or tree growth process-based models, requires validation and calibration from such ground-based biomass estimates (Drake et al. 2002).The most commonly used sampling method for forest inventories is based on hectare square plots as suggested by the FAO. However, other studies have argued that this type of plot design may not actually be adequate for characterizing carbon stocks and fluxes (Wagner et al. 2010; Keller et al. 2001). For example, Keller et al. (2001) carried out their research in the Tapajos National Park in Brazil and found that 21 plots of 0.25 hectares each were sufficient to make estimates of mean biomass. Their results were within only a 20% error sampling and 95% confidence. In turn, several methods have been suggested to improve either the accuracy of the results and/or its efficiency (amount of effort required for data sampling).

2.5.3.2. Allometry

The second step of the field-based method is to convert field data into an estimate of AGB by applying allometric regression models, also referred to as allometric equations. In other words, the field measurements provide the parameters necessary to calculate AGB using allometric equations such as measurements of Diameter at Breast Height (DBH) and/or tree height. The word allometry comes from the Greek word allos, which means others, so allometric means others than metric. It means the relationships of the growth of one part of an organism to the growth of another part or the growth of the whole organism. This term used to measure and study of growth relationship, that is the relationships between the dbh (diameter at breast height), tree height, total biomass, leaf weight etc. are calculated. It is all about studying the relative sizes of plant parts. It is useful because allows the total biomass of a forest or stand to be estimated, without having to cut down all the trees, take them back to the lab, dry the pieces in an oven, and then weigh all the pieces and also it is used to locate the growth of the significant differences in tree height with dbh, its crown shape, branching height by using regression analysis or using formula.

And finally to show this regression analysis the graphical representation curve is showed that present the increase and decrease curve of the tree with respected variables. A general equation expressing the fundamental relationship of allometric growth is $y = ax^b$ in which y is the size of one organ; x is the size of another; a is a constant; and k is known as the growth ratio. Allometric growth is usually detected by graphing the growth data on a log – log plot. In this the horizontal and vertical axes of the graph are both logarithmic scales. The general allometric growth equation has the form $y = ax^k$. Taking the logarithm of both sides produces the following equation: $\log(y) = \log(a) + k \log(x)$.

2.5.3.3. Stem Allometry

In the semi-evergreen forest light play a major determining role in the architectural pattern. Firstly in the forest understorey to limit growth of trees it has the main resources (Chazdon and Fetcher 1984; Fetcher et al. 1994) secondly because of light environments species differ and during their life- time each individuals require different light environments (Clark and Clark 1992; Sterck et al. 1999) and finally to determine mechanically tree stability and to intercept the lighting way by the tree architectural form , both are affect tree performance (Chazdon 1986; Pearcy and Yang 1996; Valladared, 1999). The environment influences essential design charater in plant both the cellular and whole level that is structure and architecture in terms of resource supply and biotic or abiotic stress (Stokes and Read 2006) trees do not retain a linear proportion between hight and diameter means that they are not geometrically self –similar (Tomlinson 1987). They maintain a constant bending moment that proportionately greater increase in diameter than in height with age through they preserve elastic by stems and branches leaves must be positioned and also to acquire water and mineral nutrients and ensure anchorage roots should be able to push through soil (Stokes and Read 2006). Incompatible influences must be controlled in plant design at any stage on different function that effect depends on the local environment (Niklas 1992; Press 1999). In different environments if plant parts are expose during development they showed varied profile of mechanics among and within plants of the same species (Niklas 1999) to maximize future probability for reproduce understory trees and saplings display an adaptive allocation pattern among leaves, branches, and stems (Lee et al. 2000) . Indeed, it is widely known that the rate of growth in tree height relative to the rate of growth in trunk diameter decreases with increasing tree size and age as a consequence of the decreasing absolute rate of growth in height (Niklas 1995). Tree growth and survival of species are influenced by allometric and architectural variations (Grubb 1977). In height growth shade-intolerant species invest more than in strength and longevity and to attain a certain height low safety margins facilitate rapid height growth with lowering biomass (King 1987; Alvarez-Buylla 1992; Martinez-Ramos 1992). To efficient light interception and reduced respiration under low light shade-tolerant species can survive (Logan 1965; Loach 1967). In a succession species efficient use of wood allow rapid height growth (King 1987) .shade tolerant species require little light partitioning horizontal light gradient and for successful establishment and survival require high light for light demanding species (Bongers et al. 2006).

2.5.3.4. Allometric equations for calculating AGB

Allometric equations provide an attractive means of estimating carbon stocks in forest biomass since they are based on existing information and easily measured variables, such as stem diameter at a breast-height, i.e. at 1.3 m above the ground surface (DBH), or a tree height (H) or bole volume (V) (e.g. Zianis and Mencuccini 2004; Pilli et al. 2006; Pokorny and Tomaskova 2007). The development of equations is based on the destructive sampling of several individuals covering the whole range of tree size and then applied to inventory data to provide ground-based estimates of biomass density at plot scale. Allometric equations are developed by using a large dataset from harvested trees which means that it is relatively time-consuming, expensive and destructive to develop (Gibbs et al. 2007). The height and stem diameter of record-size individuals from different species are particularly important because they reveal the maximum size attained by phyletically or functionally different species groups, which are crucial to a variety of ecological and evolutionary hypotheses. For these reasons, allometric (scaling) relationship between plant height (or body length) and basal stem diameter is an effort to explore contending mechanistic explanations for observed intra or interspecific mechanical or hydraulic trends (e.g. Horn 1971; Holbrook and Putz 1989; Niklas 1994a; Gallenmuller et al. 2001; Isnard et al. 2003; Rowe et al. 2004). Generalized allometric equations for different forest types are developed rather than species-specific allometric equations because tropical forests can generally contain over 300 different species in a 1 hectare plot (Chave et al. 2005). Furthermore, studies have shown that generalized allometric equations for different forest types generate accurate estimates of AGB and that efforts made to develop species or site specific regression models do not systematically improve its accuracy (Chambers et al. 2001; Keller et al. 2001; Chave et al. 2005; Gibbs et al. 2007). It is well known that this allometric relationship changes remarkably with site quality, and some analyses also suggested that it changes with temperature and water supply (Aiba and Kitayama 1999; Martinez and Lo´pez-Portillo 2003). Furthermore, site-specific factors, such as varying tree density, soil moisture, nutrients, light, topography, and disturbance, affect forest allometry. It must be emphasized that specific allometric equations for each regional forest type provides more reliable AGB results than one grouped allometric equation for all forest types. Therefore, regional forest type is an important factor to be taken into consideration when calculating forest AGB. These regional forest types are classified with regards to their mean annual rainfall, dry season length and evapotranspiration activities (Chave et al. 2005).

Several different allometric equations have been developed for many plant species in different biomes, both temperate (Ter-Mikaelian and Korzukhin 1997) and tropical (Haase & Haase 1995; Nelson et al. 1999; Keller et al. 2001) forests and the most well-known are by Brown et al. (1989), Chambers et al. (2001), Chave et al. (2001) and Chave et al. (2005). Allometric equations have been determined Foresters have also developed allometric relationships to estimate stem volume at stand level from measurements made on D and H. The wide-ranging adoption of this approach has produced many empirical allometric equations to predict biomass component or stem volume. Empirical models between stem diameter and tree height have also been used to investigate biomechanical constraints and scaling relationships of trees. Applying these different equations for the same studied forest area can yield different AGB estimates. The quality of the AGB outcomes obtained from the allometric equations will depend on the data used to create them as well as the range of parameters included. For an allometric equation to be representative of a forest area, it needs to be based on a large number of trees harvested as well as a large number of big diameter trees (Brown et al. 1989; Chave et al. 2005). Allometric equations can make use of one or more of the following parameters: DBH, tree height and species specific wood density. Moreover, in general the more parameters from field measurements included into the allometric equation, the more accurate the AGB results.

2.6. Silvicultural characteristics of the selected species

2.6.1. Akashmoni

Scientific name: *Acacia auriculiformis* A. Cunn. *ex* Benth & Hook.

2.6.1.1. Description

Acacia auriculiformis is an unarmed, fast growing, evergreen, exotic tree, with a height of 15-28m, bark grayish brown, more or less smooth in young trees which becomes dark brown or blackish and rough with longitudinal fissures at maturity. Phyllode alternate, variable in size, straight to falcate, curved 9-16 × 1-3 cm sometimes up to 20cm long. Inflorescence axillary, pedunculate, cylindric spike, 4-8cm long, glabrous. Flowers are golden yellow, very small, sessile, sweet scented, Calyx is campanulate. Fruits are a pod of 8-12 × 0.5-1 cm, flat, globrus. Seeds are elliptical, 3-5×2-3mm, long, folded orange coloured funicle. Flowering and fruiting time is from June-February. Propagation of this species is usually done by seeds and before sowing the seeds some pretreatment is needed for it successful regeneration (Ahmed et al. 2009).

2.6.1.2. Habitat and Distribution

Acacia auriculiformis can grow in deep and shallow soils, sand dunes, limestone, compacted clay, very poor soil and even saline and seasonally water logged soil. This species is native to Australia and widely cultivated in the tropics. It naturally occurs in Queensland, Papua New Guinea and Indonesia. Introduced in Bangladesh and planted as an avenue tree.

2.6.1.3. Economic uses

The tree is economically important for multipurpose uses such as shade, ornamental and wood. Generally, this species is planted as a shade and avenue tree by the side of highways, railway lines, gardens and also in all over the forests of Bangladesh. Now is getting popular as a fuelwood species also. The timber is suitable for furniture due to its attractive figure and finished very well. It is recommended for checking soil erosion and as a shelter belt in the beach. The species produced nitrogen fixation root nodules and is able to survive in adverse situations. Its bark is used as a source of tannin in Malaysia.

2.6.1.4. Harmful aspects

The harmful aspect is that some people are allergic to the pollen of its flowers (Das and Alam 2001) and the branches break easily by strong wind. No threat has been found till now for this species.

2.6.2. Teak

Scientific name: *Tectona grandis* L.f.

2.6.2.1. Description

A large deciduous tree, up to 50m tall, often with fluted trunk, bark grayish brown or whitish grey, branches 4 angled with quadrangular pith, all young parts covered with brown stellate hairs. Leaves are opposite, broadly elliptic, 15-75 × 6-50cm, cuneate, margin wavy, entire, apex acute to shortly acuminate, dark green and rough above, pale beneath. Inflorescence large, terminal panicles of about 40 × 35 cm, branches distant opposite. Flowers are small, white, rarely pinkish in color and spreading. Calyx is campanulate, 3-4.5 × 3-3.5 mm. Fruit are Subglobose to tetragonally flattened drupe, 1.5 cm in diameter. Flowering and fruiting time lies in between July-November. The propagation method primarily is through stump cuttings also by seeds (Ahmed et al. 2010).

2.6.2.2. Habitat and Distribution

Tectona grandis is usually planted in hilly forest areas also in plains as planted along roadside, parks and gardens. This species is native of Myanmar and India, distributed in Thailand, widely cultivated almost in all tropical countries of Africa and Asia. In Bangladesh, it was first introduced in the Chittagong Hill Tracts in 1979 mainly to check the growth and survivability in this region as a pilot project and now planted all over the country along roadsides, road dividers, gardens and village thickets.

2.6.2.3. Economic uses

It is the most valuable timber tree in Bangladesh. The timber is much valued for all kinds of furniture, construction purposes and ship building. It has also some medicinal value. The bark is used as astringent. Roots flowers and bark are used in bronchitis. Oil extracted from seeds is used for hair growth and in the treatment of skin diseases like scabies. The conservation status of this species is least concern.

2.6.3. Chapalish

Scientific name: *Artocarpus chaplasha* Buch-Ham. *ex* Wall.

2.6.3.1. Description

Artocarpus chaplasha is a large deciduous tree, up to 30m tall with milky latex, young shoots covered with long hairs. Leaves are simple, alternate, petiolate and stipulate, juvenile leaves vary large up to 90 cm. Plant monoecious, flowers are densely crowded globose receptacles, solitary and axillary. Fruit are Syncarp, globose, tuberculate, 7-10cm across. Seeds are oblong, 1.2cm long. Flowering starts from April and within August fruits get ripens. Usually propagation is done by seeds (Ahmed et al. 2009).

2.6.3.2. Habitat and Distribution

This species is widely found in deciduous and evergreen forests of the world. It is native to India. In Bangladesh, this plant had been recorded from Tangail (Madhupur), forests of Chittagong, Cox's Bazar and Sylhet and the Chittagong Hill Tracts (Das and Alam 2001).

2.6.3.3. Economic uses

Fruits of this species are much liked by elephants. Heartwood is valuable, yellowish brown, takes good polish, mostly used for furniture, doors, windows and railway sleepers.

2.6.3.4. Threats to the species

In Bangladesh this species is being threatened for habitat destruction and over exploitation. Still now conservation status has not been evaluated but seems to be rare. So, new plantation is needed in the original forest habitats.

CHAPTER THREE: MATERIALS AND METHODS

3.1. Materials

3.1.1. Study Area

The study was conducted in and around the Satchari National Park (SNP), situated in the Paikpara Union of Chunarughat Upazila (sub district), Habiganj district, North-Eastern Bangladesh. Satchari National Park (SNP) is situated in the hilly region of the country and is one of the newest among the eighteen protected areas of Bangladesh (Mukul et al. 2006). The Satchari National Park has been established to preserve the remaining natural hill forest patch of Raghunandan Hill Reserve Forest, which was reserved in 1914 with a forest area of 6,205 hectares as per the Forest Act of 1878 and Assam Forest Manual of 1898. The park has been established in 2005 under the Wildlife Preservation Amendment Act 1974, located between longitudes 91°25´ to 91°30´, latitude 24°5´ to 24°10´. Administratively, SNP is situated in the Paikpara Union of Chunarughat Upazila in the district of Habigonj (**Figure 3.1**). The forest is under the jurisdiction of Satchari Wildlife Range under Wildlife Management & Nature Conservation Division Sylhet, Head Quarter Moulvibazar and stands on the Dhaka-Sylhet Old Highway and is about 130-140 km northeast of Dhaka, between Teliapara and Srimangal and about 60 km south west of Srimongol (IRG 2009).

The word Satchari comes from seven streams (locally called '*chara*') and refers to the streams that flow through the forest. This park has been notified as Protected Areas of Bangladesh in 2006 to protect and preserve the remaining patch of natural forests within the forest of Raghunandan Hill Reserve. The area of the park is about 242.82 ha (600 acres) which comprises the forests of Raghunandan Hills Reserve within the Satchari Range but the total area of Satchari Wildlife range is about 1760 ha (Mollah et al. 2004; NSP 2006a)

3.1.2. Boundary

Satchari National Park is bordered by Raghunandan hill reserved forest on the northwestern part and the southern boundary of the forest is bounded by Indian border line. Other adjacent areas are covered by tea estates, coffee, rubber and agar plantations and paddy fields. Fossils remain in the forest floors of the park evident of forest from millions of years ago. There is one forest village located within the park; a tribal community, the *Tripura tribe*. The other settlements that have stakes with the reserve are located about 3-8 km away from the reserve (IRG 2009).

3.1.3. Topography and Climate

The topography of the national park is undulating with slopes and hillocks, locally called *tilla*, ranging from 10-50 m and are scattered in the forest. There are number of small narrow natural canals and streams all of which dry out following the end of rainy season in October-November. Annual average rainfall of the area is 4162 mm. July is being the wettest having an average of about 1250 mm of rain, while December is the driest virtually having no or very little rainfall. May and October are the hottest months having an average maximum temperature around 32°C, while January is the coldest when the minimum temperature drops to about 12°C. The relative humidity is about 74% during December while it is over 90% during July-August (Choudhury et al. 2004; IRG 2009).

3.1.4. Bio-ecological zone

The park falls under the Bio-ecological Zone-9b with broad zone “Sylhet Hills” (Nishat et al. 2002). According to Bangladesh agro-ecological zoning, this area belongs to Region 29: Northern and Eastern Hills, sub-region 29c: Low Hills and Piedmont Plains (FAO 1988) subjected to massive flash floods. The soil texture in general is supposed to be sandy loam to silty clay and more acidic than the adjoining ecological zones (Choudhury et al. 2004).

3.1.5. Vegetation type

The forest is semi-/and mixed evergreen, where tall trees are deciduous and the under storey evergreen. The forest originally supported an indigenous vegetation cover of mixed tropical evergreen forest that once covered the Sylhet divisions and ran down to the Chittagong Hill Tracts. However, almost all of the original forest cover has been removed or substantially altered and thus has turned into a secondary forest. The large scale conversion of the indigenous forest cover to plantations has changed its forest type entity (Choudhury et al. 2004). Today, natural forests are almost entirely restricted to the Satchari National Park, while the rest of the study area is subjected to different levels of human disturbance (Choudhury et al. 2004; Mollah et al. 2004). Some of these disturbed forest areas were converted extensively into agricultural fields, orchards, human settlements, sungrass fields and plantations. Currently the forest has turned to a secondary forest because of the substantial alteration of the original forest except 200 ha of natural forest (Mukul et al. 2010; Uddin 2011).

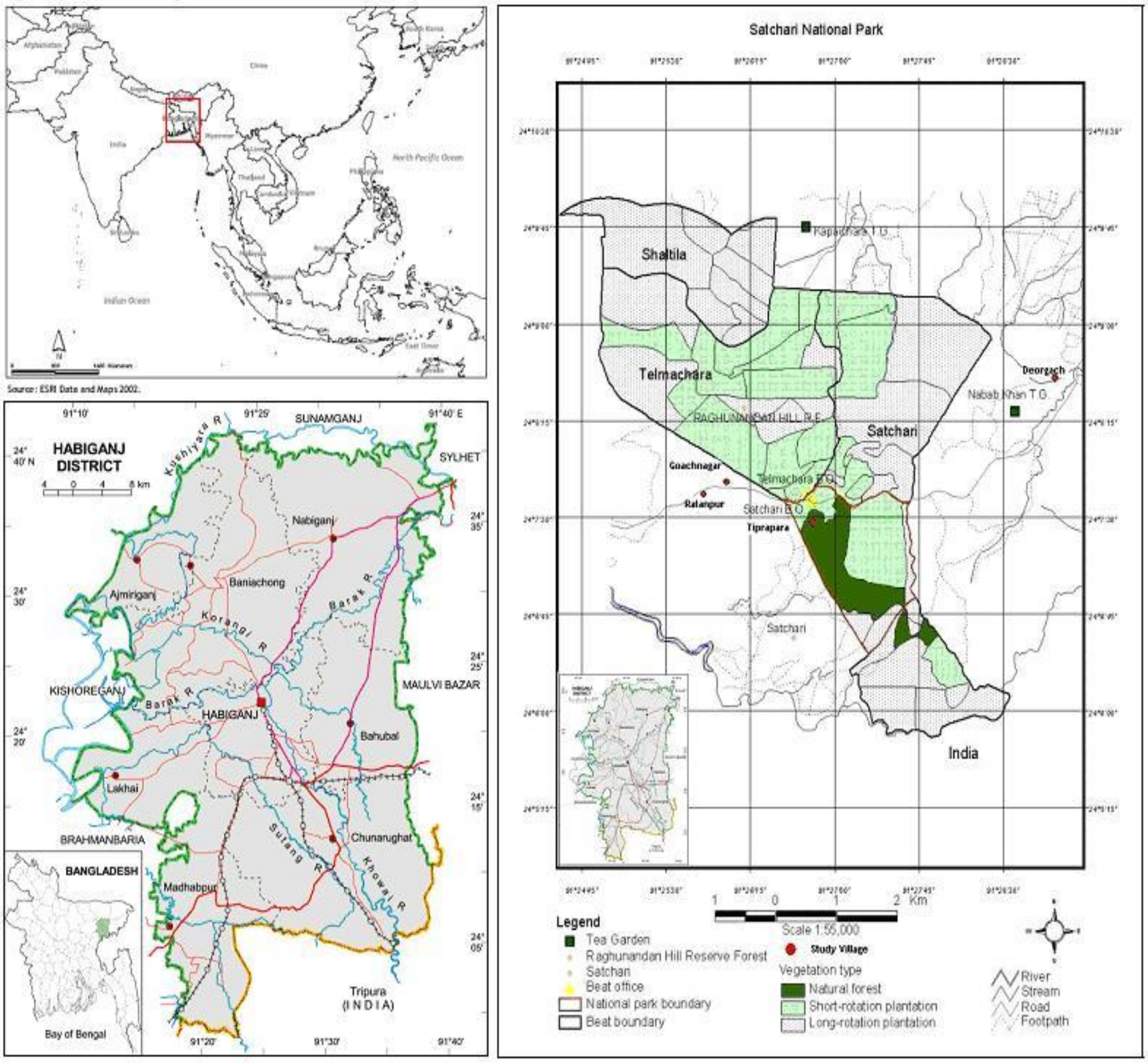


Figure 3.1. Map of the study area **Source:** (Mukul et al. 2006)

3.1.6. Biodiversity

SNP is a one of the most diversified forest in terms of both flora and fauna (about 241 species) in Bangladesh. From various sources it was found that a total of 24 mammals (including 6 species of non-human primates), 149 birds, 6 amphibians, 18 reptiles have been recorded from this forest (NSP 2006b). Hoolock Gibbon (*Hylobates hoolock*), Capped Langur, Fishing Cat, Wild Boar and Barking Deer are key mammals of this forest. Moreover, it is also one of the last habitat of Hollock Gibbons and one of rare bird species Hooded Pitta (*Pitta sordida*) in Bangladesh (Mukul 2007; Uddin 2011).

Complete survey information on the floral composition of SNP is not available till now. Formerly a study was conducted by IUCN Bangladesh and according to the report, the major timber trees are represented by Jarul (*Lagerstroemia speciosa*), Chapalish (*Artocarpus chama*), Shegun (*Tectona grandis*), Lohakath (*Xylia dolabriformis*), Kadam (*Anthocephalus chinensis*), Shimul (*Bombax ceiba*), Kanthal (*Artocarpus heterophyllus*), Champa (*Michelia champaca*), Chikrashi (*Chickrassia tabularis*), Koroi (*Albizia procera*), Garjan (*Dipterocarpus spp.*), Dewa (*Artocarpus lakoocha*), Gamar (*Gmelina arborea*), Jam (*Syzygium spp.*), Sundhi (*Michelia oblonga*), Bohera (*Terminalia belerica*) etc. Among exotic short-rotational trees, Acacia hybrid (*Acacia sp.*), Mangium (*Acacia mangium*), Malacanna (*Albizia falcataria*), Eucalyptus (*Eucalyptus camaldulensis*), Akashmoni (*Acacia auriculilormis*), are common in plantation areas. Moreover, in mid seventies an oil-palm (*Elaeis guineensis*) plantation was raised in a sizeable amount of area in this park with huge investment (Choudhury et al. 2004; Mukul 2007; Uddin 2011). But now they are considered to be one of the major threats to that park as they do not bear any commercial value nor provide foods to wild animals. There are many types of bamboo such as Jai bansh (*Bambusa burmanica*), Muli bansh (*Melocanna baccifera*) and various cane like Jali bet (*Calamus guruba*), Golla bet (*Daemonorops jenkinsianus*) in the national park. Besides, there are many types of climbers, vines, herbs and shrubs (IRG 2009).

3.1.7. Selection of the study area

Satchari National Park has been selected for this study because previously no study was conducted in this national park on carbon sequestrations of the selected species through developing allometric biomass equations by any researchers and/or governmental organization of Bangladesh. This forest is one of the most diversified forests in the country. So, this study could be a good intervention for the Bangladesh government in case of carbon trading of global climate change related issues.

3.1.8. Selection of the species

It was found from the field survey that Satchari National Park is dominated by some indigenous and exotic species like Chapalish (*Artocarpus chama*), Shegun (*Tectona grandis*), Lohakath (*Xylia dolabriformis*), Kadam (*Anthocephalus chinensis*), Kanthal (*Artocarpus heterophyllus*), Chikrashi (*Chickrassia tabularis*), Koroi (*Albizia procera*), Garjan (*Dipterocarpus spp.*), Dewa (*Artocarpus lakoocha*), Gamar (*Gmelina arborea*), Jam (*Syzygium spp.*), Bohera (*Terminalia belerica*), Acacia hybrid (*Acacia sp.*), Mangium

(*Acacia mangium*), Malacanna (*Albizia falcataria*), Eucalyptus (*Eucalyptus camaldulensis*), Akashmoni (*Acacia auriculilormis*). Among these species Chapalish (*Artocarpus chama*), Shegun (*Tectona grandis*), Acacia hybrid (*Acacia sp.*), Eucalyptus (*Eucalyptus camaldulensis*), Akashmoni (*Acacia auriculilormis*) are the most dominated species in the park. From them, Chapalish (*Artocarpus chaplasha*), Shegun (*Tectona grandis*) Akashmoni (*Acacia auriculilormis*) has been selected for this study as these are not only the dominated species in the park but also in the country as a whole.

3.2. Methods

The approach of forest data collection is through manual and field based operations. This approach is labor intensive (Couteron et al. 2001; Hansen et al. 2002) in nature hence costly in terms of the length of time spent in the field. A number of approaches have been developed to estimate the above ground biomass of forests and woodlands. These methods differ in procedure, complexity, time requirement depending on the specific aim of estimation procedure. Among them, nondestructive allometric biomass equation method has been selected for estimating the stem biomass of the selected species since felling of trees is not allowed in our country due to the existing logging ban (e.g. Sarker et al. 2011).

3.2.1. Sampling procedure

The primary objective of this study is to estimate the aboveground stem biomass of the selected species. For this account, a reconnaissance survey was carried out in order to identify the present location of the selected species, amount of plantation area or natural distribution as well as present land use pattern of the study area. Among those 10 sample plots were selected through the arbitrary random sampling method in different parts of the study area. However, many well established forest inventory programs, such as the United States Forest Inventory and Analysis (FIA) program, use clustered sample units, commonly referred to as subplots (Daniel et al. 2009). Clustered plot designs tend to capture more micro site variation in vegetation, soil etc. thereby reducing among plot variation (increasing overall precision). For the aboveground stem biomass of selected species in SNP, a clustered plot composed of five circular subplots with a radius of 15 m was arranged as in following figure 3.2 has been adopted thus taking advantage of the increased precision of clustered sampling. In this way, data was collected from 50 sample plots. The geographic position point of each plot was recorded from the centre of the field and all trees have been identified by local name and dendrometric data of the selected species were recorded in the field.

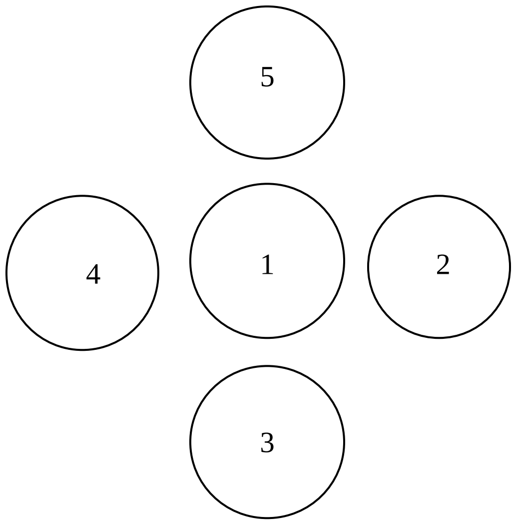


Figure 3.2. Schematic of plot layout. Each plot is 15m in radius

3.2.2. Field measurement

In order to estimate the above ground stem biomass, diameter at breast height, height and wood density was calculated. These three variables are very important to estimate biomass of the trees and measurement procedures are as follows:

3.2.2.1. Diameter at Breast Height (DBH)

DBH is a standard dendrometric measurement used to determine the diameter of a tree and to estimate tree volume and biomass, they give a high level of consistency, are easy to measure and in irregular forests with different species and tree ages an histogram showing the number of trees in different diameter classes is a useful way of characterizing the structure of the forest (Philip 1994). Within every plot all the trees except diseased, dead, dying with DBH more than 10 cm were measured and in this way DBH of 100 individual trees for all the three selected species was measured. Trees with less than DBH 10 cm have been ignored as the biomass amount is negligible. The measurements were done using diameter tape, and the breast height was considered to be at 1.3 m from the soil level on the highest side of the tree (Philip 1994; MacDicken 1997). On trees forking below 1.3 m from the ground level, each stem was measured and recorded separately. However for trees with buttress roots, diameter was measured above the buttress roots when possible in order to have a more representative diameter for the entire tree trunk.

3.2.2.2. Stem Height

The accuracy of height measurement is important since it is one of the tree variables used to estimate tree stem biomass. During field survey bole height of the trees has been considered as the stem height and it is defined as the distance between ground level to Crown Point of the clear main stem of a tree. Crown point is the position of the first crown forming living or dead branches. Stem height was measured with the help of Sunntu Clinometer and the slope of the ground was also measured by using Sunntu Clinometer. Following formula has been used to calculate the stem height:

$$\text{Height} = \frac{\text{Top height (\%)- Bottom height (\%)}}{100} \times \text{Distance}$$

3.2.2.3. Wood density

In order to measure wood density wood samples from 100 sample trees of each species were collected with the tree increment borer (2.1 mm radius). These samples were kept in air tight packet in order to prevent moisture loss and brought to laboratory for laboratory analysis. Fresh weight and oven dried weight of the wood samples was measured with the electronic precision balance. Green volume of collected wood samples was computed by water displacement method and then the samples were oven dried for 24 hours at 105°C. After drying in oven, wood densities were computed as a ratio of oven dry weight to green volume of all samples of selected species.

3.2.2.4. Form factor

Trees are not uniform in shape to its whole length. With the increasing height, diameter of an individual tree is reduced. As a result trees form factors are calculated in order to estimate the actual volume of trees. In order to calculate the form factor at first cylindrical volume of tree stems was computed by equation 1 and then boles has been divided into segments of 3 meter ocularly and the diameter of the segments has been measured by Spiegel Relaskop. After that volume of each segment of all individual trees were computed by the equation 2. Actual volume of an individual stem was calculated by summing up the volume of each segment (Eq. 3).

The ratio between stem actual volume (v) to cylindrical volume (V) gave the form factor for the tree stem.

$$V = \pi r^2 H \text{……………………..} \quad (1)$$

$$\nu = 3.1416 \times r^2 \times 3 \text{ m……………………..} \quad (2)$$

$$\nu = \nu_1 + \nu_2 + \text{…………} + \nu_n \text{ ………………….} \quad (3)$$

Where,

V = Cylindrical volume of an individual, ν = Actual volume, r = D/2, h = height in 3 m, H = Total stem height (m).

3.2.3. Above ground stem biomass estimation

A simple geometrical argument suggests that the total aboveground biomass (AGB, in kg) of a tree with diameter D should be proportional to the product of wood specific gravity (ρ, oven-dry wood over green volume), times trunk basal area ($BA=\pi D^2/4$), times total tree height (H). Hence, the following (King et al. 2006) relationship should hold across forests. This allometric equation also includes all three parameters: DBH, height and species specific wood density.

$$M_S = ff \times \rho \times (D^2/4) \times H$$

Where,

M_S = stem biomass, ff = form factor, ρ = wood density, D = diameter, H = height.

3.2.4. Regression models

One of the main objectives of this study is to develop allometric model for above ground stem biomass of the selected species. For these following eighteen allometric models were developed for the above ground stem biomass of selected species. To evaluate the regression models defined on the measured variables dry weight (W), diameter at breast height (DBH), tree height (h) and wood density (d), three considerations are important for the 1) statistical correctness of the regression; 2) the accuracy of the obtained estimates has to be evaluated; 3) the model must be of practical use (Draper and Smith 1981). The model having the highest coefficient of determination (R^2) value had been selected as the best fitted based on a penalized likelihood criterion (Burnham and Anderson 2002; Johnson and Omland 2004).

Table 3.1. Regression models for aboveground biomass estimation of selected species of Satchari national park

No.	Model
1	$Y = \alpha + \beta$ DBH
2	$Y= \alpha + \beta$ (DBH^2.H)
3	$Y= \alpha + \beta$ DBH + β_1DBH^2
4	$Y= \alpha + \beta$ DBH + β1H
5	$Y= \alpha + \beta$ DBH + β1H + $\beta_2\rho$
6	$Y= \alpha + \beta$ (DBH x H)^2 + $\beta_1\rho$
7	$Y= \alpha + \beta$ (DBH^2.H. ρ)
8	Ln $Y= \alpha$ + blnDBH + $\beta_1$lnρ
9	Ln $Y= \alpha + \beta$ lnDBH
10	Ln $Y= \alpha + \beta$ lnDBH^2 + $\beta_1$lnρ
11	Ln $Y= \alpha + \beta$ lnH
12	Ln $Y= \alpha + \beta$ lnDBH + β1lnDBH.H
13	Ln $Y= \alpha + \beta$ lnDBH + $\beta_1$lnDBH.H + $\beta_2$lnρ
14	Ln $Y= \alpha + \beta$ lnDBH^2 + $\beta_1$lnH^2
15	Ln $Y= \alpha + \beta$ ln(DBH^2.H. ρ)
16	$Y = (\alpha$ DBH$^2)^{\beta}$
17	Ln $Y = \alpha + \beta$ ln (DBH^2 x ρ)
18	LnY $= \alpha + \beta$ ln (DBH^2 x H)

The Akaike information criterion (AIC) is based on the number of parameters.

$$AIC= -2 \ln (L) +2 p.$$

In this formula, L is the likelihood of the fitted model; p is the total number of parameters in the model. The best statistical model minimizes the value of AIC. As an alternative statistic, residual standard error (RSE) was also reported. Various statistics for evaluating goodness-of-fit have also been advocated in the literature (Parresol 1999), but AIC and RSE reported together provide sufficient information on the quality of a statistical fit for a mixed-species regression model. Moreover, plots of predicted biomass versus residual biomass and plots of predicted biomass versus estimated biomass have also been developed to check the accuracy of the best fitted model. All statistical analyses were carried out with the R software package (http://www.r-project.org/).

CHAPTER FOUR: RESULTS

4.1. Aboveground stem biomass of studied species

Data was collected from 101 individuals of each studied species. Table 4.1 summarized the mean DBH, H and WD of the studied species. Among them except the mean height all the size ranges of *A. chaplasha* trees was much larger than the other two species. The highest mean DBH was found for *A. chaplasha* (0.52 ± 0.22 m) followed by *T. grandis* (0.36 ± 0.10 m) and *A. auriculiformis* (0.30 ± 0.09 m). Moreover, *A. chaplasha* had also the highest mean basal area (0.562 ± 0.181 m^2/ha) followed by *T. grandis* (0.242 ± 0.07 m^2/ha) and *A. auriculiformis* (0.237 ± 0.05 m^2/ha). However, highest mean height was found for *T. grandis* (11.20 ± 4.00) followed by *A. auriculiformis* (10.26 ± 2.76) and *A. chaplasha* (9.71 ± 2.87). Wood density (WD) was found to vary largely within species and the highest mean WD was found in *A. auriculiformis* (607.55 ± 116.03) (kg/m^3) and lowest in *A. chaplasha* (403.69 ± 104.05) (kg/m^3). In case of total above ground biomass highest amount of biomass was found in *A. chaplasha* (174.9 Mg/ha) followed by *A. auriculiformis* (97.67 Mg/ha) and *T. grandis* (97.29 Mg/ha).

Table 4.1. Mean DBH, height, wood density, basal area, biomass and organic carbon content in the stem of the studied species in SNP

Species	Mean DBH(m) ± SD*	Mean height(m) ± SD	Mean WD ± SD (kg/m³)	Mean basal area (m²/ha)	Biomass (Mg*/ha)
Atocarpus chaplasha	0.52 ± 0.22	9.71 ± 2.87	403.69 ± 104.05	0.562 ± 0.18	174.9
Tectona grandis	0.36 ± 0.10	11.20 ± 4.00	517.81 ± 114.25	0.242 ± 0.07	97.29
Acacia auriculiformis	0.30 ± 0.09	10.26 ± 2.76	607.55 ± 116.03	0.237 ± 0.05	97.67

*SD means Standard deviation, Mg means megagrams

All species specific regression models relating biomass with measured tree dimensions were highly significant ($p<0.001$). The coefficient of determination (R^2) was used to evaluate the amount of variation explained by a regression and is often used to select the best regression model. In addition to AIC, RSE and F statistics had been used to determine the best predictive model. Eighteen models had been used to evaluate the variation in statistical regression equation and the model that satisfied lower AIC and RSE and higher F value had been considered as the best- fitted five regression models for above ground stem biomass estimation of selected species of Satchari National Park (SNP).

4.1.1. *Artocarpus chaplasha*

4.1.1.1 Allometric models for above ground stem biomass estimation

All models except model 11 allow reasonably good estimates of the biomass production of the studied species from their dendrometric measurements (Table no.4.2). The parameters of the best fit models developed for estimating aboveground stem biomass as a function of DBH, Height (H) and wood density (ρ) were statistically significant ($p<0.001$). The best fitted model based on combinations of DBH, Height(H) and wood density (ρ) model 15 and 13 (Table 4.2) presented the highest R^2 values (0.99 and 0.98 respectively) and the lowest AIC and RSE value and higher F value (-427.616, 0.029, 240880 and -44.09, 0.189, 1804.47 respectively). Three other best predicted models were model 14 with a R^2 value 0.97, AIC value 4.21, RSE=0.230 and F value1790 followed by model 18 (R^2=0.97, AIC= -3.08, RSE=0.234, F=3502.70) and non linear (power) model 16 (R^2=0.89, AIC= -38.82, RSE=0.451, F=868.76) (Table 4.2).

The best fitted model no. 15 represented a strong relationship between natural logarithm of biomass and combinations of natural logarithm of DBH^2, H and wood density. Linear trend line showed that tree dendrometric values were strongly correlated with biomass (Figure 4.1 o). Moreover, model 13 also represented the better relationship between the studied variables (Figure 4.1 n). The entire scaling parameters (regressions co-efficient) were statistically significant at $p<0.001$. However, the lowest R^2 value (R^2=0.16) was found for model 11 that represented the correlation between natural logarithm of biomass and logarithm of tree height (Figure 4.1 k). The best predicted model had also been tested by estimated versus predicted biomass plot for all the allometric models (Annex 1).

Table 4.2. Regression model for estimation of aboveground stem biomass of *Artocarpus chaplasha*

No.	Model	Intercept	β	β_1	β_2	R^2	RSE	F***	AIC
1.	$Y = \alpha + bDBH$	-667.104	2765.7***	-	-	0.62	485.797	160.32	1540.13
2.	$Y= \alpha + \beta\ (DBH^2.H)$	-97.56	266.407***	-	-	0.89	253.186	855.72	1408.49
3.	$Y= \alpha + \beta\ DBH + \beta_1 DBH^2$	151.143	-1316.56***	4082.59	-	0.71	424.961	120.44	1514.08
4.	$Y= \alpha + \beta\ DBH + \beta_1 H$	-1522.92	2463.298***	104.462***	-	0.76	389.223	152.99	1496.39
5.	$Y= \alpha + \beta\ DBH + \beta_1 H + \beta_2 \rho$	-2026.34	2191.997***	88.704***	1.977***	0.82	341.365	142.73	1470.80
6.	$Y= \alpha + \beta\ (DBH \times H)^2 + \beta_1 \rho$	-568.127	17.798***	1.744***	-	0.93	198.628	726.61	1360.45
7.	$Y= \alpha + \beta\ (DBH^2.H.\ \rho)$	-5.27395	0.546129***	-		0.99	23.444	111250.5	927.84
8.	$Ln\ Y= \alpha + b lnDBH + \beta_1 ln\rho$	-0.46668	1.98336***	1.34679***	-	0.94	0.323	867.26	66.14
9.	$Ln\ Y= \alpha + \beta\ lnDBH$	7.76051	2.2237***	-	-	0.89	0.451	868.76	129.64
10.	$Ln\ Y= \alpha + \beta\ lnDBH^2 + \beta_1 ln\rho$	-0.46668	0.99168***	1.34679***	-	0.94	0.328	867.26	66.14
11.	$Ln\ Y= \alpha + \beta\ lnH$	2.0731	1.7738***	-	-	0.16	1.285	20.13	341.22
12.	$Ln\ Y= \alpha + \beta\ lnDBH + \beta_1 lnDBH.H$	7.74703	3.41084***	-0.12872***	-	0.95	0.313	952.86	57.12
13.	$Ln\ Y= \alpha + \beta\ lnDBH + \beta_1 lnDBH.H + \beta_2 ln\rho$	1.014996	3.021674***	-0.10785***	1.10239***	0.98	0.189	1804.47	-44.09
14.	$Ln\ Y= \alpha + \beta\ lnDBH^2 + \beta_1 lnH^2$	5.01663	1.06398***	0.5999***	-	0.97	0.23	1790	-4.22
15.	$Ln\ Y= \alpha + \beta\ ln(DBH^2.H.\ \rho)$	-0.53361	0.988759***	-	-	0.99	0.029	240880	-427.62
16.	$Y = (\alpha\ DBH^2)^{\beta}$	2346.112	1.11185***	-	-	0.89	0.451	868.76	-38.82
17.	$Ln\ Y = \alpha + \beta\ ln\ (DBH^2 \times \rho)$	1.48141	1.03065***	-	-	0.94	0.334	1660.93	69.25
18.	$LnY = \alpha + \beta\ ln\ (DBH^2 \times H)$	5.30995	1.07738***	-	-	0.97	0.234	3502.70	-3.08

DBH is diameter at breast height (1.37m), H is height (m), ρ is wood density (kg/m^3),
Parameters α, β, β_1, β_2 are the models' regression coefficient, residual standard error (RSE), co-efficient of determination (R^2), and Akaike Information Criterion (AIC).
***$p< 0.001$, ** $p<0.01$, *$p< 0.05$.

Figure 4.1. Relationship between independent variables (DBH, H, ρ) and aboveground stem biomass

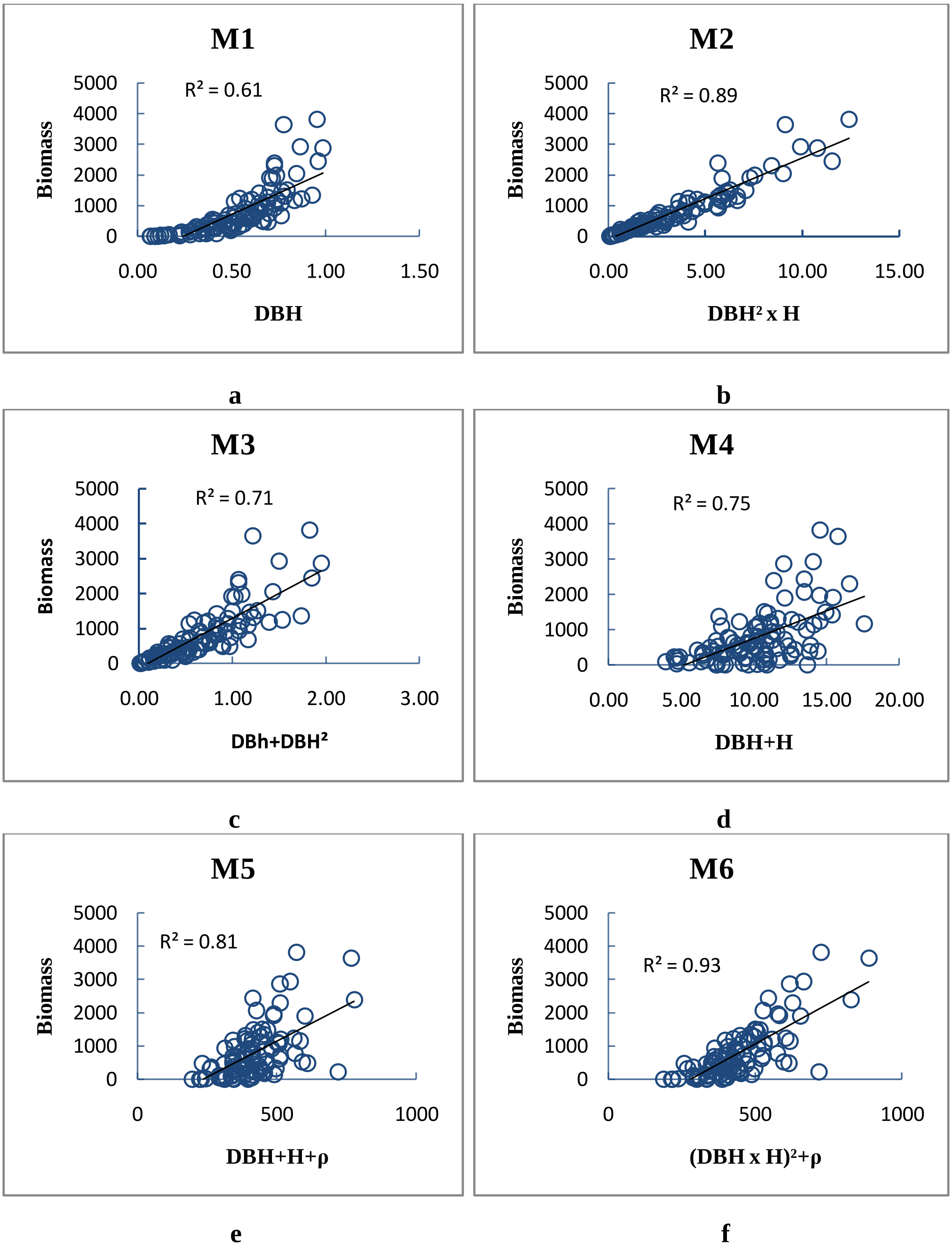


Figure 4.1: **(a)** Relation between DBH and above ground stem biomass. **(b)** Relation between DBH^2 x H and above ground stem biomass (c) Relation between DBH + DBH^2 and above ground stem biomass **(d)** Relation between DBH + H and above ground stem biomass (e) Relation between DBH + H + ρ and above ground stem biomass **(f)** Relation between $(DBH + H)^2$ and above ground stem biomass

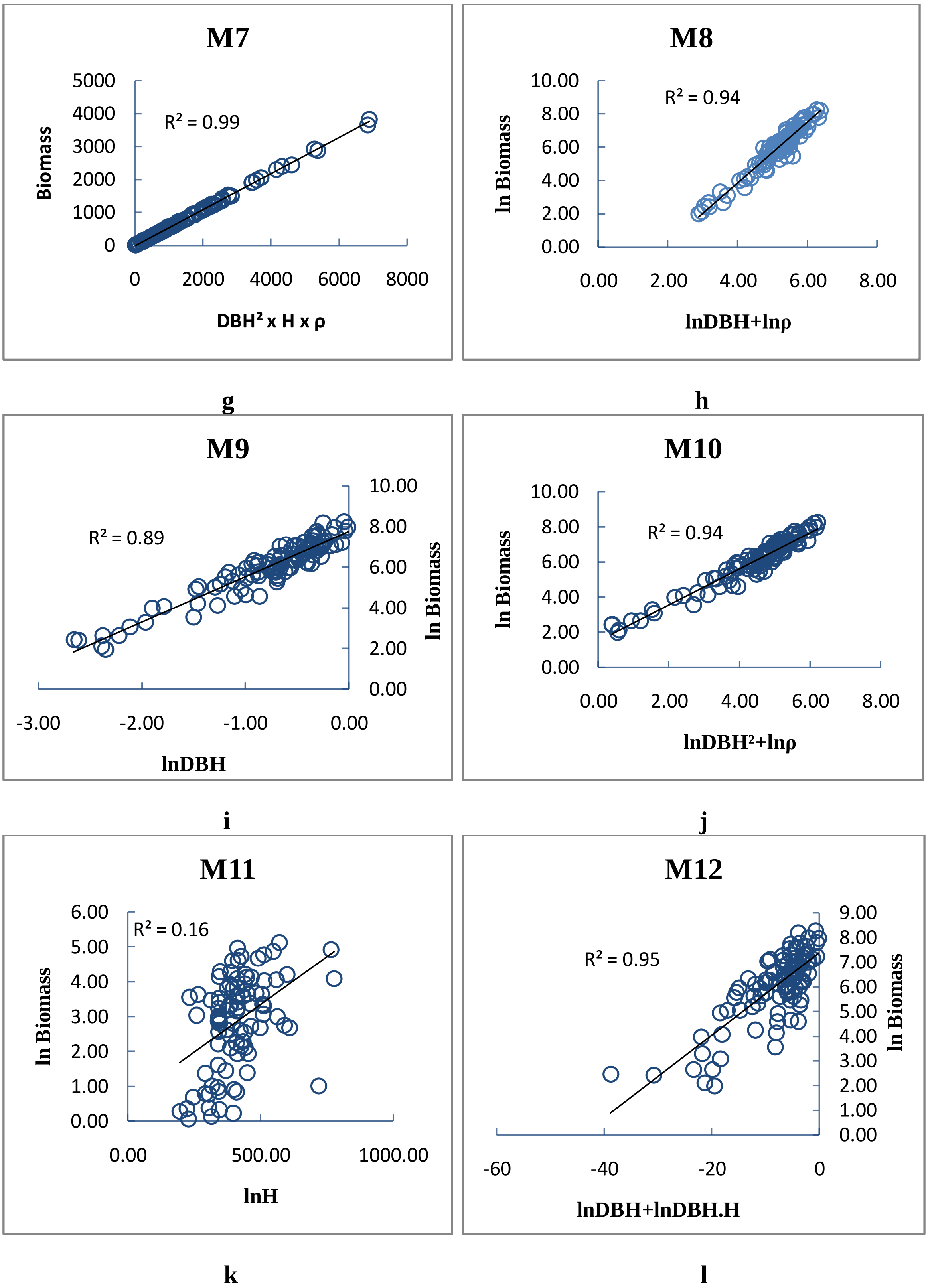


Figure 4.1. (g) Relation between **DBH² x H x ρ** and above ground stem biomass **(h)** Relation between lnDBH x lnρ and ln biomass **(i)** Relation between lnDBH and ln biomass **(j)** Relation between lnDBH^2 + lnρ and ln biomass **(k)** Relation between lnH and ln biomass **(l)** Relation between lnDBH² + lnDBH x H and ln biomass

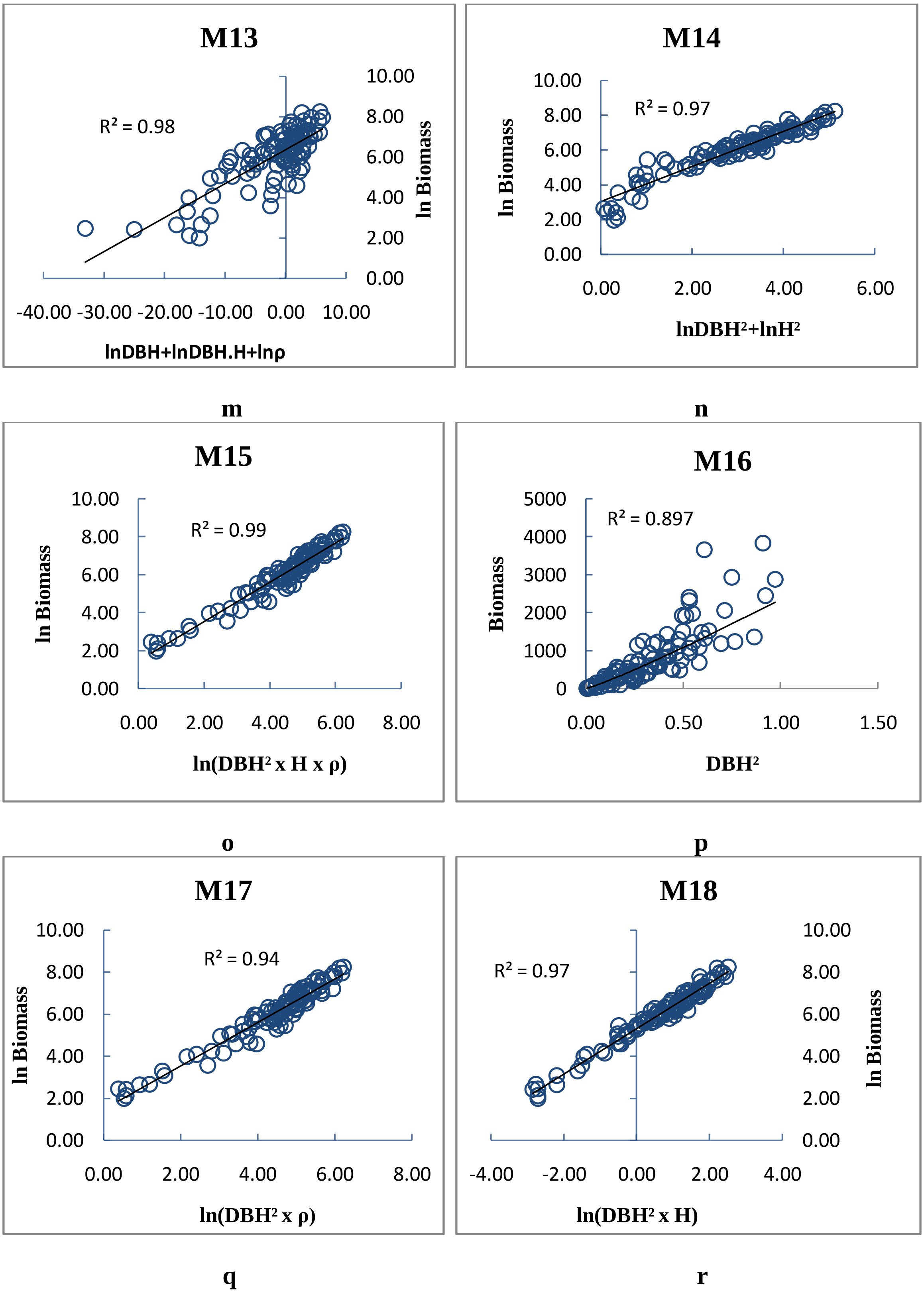


Figure 4.1. (m) Relation between lnDBH + lnDBH.H + lnρ and ln biomass. **(n)** Relation between $\ln DBH^2$ x $\ln H^2$ and ln biomass **(o)** Relation between ln(DBH^2 x H x ρ) and ln biomass **(p)** Relation between DBH^2 and above ground stem biomass **(q)** Relation between ln(DBH^2 x ρ) and ln biomass **(r)** Relation between ln(DBH^2 x H) and ln biomass

4.1.1.2. Predicted biomass versus residual biomass plot

The predicted biomass versus residual was plotted to check the accuracy of the best fitted model of *A. chaplasha*. The results showed that residual error remained constant with the increase of predicted biomass only for linear model 15 (Figure 4.2 o) and this model maintains strong non-colinearity than the other models. That is why this model could be the best fitted model for biomass estimation of *A. chaplasha* at SNP.

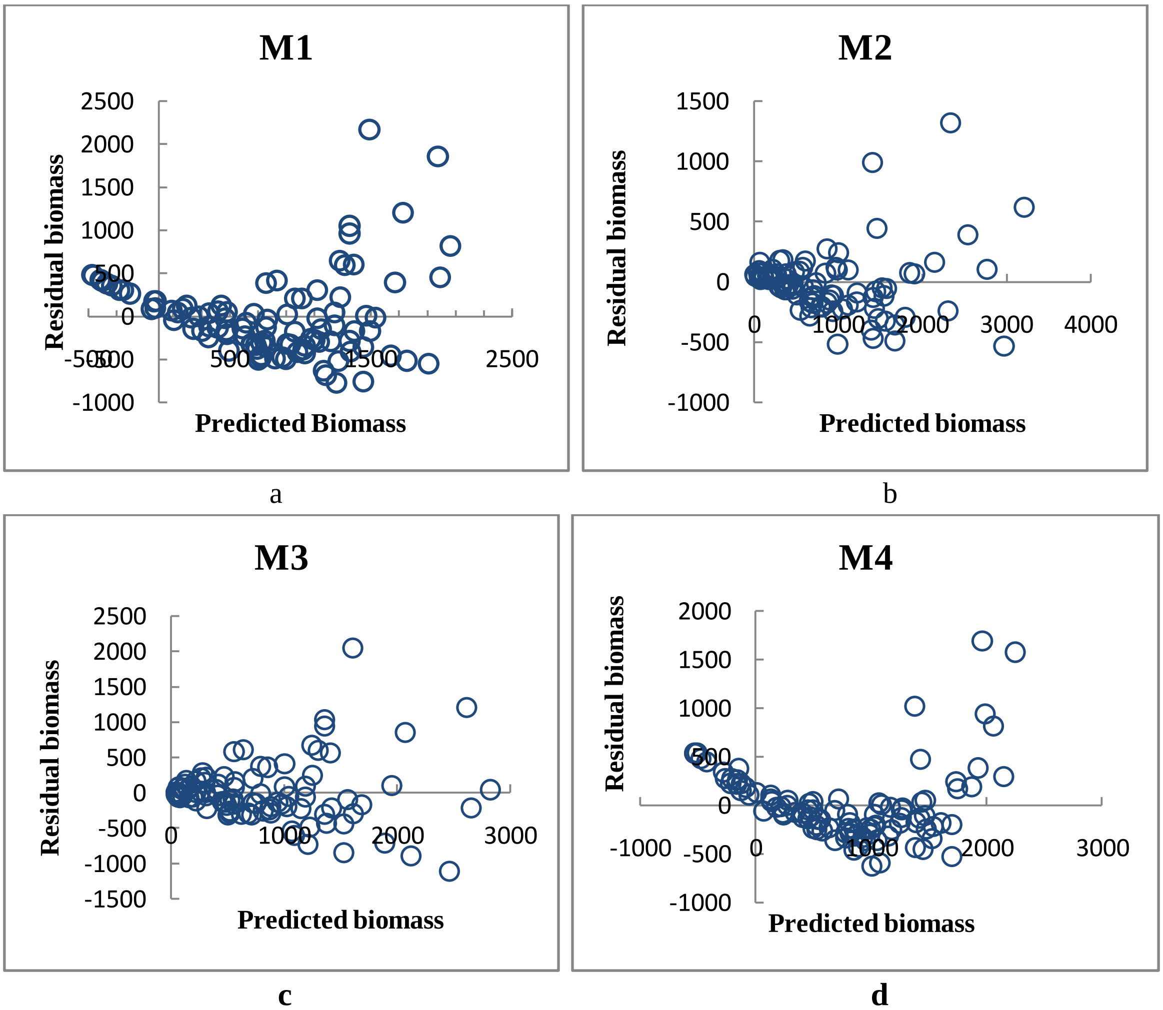
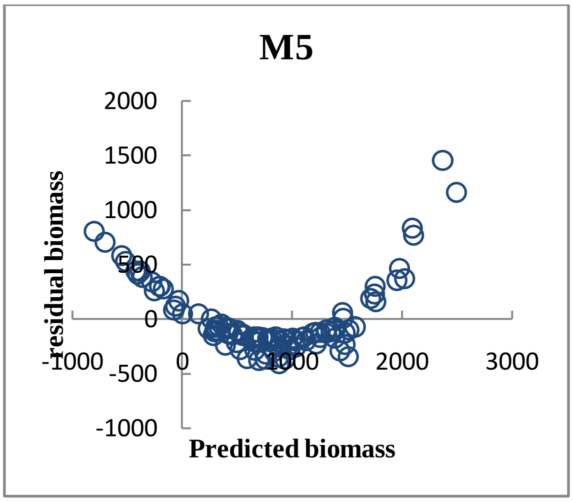
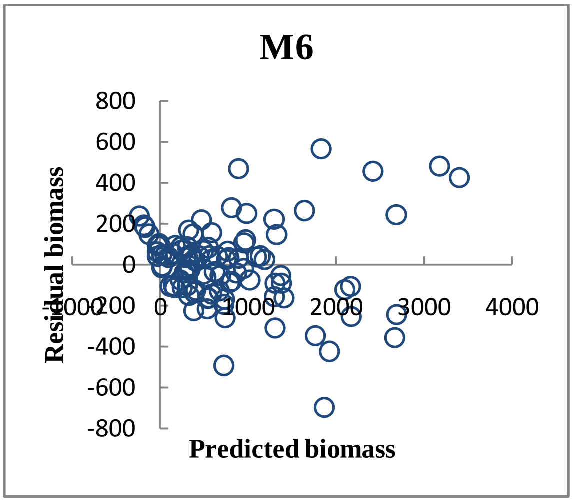


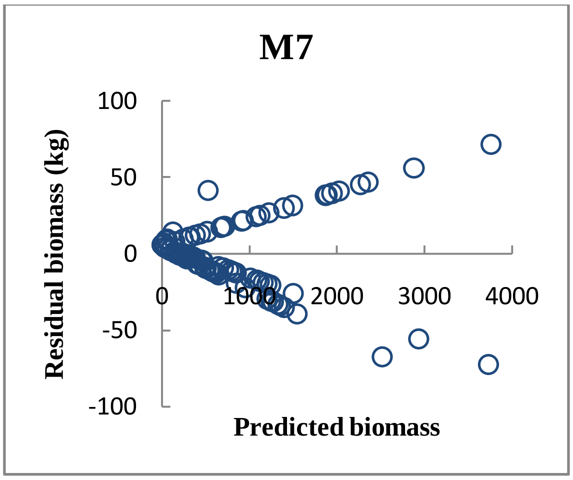
Figure 4.2. Relationship between predicted and residual biomass (a), (b), (c), (d)

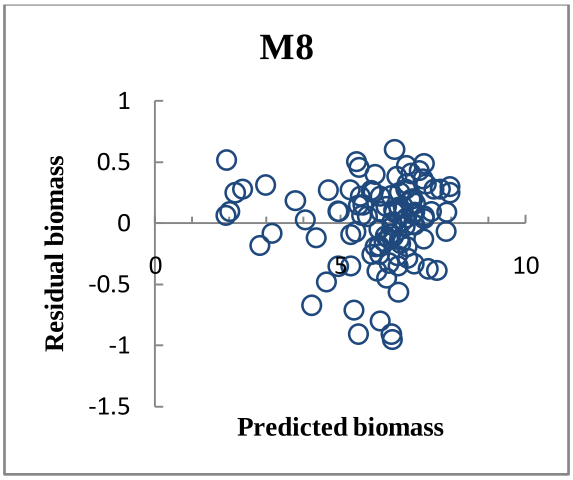




e

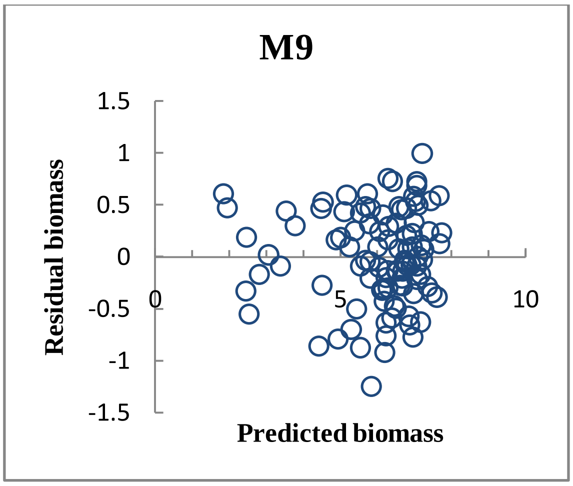
f

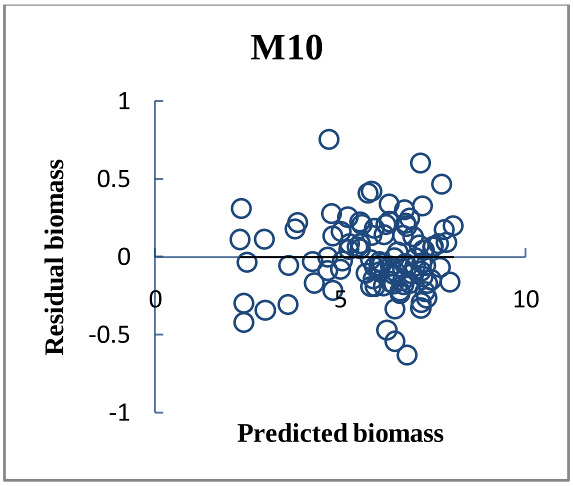




g

h





i

j

Figure 4.2. Relationship between predicted and residual biomass (e), (f), (g)

Relationship between ln predicted and residual biomass (h), (i), (j)

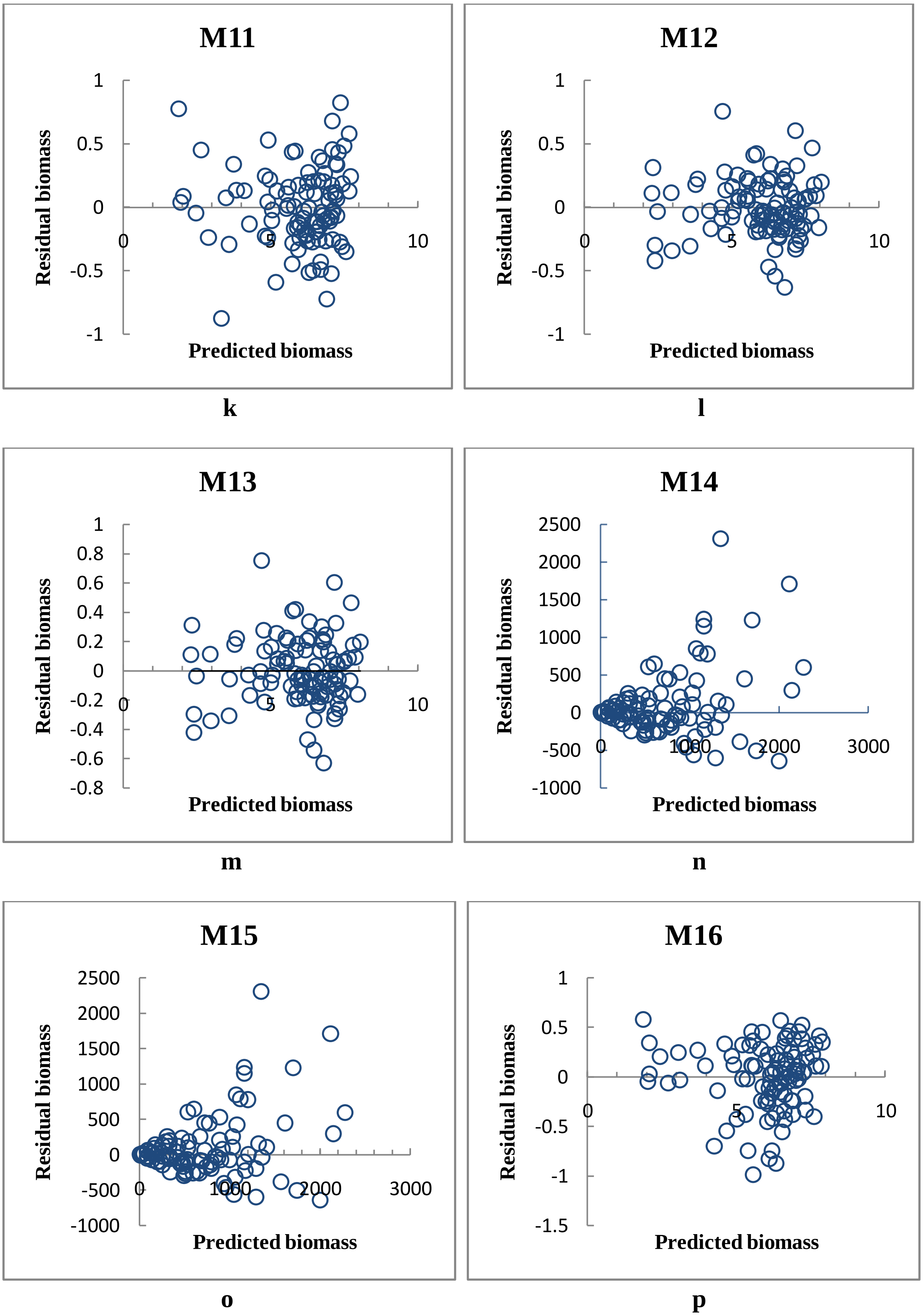
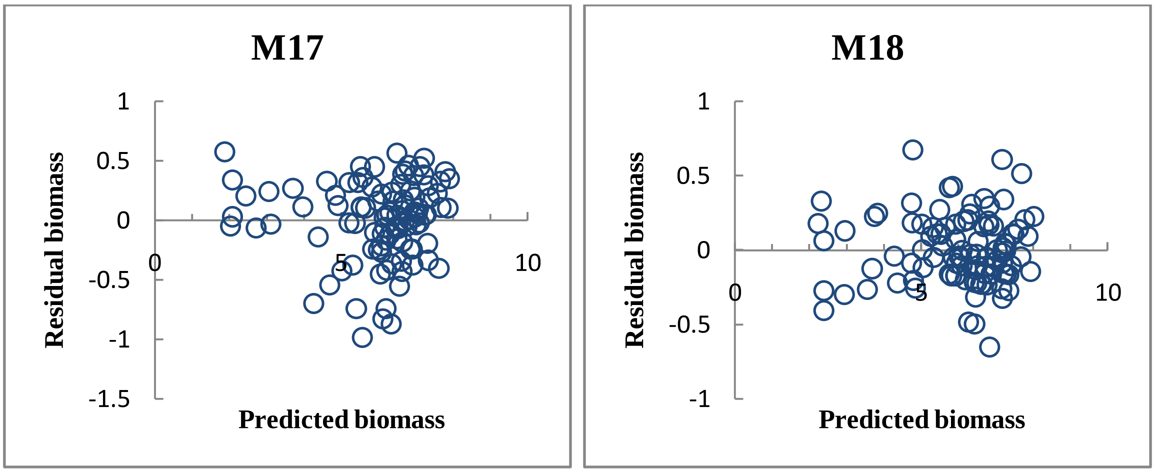


Figure 4.2. Relationship between ln predicted and residual biomass (k), (l), (m)
Relationship between ln predicted and residual biomass (n), (o)
Relationship between predicted and residual biomass (p)



q r

Figure 4.2. Relationship between ln predicted and residual biomass (q), (r)

4.2.2. *Tectona grandis*

4.2.2.1. Allometric models for above ground stem biomass estimation

The coefficient of determination (R^2) of the allometric equations of *T. grandis* ranged from 0.34 to 0.94. The highest R^2 value (0.94) was found from linear regression model 15 (AIC= -76.89, RSE= 0.162, F=1761). This model had been considered as the best- fitted regression model followed by model 13 (R^2= 0.93, AIC= -52.91, RSE=0.181, F=466.1), model 14 (R^2=0.84, AIC= 31.89, RSE=0.276, F=270.8), model 18 (R^2=0.84, AIC= -33.32, RSE=0.279, F=525.6) and non-linear model 16 (R^2=0.70, AIC= -72.28, RSE=0.166, F=236.2) (Table 4.3) to accurately estimate the above ground stem biomass of *T. grandis* of Satchari National Park (SNP).

The best fitted model 15 represented the positive relationship and higher coefficient of determination (R^2) between natural logarithm of DBH, Height and wood density and natural logarithm of above ground stem biomass $\ln(DBH^2.H.\rho)$ (Figure 4.3 o). Although R^2 value was not good for non-linear (power) model 20 (R^2=0.70) but it had been considered as the second best fitted model because of its lower AIC value (Table 4.4) and the positive relationship between Biomass and DBH^2 (Figure 4.3 p). Model 13 (Figure 4.3 m) did not represent good relationship between natural logarithm of tree dimensions $\ln DBH+\ln(DBH).H+\ln\rho$ and natural logarithm of stem biomass. Model 14 and model 18 demonstrated the positive relationship between logarithm of biomass and natural logarithm of DBH^2 and H^2 ($\ln DBH^2+\ln H^2$) and logarithm of DBH^2 multiplied by height $\ln(DBH^2.H)$ accordingly (Figure 4.3 n and r). The regression models had also been assessed by plotting estimated biomass versus predicted biomass for all allometric equation of *T. grandis* and the plots estimated versus predicted biomass are shown in Annex 2.

Table 4.3. Regression model for estimation of aboveground stem biomass of *Tectona grandis*

No.	Model	Intercept	β	β_1	β_2	R^2	RSE	F***	AIC
1.	$Y = \alpha + bDBH$	-509.1	2638.1***	-	-	0.63	209.3	169.6	1370.01
2.	$Y= \alpha + \beta (DBH^2.H)$	74.32	221.29***	-	-	0.75	169.4	310.8	1327.36
3.	$Y= \alpha + \beta DBH + \beta_1 DBH^2$	-136.4	683	2357.7	-	0.64	206.7	88.71	1368.47
4.	$Y= \alpha + \beta DBH + \beta_1 H$	-695.05	2411.298***	23.838***	-	0.70	188.5	116.6	1349.87
5.	$Y= \alpha + \beta DBH + \beta_1 H + \beta_2 \rho$	-1176.05	2344.642***	26.6905***	0.9132***	0.79	157.5	125.7	1314.59
6.	$Y= \alpha + \beta (DBH \times H)^2 + \beta_1 \rho$	-331.096	10.0705***	1.0566***	-	0.68	194	107.2	1355.72
7.	$Y= \alpha + \beta (DBH^2.H.\ \rho)$	51.27036	0.45657***	-	-	0.93	87.37	1442	1193.57
8.	$\ln Y= \alpha + b\ln DBH + \beta_1 \ln\rho$	2.0215	2.1067***	0.9735***	-	0.78	0.325	182	64.73
9.	$\ln Y= \alpha + \beta \ln DBH$	8.1226	2.1428***	-	-	0.70	0.382	236.2	96.19
10.	$\ln Y= \alpha + \beta \ln DBH^2 + \beta_1 \ln\rho$	2.02149	1.05334***	0.9735***	-	0.78	0.325	182	64.73
11.	$\ln Y= \alpha + \beta \ln H$	3.2089	1.1167***	-	-	0.34	0.571	51.04	177.37
12.	$\ln Y= \alpha + \beta \ln DBH + \beta_1 \ln DBH.H$	7.875462	2.563565***	-0.05967***	-	0.82	0.295	232.7	44.72
13.	$\ln Y= \alpha + \beta \ln DBH + \beta_1 \ln DBH.H + \beta_2 \ln\rho$	0.820423	2.567546***	-0.06613***	0.004***	0.93	0.181	466.1	-52.91
14.	$\ln Y= \alpha + \beta \ln DBH^2 + \beta_1 \ln H^2$	6.08537	0.94116***	0.37396***	-	0.84	0.2765	270.8	31.89
15.	$\ln Y= \alpha + \beta \ln(DBH^2.H.\ \rho)$	0.07908	0.89315***	-	-	0.94	0.162	1761	-76.89
16.	$Y = (\alpha\ DBH^2)^{\beta}$	3369.936	1.0714***	-	-	0.70	0.166	236.2	-72.28
17.	$\ln Y = \alpha + \beta \ln (DBH^2 \times \rho)$	1.56917	1.04238***	-	-	0.78	0.324	366.8	62.96
18.	$\ln Y = \alpha + \beta \ln (DBH^2 \times H)$	5.64533	0.87448***	-	-	0.84	0.2798	525.6	-33.32

DBH is diameter at breast height (1.37m), H is height (m), ρ is wood density (kg/m^3)

Parameters α, β, β_1, β_2 are the models' regression coefficient, residual standard error (RSE), co-efficient of determination (R^2) and Akaike Information Criterion (AIC).

***p< 0.001, ** p<0.01, *p< 0.05.

Figure 4.3. Relationship between independent variables (DBH, H, ρ) and aboveground stem biomass

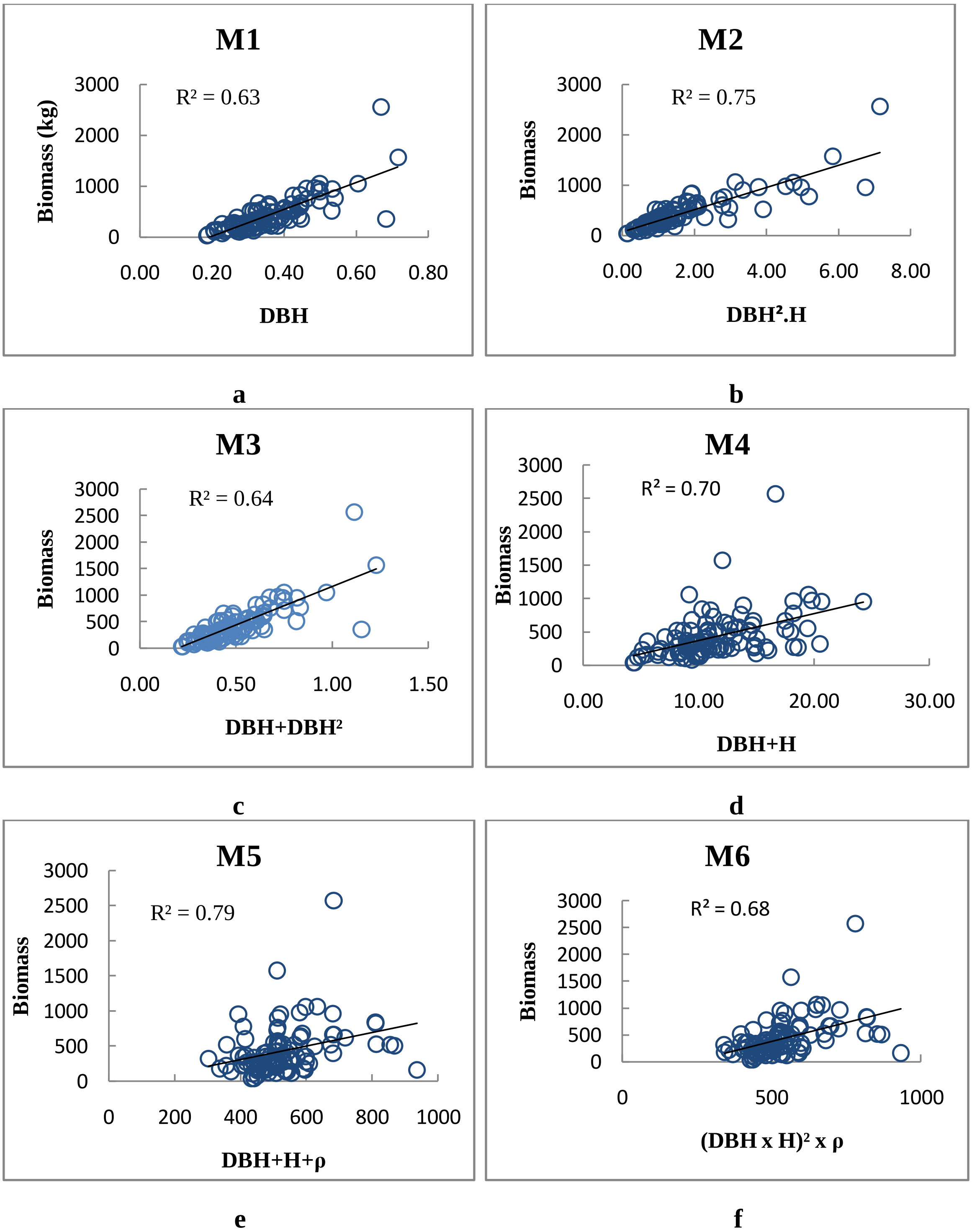
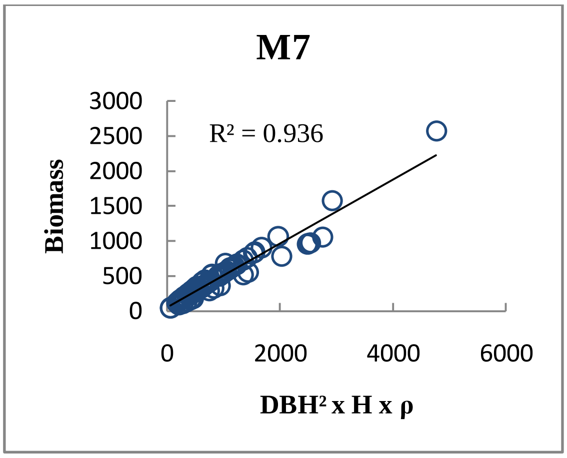
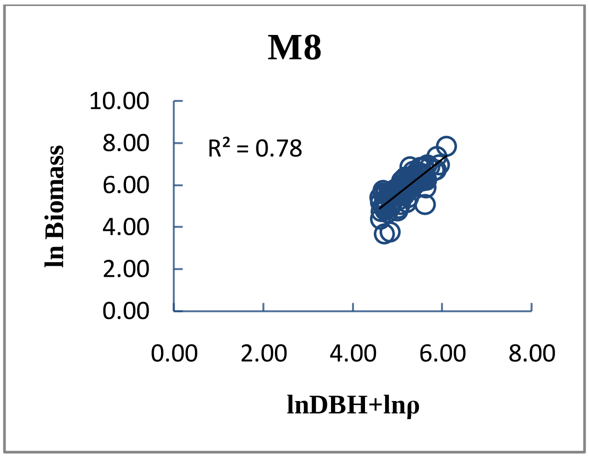
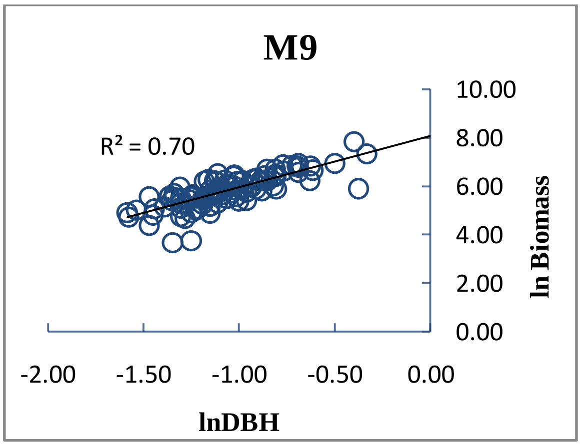


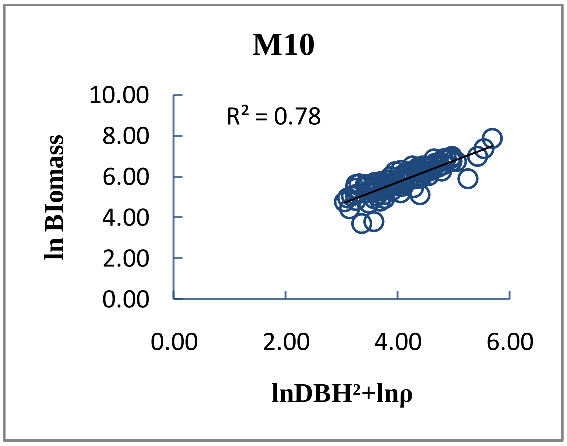
Figure 4.3. (a) Relation between DBH and above ground stem biomass. **(b)** Relation between DBH^2 x H and above ground stem biomass (c) Relation between DBH + DBH^2 and above ground stem biomass **(d)** Relation between DBH + H and above ground stem biomass (e) Relation between DBH + H + ρ and above ground stem biomass **(f)** Relation between $(DBH + H)^2$ and above ground stem biomass.



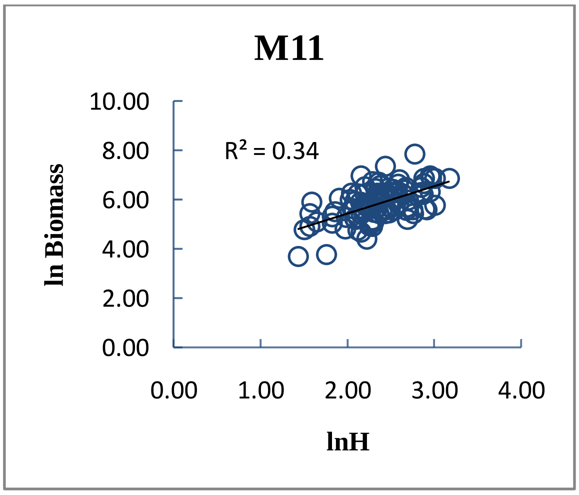


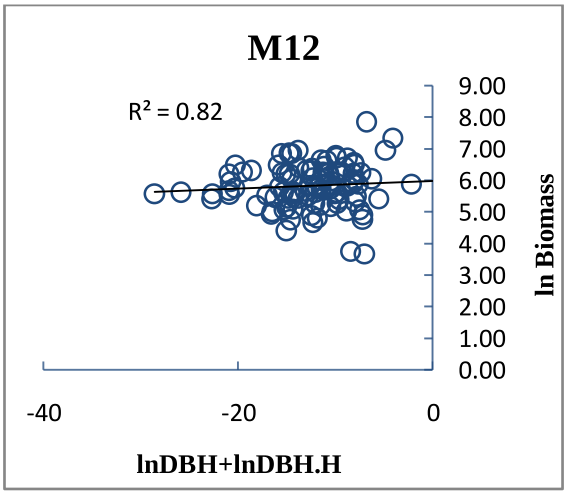
g h





i **j**





k **l**

Figure 4.3. (g) Relation between **DBH^2 x H x ρ** and above ground stem biomass **(h)** Relation between lnDBH x lnρ and ln biomass **(i)** Relation between lnDBH and ln biomass **(j)** Relation between $\ln DBH^2$ + lnρ and ln biomass **(k)** Relation between lnH and ln biomass **(l)** Relation between $\ln DBH^2$ + lnDBH x H and ln biomass.

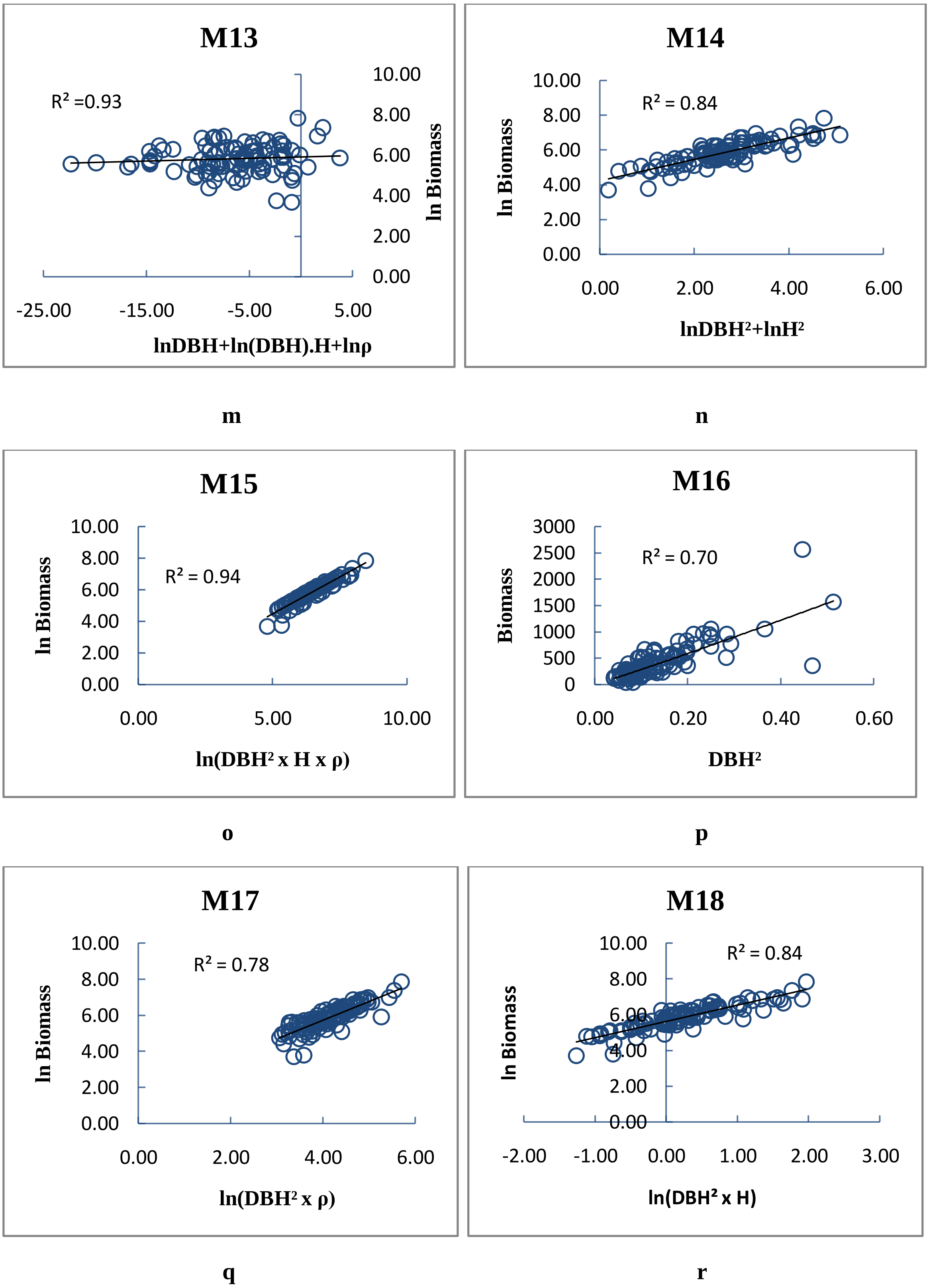
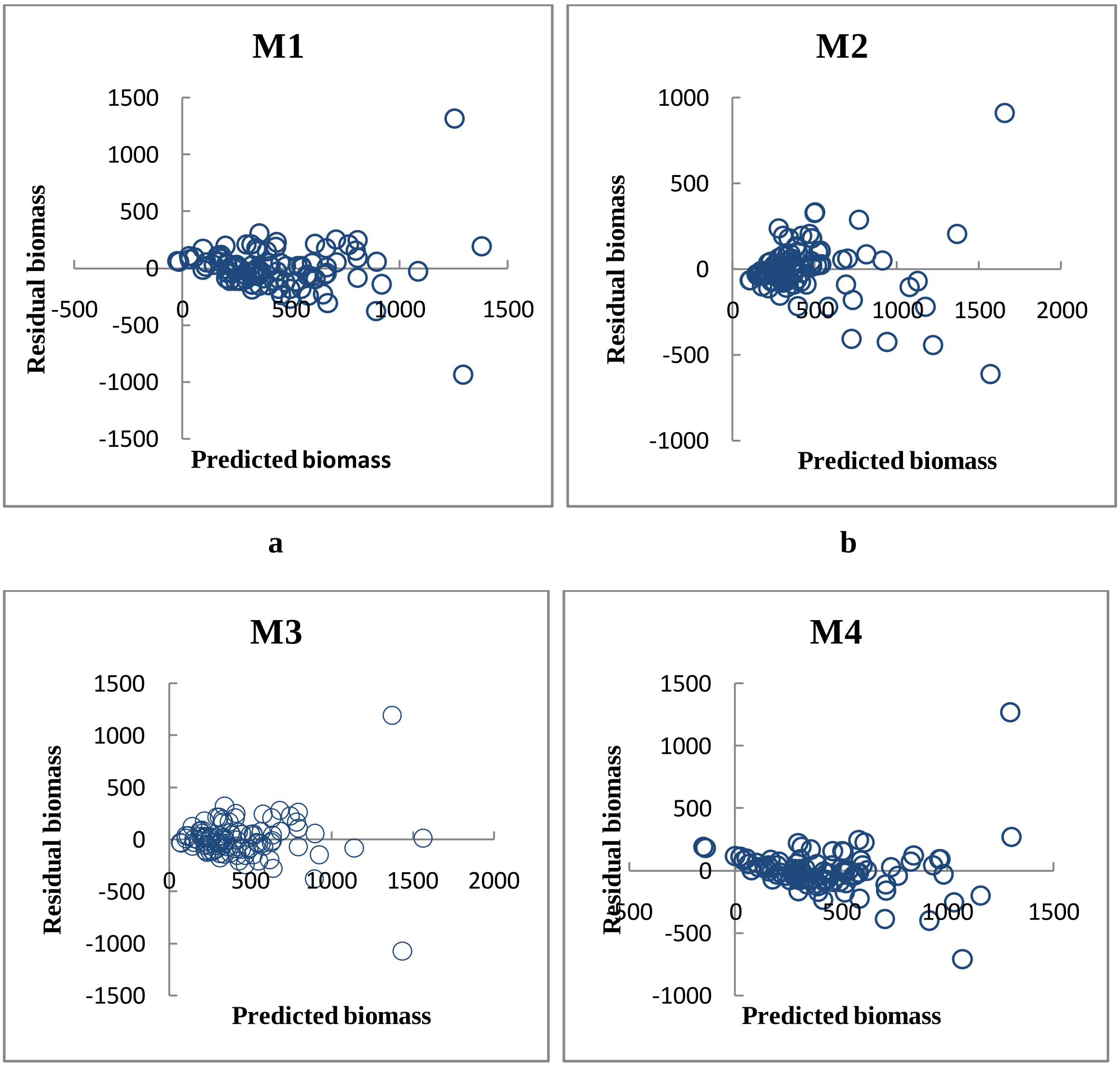


Figure 4.3. **(m)** Relation between lnDBH + lnDBH.H + lnρ and ln biomass. **(n)** Relation between $\ln DBH^2 \times \ln H^2$ and ln biomass **(o)** Relation between $\ln(DBH^2 \times H \times \rho)$ and ln biomass **(p)** Relation between DBH^2 and above ground stem biomass **(q)** Relation between $\ln(DBH^2 \times \rho)$ and ln biomass **(r)** Relation between $\ln(DBH^2 \times H)$ and ln biomass

4.2.2.2. Predicted biomass versus residual biomass plot

Residual error found through the analysis was plotted against the predicted biomass to check whether the residual error increases or not with the predicted biomass for all the models of *T. grandis*. The results showed that residual error did not increase with the increase of predicted biomass only for linear model 15 (Figure 4.4 o) and this model retained strong non-colinearity than the other models. That is why this model could be the best fitted model for biomass estimation of *T. grandis* in SNP.



c

d

Figure 4.4. Relationship between predicted and residual biomass (a), (b), (c), (d)

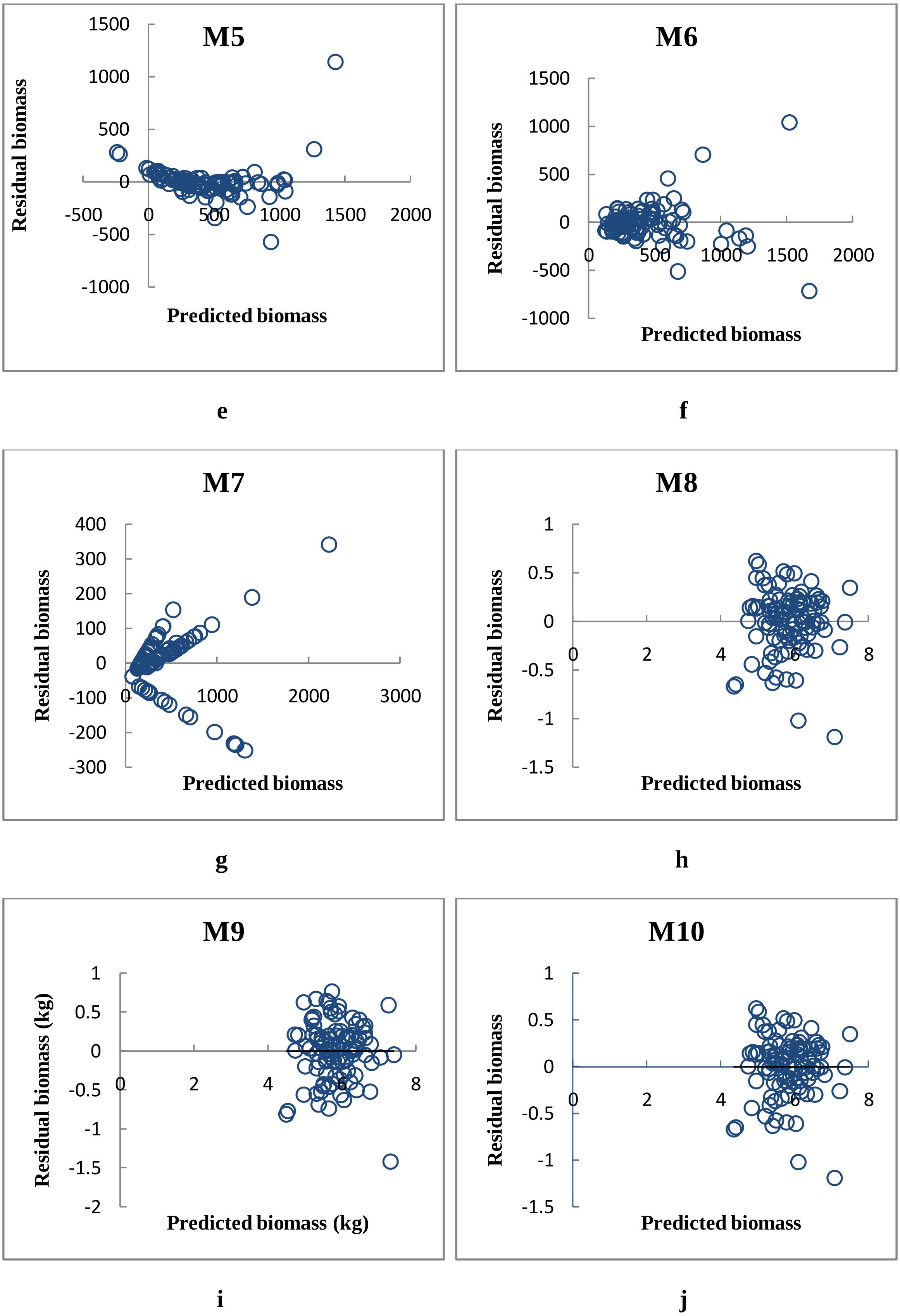


Figure 4.4. Relationship between predicted and residual biomass (e), (f), (g)
Relationship between ln predicted and residual biomass (h), (i), (j)

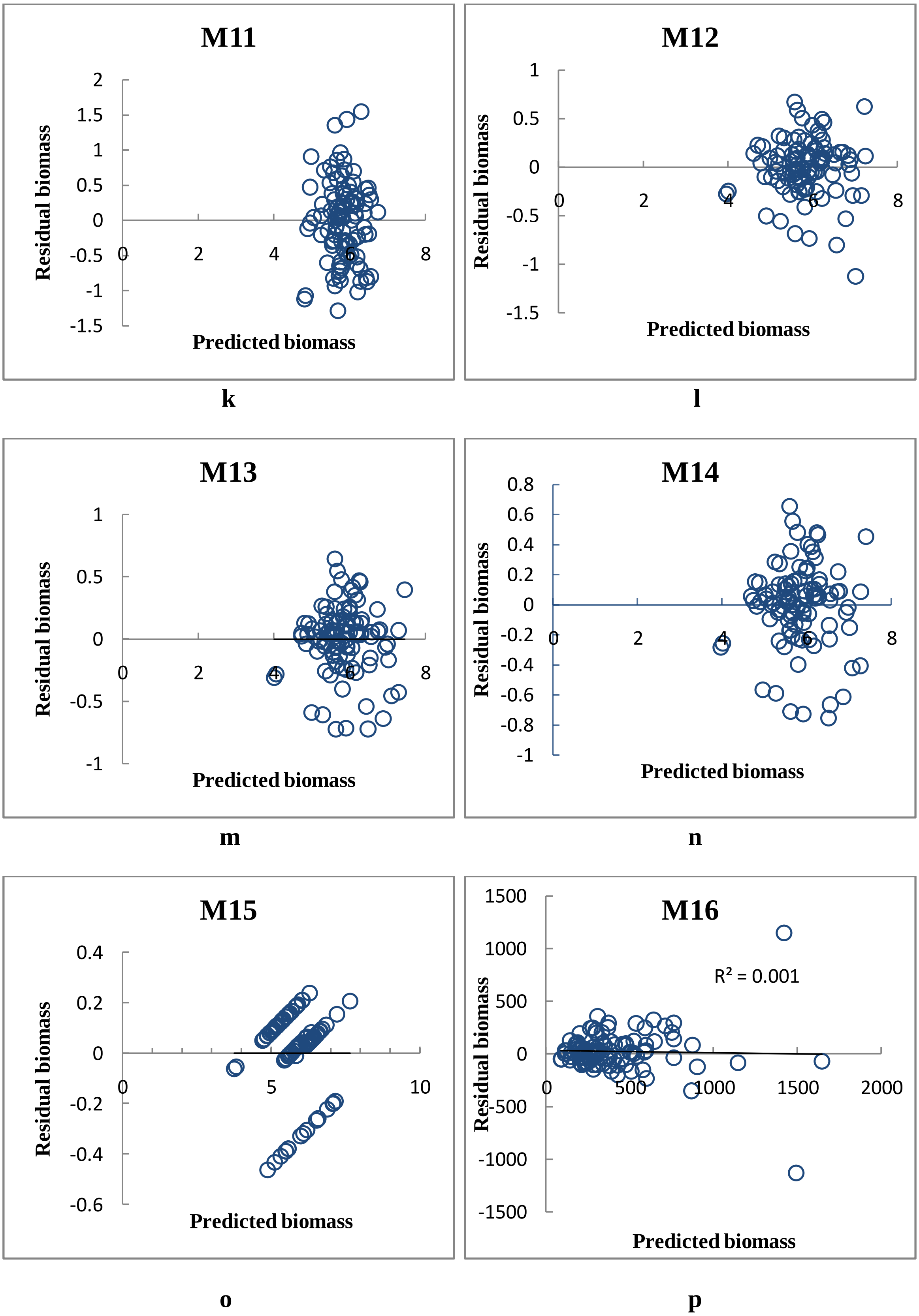


Figure 4.4. Relationship between ln predicted and residual biomass (k), (l), (m)

Relationship between ln predicted and residual biomass (n), (o)

Relationship between predicted and residual biomass (p)

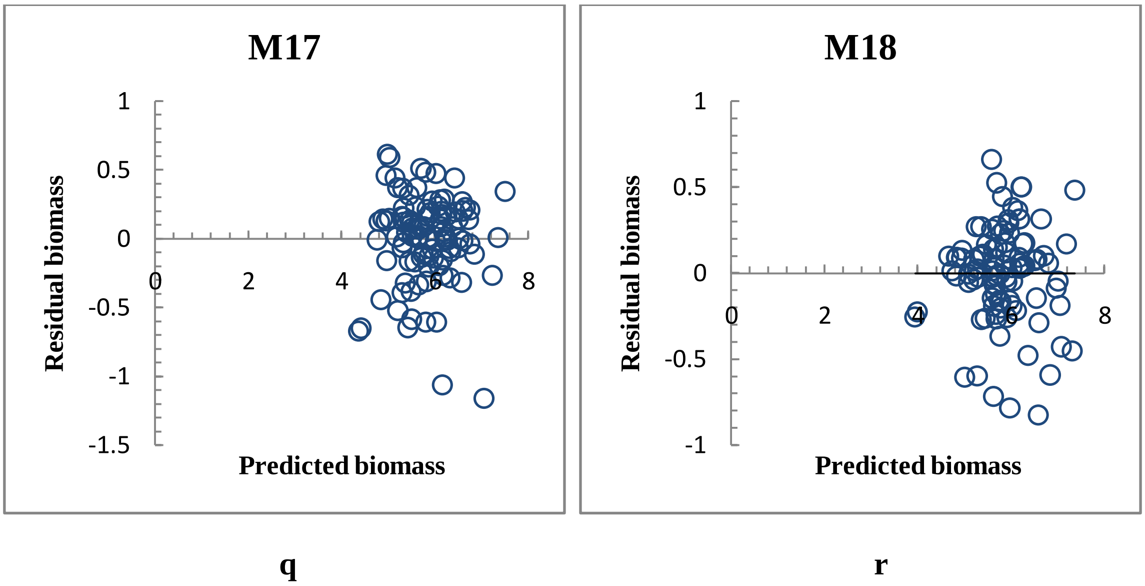


Figure 4.4. Relationship between ln predicted and residual biomass (q), (r)

4.2.3. *Acacia auriculiformis*

4.2.3.1. Allometric models for above ground biomass estimation

The developed allometric equation of *A. auriculiformis* did not had the higher coefficient of determination (R^2) value like other two species of Satchari National Park. The best fitted model to accurately estimate the above ground stem biomass of *A. auriculiformis* were model 16 (Figure 4.5 p) followed by model 15 which was based on the relationship between natural logarithm of biomass and combinations of natural logarithm of DBH, Height and wood density (Figure 4.5 o), model 13 (R^2=0.78, AIC= 169.98, RSE=0.545, F=115.3), model 14 (R^2=0.84, AIC= -31.89, RSE=0.276, F=270.8) (Figure 4.5 n), model 17 (R^2=0.74, AIC= 181.29, RSE=0.5582, F=289.4) (Figure 4.5 q) and model 16 (R^2=0.75, AIC= 181.329, RSE=0.58, F=147) (Figure 4.5 p) (Table 4.4). Although, the highest R^2 value (0.78) was found for multiple regressions model 13 (Figure 4.5 m) but it had not been regarded as the best fitted model because of its higher AIC (169.98), RSE (0.545) value (Table 4.4). Thus, non linear (power) model 16 had been selected as the best fitted model because of its lowest AIC and RSE value (20.23 and 0.262 respectively). Moreover, this model described the positive relationship between DBH^2 and aboveground stem biomass and the values are not scattered from the trendline. In addition to allometric regression model R^2 value of this model was also found highest in estimated biomass versus predicted biomass plots (Annex 3).

Table 4.4. Regression model for estimation of aboveground stem biomass of *Acacia auriculiformis*

No.	Model	Intercept	β	β_1	β_2	R^2	RSE	F***	AIC
1.	$Y = \alpha + bDBH$	-733.79	3476.84***	-	-	0.71	206.92	244	1367.83
2.	$Y = \alpha + \beta\ (DBH^2.H)$	-89	367.86***	-	-	0.70	208.36	239.56	1369.13
3.	$Y = \alpha + \beta\ DBH + \beta_1 DBH^2$	-31.21	-890.7	6205.07***	-	0.76	188.52	158.7	1349.61
4.	$Y = \alpha + \beta\ DBH + \beta_1 H$	-704.973	3573.289***	-5.575	-	0.71	207.7	121.4	1369.46
5.	$Y = \alpha + \beta\ DBH + \beta_1 H + \beta_2 \rho$	-1070.88	3140.615***	-1.1921	0.745***	0.74	192.6	99.71	1355.21
6.	$Y = \alpha + \beta\ (DBH \times H)^2 + \beta_1 \rho$	-666.88	20.4607***	1.1857***	-	0.69	215.5	109.2	1376.96
7.	$Y = \alpha + \beta\ (DBH^2.H.\ \rho)$	-72.5047	0.556***	-	-	0.83	156.32	502.50	1311.09
8.	$Ln\ Y = \alpha + b lnDBH + \beta_1 ln\rho$	2.4396	3.0907***	1.025**	-	0.75	0.58	147	181.32
9.	$Ln\ Y = \alpha + \beta\ lnDBH$	9.7249	3.3223***	-	-	0.72	0.604	262.1	188.65
10.	$Ln\ Y = \alpha + \beta\ lnDBH^2 + \beta_1 ln\rho$	2.4334	1.5448***	1.025**	-	0.75	0.58	146.9	181.38
11.	$Ln\ Y = \alpha + \beta\ lnH$	-1.048	2.7194***		-	0.43	0.865	76.67	261.42
12.	$Ln\ Y = \alpha + \beta\ lnDBH + \beta_1 lnDBH.H$	8.621	3.5024***	-0.0722**	-	0.75	0.578	147.6	181.03
13.	$Ln\ Y = \alpha + \beta\ lnDBH + \beta_1 lnDBH.H + \beta_2 ln\rho$	0.85579	3.2638***	-0.0809***	1.1522***	0.78	0.545	115.3	169.98
14.	$Ln\ Y = \alpha + \beta\ lnDBH^2 + \beta_1 lnH^2$	6.7604	1.4116***	0.4146**	-	0.75	0.579	146.9	181.37
15.	$Ln\ Y = \alpha + \beta\ ln(DBH^2.H.\ \rho)$	-2.0365	1.16073***	-	-	0.77	0.543	347.5	167.21
16.	$Y = (\alpha\ DBH^2)^{\beta}$	10654.906	1.6606***	-	-	0.72	0.2622	261.8	20.23
17.	$Ln\ Y = \alpha + \beta\ ln\ (DBH^2 \times \rho)$	-0.55671	1.461***	-	-	0.74	0.5821	289.4	181.29
18.	$LnY = \alpha + \beta\ ln\ (DBH^2 \times H)$	5.39731	1.24404***	-	-	0.74	0.5842	286.6	182.01

DBH is diameter at breast height (1.37m), H is height (m), ρ is wood density (kg/m^3),
Parameters α, β, β_1, β_2 are the models' regression coefficients, residual standard error (RSE), co-efficient of determination (R^2), and Akaike Information Criterion (AIC).
*** $p< 0.001$ ** $p<0.01$ *$p< 0.05$

Figure 4.5. Relationship between independent variables (DBH, H, ρ) and aboveground stem biomass

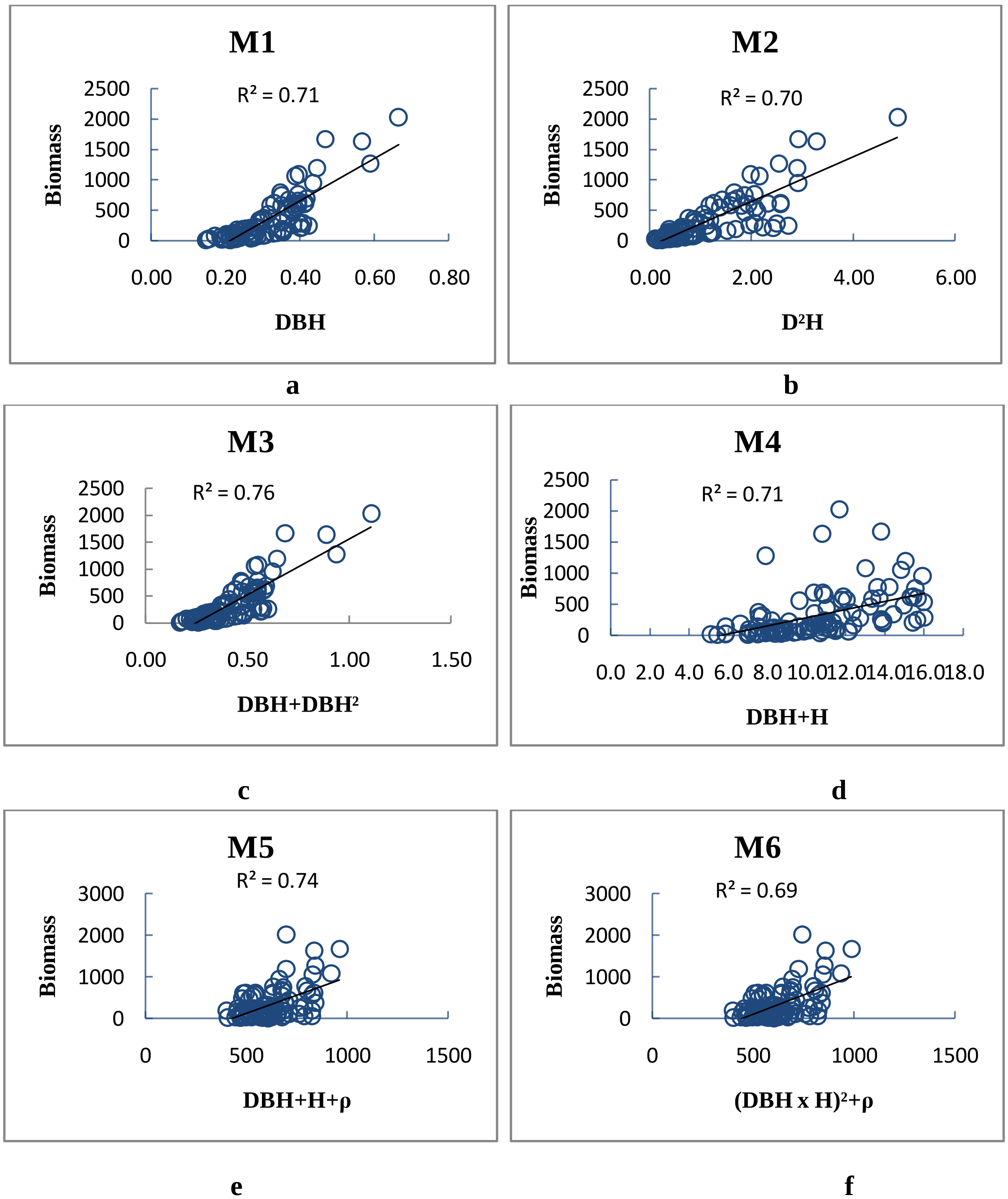


Figure 4.5. (a) Relation between DBH and above ground stem biomass. **(b)** Relation between DBH^2 x H and above ground stem biomass (c) Relation between DBH + DBH^2 and above ground stem biomass **(d)** Relation between DBH + H and above ground stem biomass (e) Relation between DBH + H + ρ and above ground stem biomass **(f)** Relation between $(DBH + H)^2$ and above ground stem biomass

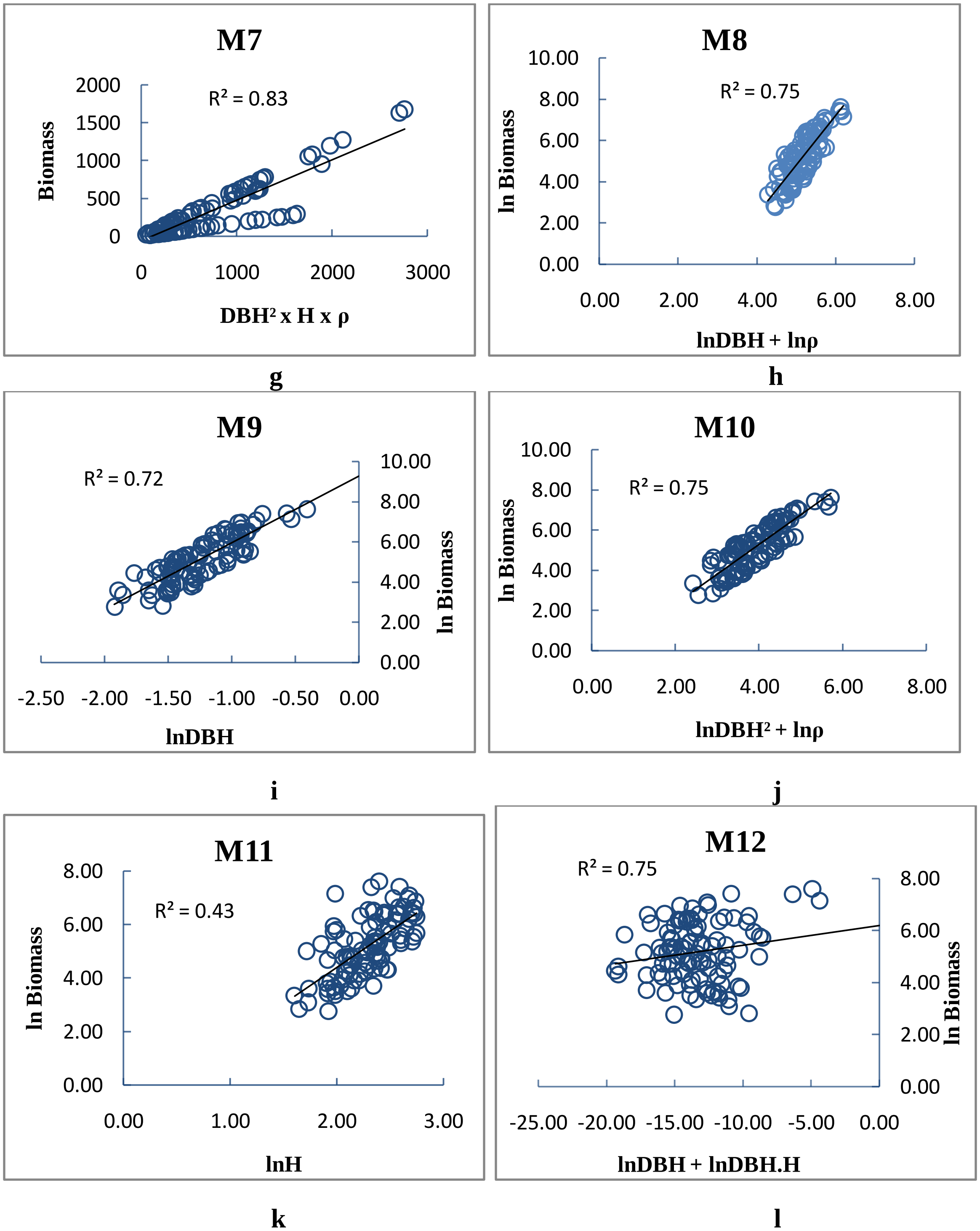


Figure 4.5. (g) Relation between **DBH^2 x H x ρ** and above ground stem biomass **(h)** Relation between lnDBH x lnρ and ln biomass **(i)** Relation between lnDBH and ln biomass **(j)** Relation between $\ln DBH^2$ + lnρ and ln biomass **(k)** Relation between lnH and ln biomass **(l)** Relation between $\ln DBH^2$ + lnDBH x H and ln biomass

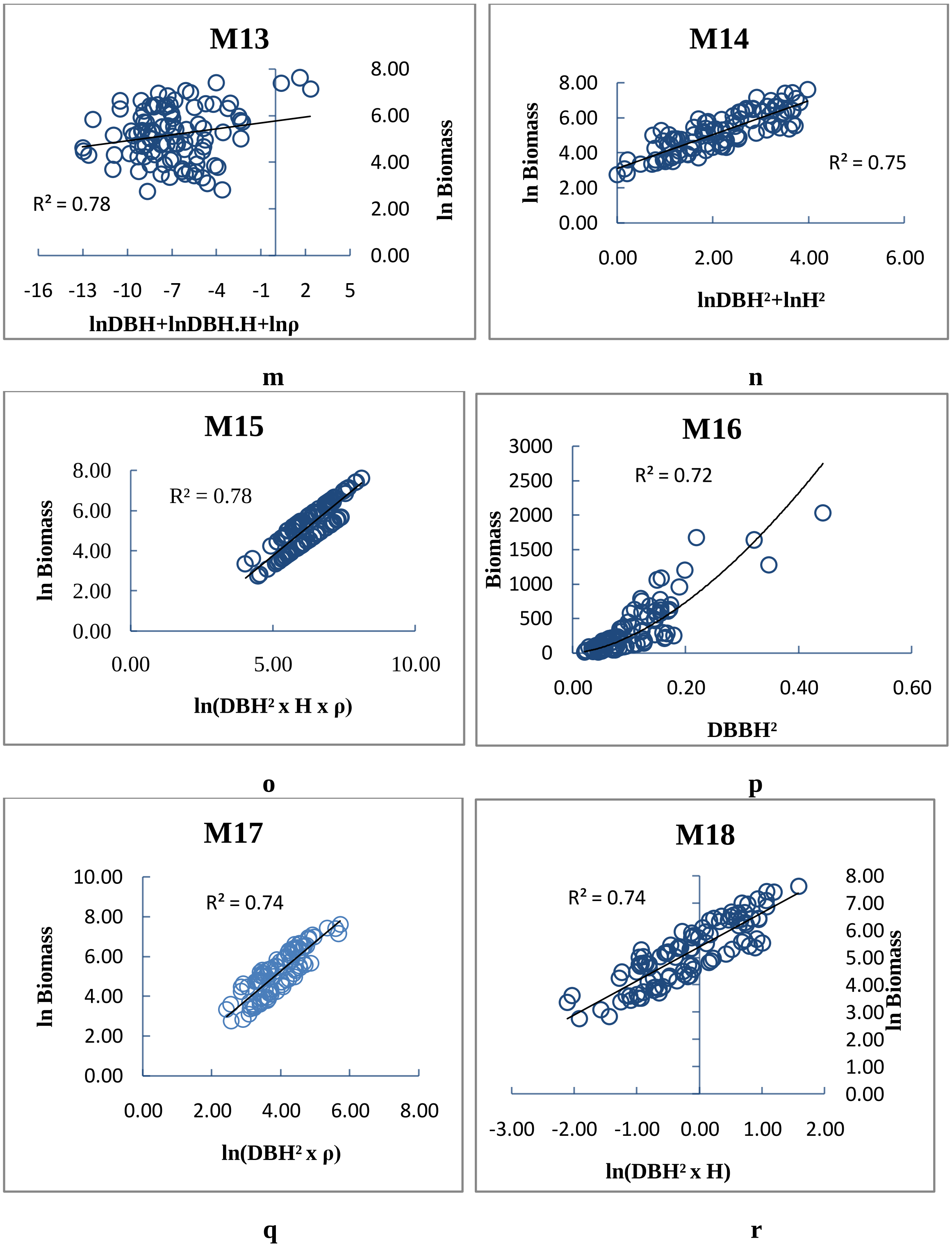


Figure 4.5 (m) Relation between lnDBH + lnDBH.H + lnρ and ln biomass. **(n)** Relation between $\ln DBH^2$ x $\ln H^2$ and ln biomass **(o)** Relation between ln(DBH^2 x H x ρ) and ln biomass **(p)** Relation between DBH^2 and above ground stem biomass **(q)** Relation between ln(DBH^2 x ρ) and ln biomass **(r)** Relation between ln(DBH^2 x H) and ln biomass

4.2.3.2. Predicted biomass versus residual biomass plot

In order to check the accuracy of the best fitted model for biomass estimation of *A. auriculiformis* predicted biomass had been plotted versus the residual biomass. Results showed that non-linear model 16 (Figure 4.6 p) maintained strong non-colinearity than the other models. In this model the residual biomass did not increase with the increase of prediction. That is why this model could be the best fitted model for biomass estimation of *A. auriculiformis* at SNP.

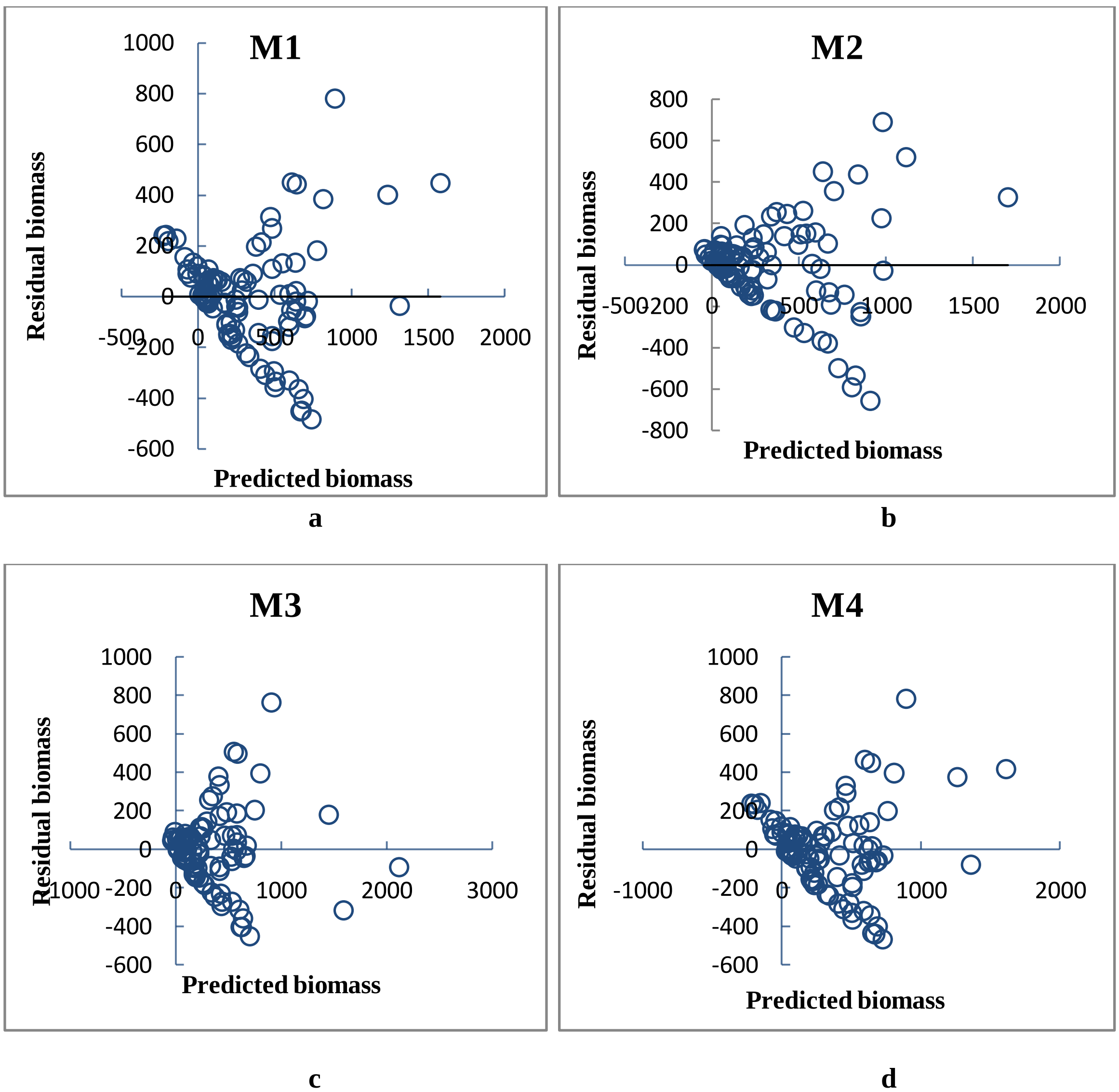
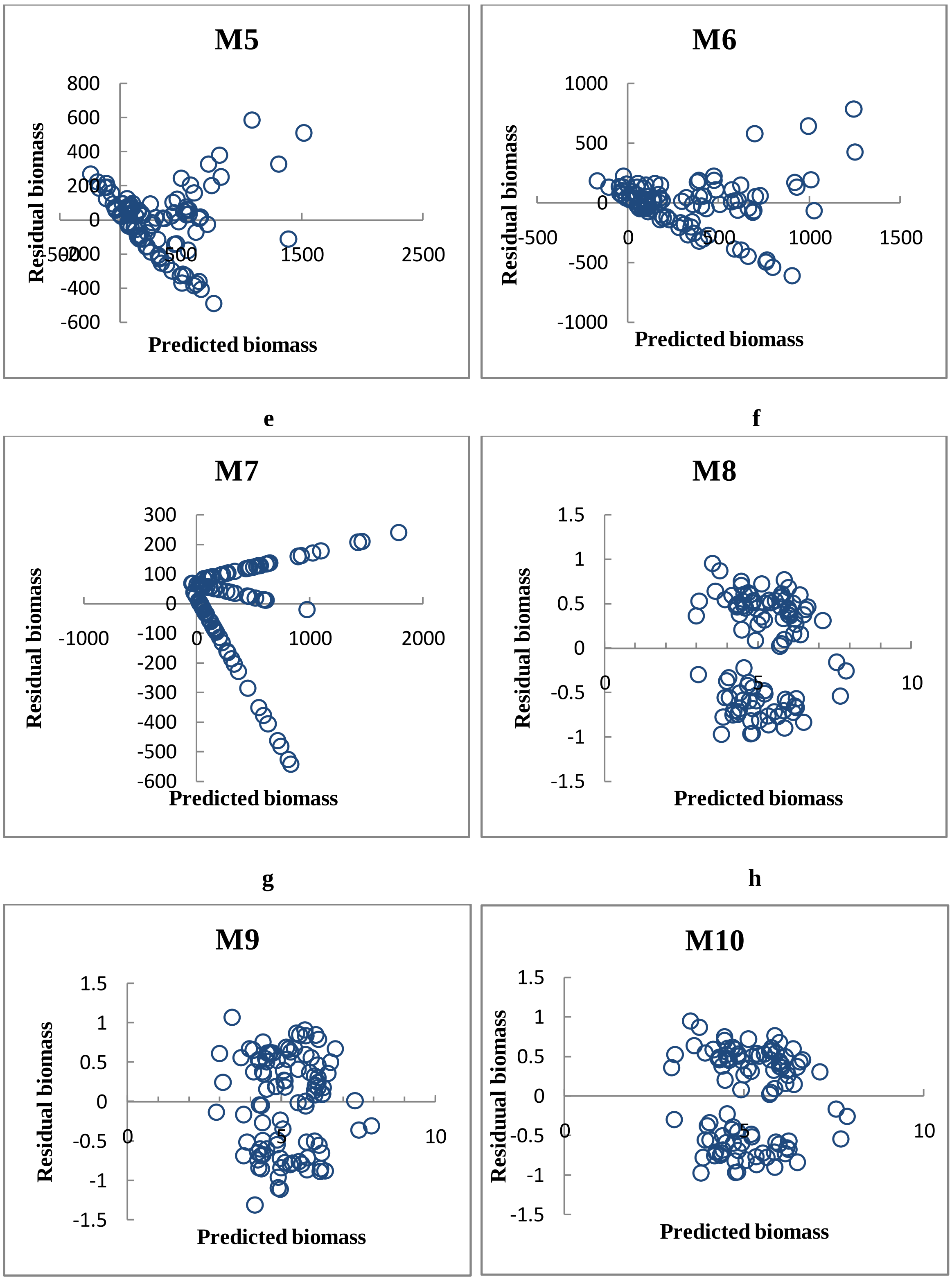


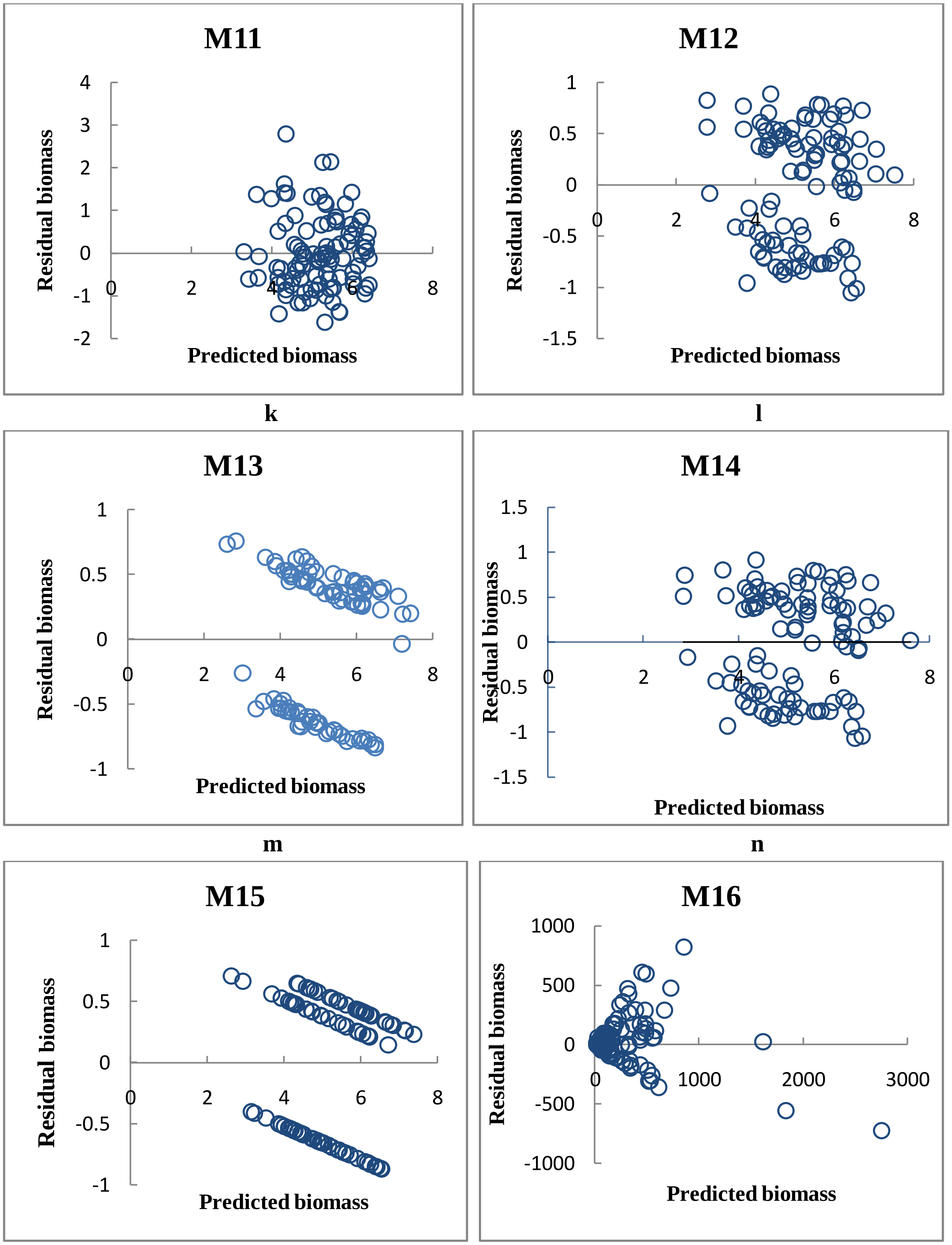
Figure 4.6. Relationship between predicted and residual biomass (a), (b), (c), (d)



i j

Figure 4.6. Relationship between predicted and residual biomass (e), (f), (g)

Relationship between ln predicted and residual biomass (h), (i), (j)

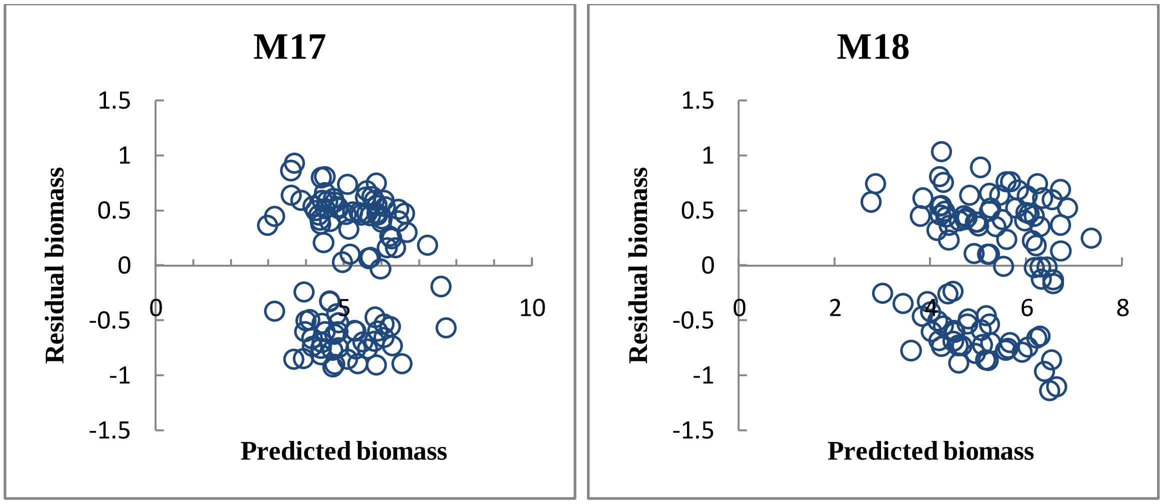


o p

Figure 4.6. Relationship between ln predicted and residual biomass (k), (l), (m)

Relationship between ln predicted and residual biomass (n), (o),

Relationship between predicted and residual biomass (p)



q

r

Figure 4.6 Relationship between ln predicted and residual biomass (q), (r)

CHAPTER FIVE: DISCUSSION

5. Discussion

Species specific biomass equations were developed for Satchari National Park (SNP). Although the number of trees used for equation fitting was low, this is often the case with biomass studies due to the amount of labor required to weigh trees. Highest amount of above ground stem biomass (AGSB) was found in *A. chaplasha* (174.90 Mg/ha) followed by *A. auriculiformis* (97.67 Mg/ha) and *T. grandis* (97.29 Mg/ha). AGSB was significantly related to DBH of the trees. A considerable amount of literature had sought to find the best biomass regression model (Brown et al. 1989; Shepashenko et al. 1998, Wirth et al. 2004; Chave et al. 2004; 2005). Most of these studies constructed complex models, with many fitted parameters, in order to minimize the goodness of fit measures. However, the principle of parsimony stipulates that the quality of a fit should depend on the model complexity, as measured by the number of parameters in the models (Burnham and Anderson 2002). To account for this principle, we selected eighteen sets of models based on their mathematical simplicity by using following explanatory variables DBH (m), H (m) and wood density (ρ) (kg/m3) to find out the best fitted model for biomass estimation of the selected species. Based on criteria of goodness of fit and of parsimony, we selected a regression model that will accurately estimate the above ground stem biomass of the selected three species. The goodness of fit of our model was measured by the residual standard error of the fit (RSE), and by a penalized likelihood criterion as Akaike Information Criterion (AIC). Most of the studies all over the world found a significant relationship between diameter and AGSB (Brown et al. 1989; Brown and Iverson 1992; Chave et al. 2004; 2005; Segura and Kanninen 2005; Medeiros and Sampaio, 2008). Moreover, inclusion of D^2H resulted in the best fitting had been found by various researchers across the world (Deans et al. 1996; Dawkins 1961; Ogawa et al. 1965; Brown et al. 1989; Brown 1997; Schroeder et al. 1997). Better R^2 value was also found in this study from the relationship between AGSB and combination of ln DBH and ln H (M12). Model no. 15 was found the best fitted model for *A. chaplasha* and *T. grandis* in this study. Results from the scatter plot showed strong positive relationship in between ρD^2H and AGSB (for *A. chaplasha* R^2=0.99; RSE =11.78; AIC=-427.62 and T. *grandis* R^2=0.94; RSE =0.162; AIC=-76.89) (Table 4.2 and 4.3). This suggested that including wood density leads to an important improvement for AGB estimation models. Although significant relationship can be found between biomass and D^2H, but when wood density as a predictor is considered significantly improve the biomass equation. Many authors reported that a higher estimation of the biomass equations for a primary forest was related to higher wood density, whereas equations of lower wood density trees usually showed a lower biomass estimate for early successional secondary forest (Brown et al. 1989; Brown 1997; Nelson et al. 1999; Ketterings et al. 2001; Chave et al. 2004; 2005; Kenzo et al. 2009; Ebuy et al. 2011). The differences in the allometric relationship for different tree species mainly attributed to the differences in the specific gravity (weight per volume) of the species wood (Komiyama et al. 2002; Aboal et al. 2005; Navar 2009b). The value of regression coefficient (β=0.98 and 0.89 for *A. chaplasha* and *T. grandis* respectively) was found close to one for both species. Most studies using ρD^2H or D^2H as a predictor found a value for regression coefficient (β) close to one (Deans et al. 1996, Chave et al. 2005).

Even though R^2 value of model no 15 and 13 of *A. chaplasha* (for model no 15, R^2=0.99 and for model no 13 R^2=0.98) and *T. grandis* (for model no 15, R^2=0.94 and for model no 13 R^2=0.93) was very much closer to their respective model but results from scatter plot showed that the independent variables of model no. 13 did not show positive relationship with dependent variable (AGSB) like model no. 15. That is why model no. 15 had been selected as the best fitted model for AGSB estimation of the *A. chaplasha* and *T. grandis* species.

However, the best fitted model for *A. auriculiformis* was found non-linear model no.16. Although R^2 value (0.72) of this model was lesser than that of model no. 13 (R^2=0.781) but the former model represented the lowest RSE and AIC value and showed positive relationship between AGSB and independent variable DBH among the tested model (Table 4.4). Moreover, R^2 value of *A. auriculiformis* was found the lowest among the selected species. This could be due to intrinsic physical structure, bushy and complicated shapes which might have made it difficult to accurately predict their biomass from the dendrometric measures considered in this study.

Among the models the lowest R^2 value was found in model no. 11, for all the species where lnH was plotted against the ln AGSB (for *A. chaplasha* R^2=0.16; for *A. auriculiformis* R^2=0.43 and *T. grandis* R^2=0.34). Tree height cannot be easily measured in closed communities and its determination in large groups of plants is a laborious work. Since, in most cases, height as an isolated variable is not a good estimator and the improvement in adding it to diameter is small, some authors have concluded it is not worthwhile including it in their allometric equations (Haase and Haase 1995; Rayachhetry et al. 2001; Chave et al. 2005). Smith III and Whelan (2006) found a good relation between height and biomass in Florida mangroves but diameter gave a similar fit and they recommended the use of this last variable. This study also recommends that AGSB should not be estimated only by height as an isolated variable. Inclusion of height improved estimation in most cases but only for *A. auriculiformis* there was a reasonable difference. This probably occurred because D and H were highly correlated in the other two species but not in *A. auriculiformis*.

The biomass of branches and twigs were always difficult to predict with relatively good precision compared with the stem biomass. This is in agreement with observation by Navar (2009a) that the ability to predict the biomass of large woody components such as stems and total aboveground biomass was more accurate than that of smaller components such as branches and twigs. This was also supported by earlier studies (Medeiros and Sampaio 2008; Sawadogo et al. 2010). Sawadogo et al. (2010) suggested that within a given species, individual tree habitat (microclimate and competition with neighbors) mostly influence its upper structure; i.e., its crown geometry (as compared to stem) creating large variability at this level from tree to tree making biomass prediction difficult for this component. Moreover, stem of trees considerably allocate a greater proportion of tree biomass than the rest of the parts of the trees. That is why only above ground stem biomass has been considered in this study to predict the biomass of the selected species. Furthermore due to the existing logging ban in our country it was not possible to harvest the trees thus estimate the biomass of the whole tree of these species. Actual model performance, expressed as goodness of fit (R^2) depended on both the species involved and the biomass component to be estimated. The relationship was much stronger for trees with larger biomass weights (i.e., those having a larger proportion of their biomass in the stem or total aboveground biomass such as *A. chaplasha*, *A. auriculiformis* and *T. grandis*).

In the present study eighteen sets of equation elucidated significant relationship between independent variables and dependent variable, AGSB and also with logarithmically transformed variables in both simple linear and non-linear (power) model for all the three species ($p<0.001$). Results from the scatter plot showed that R^2 values of simple linear models are lower than that of log-log linear models. Packard and Boardman (2008) argued that fitting linear model on log-transformed data leads to results that are biased and misleading because such models operate in geometric rather than arithmetic space and those analyses should be performed on the original scale. However, Kerkhoff and Enquist (2009) noted that many allometric characteristics of organisms are multiplicative by nature and thus fitting models to log-transformed data is perfectly acceptable because accounting for proportional rather than absolute variation is most important. Study results also supported the latter view.

All models had significant parameters and predicted the biomass reasonably well, indicated by the small standard error and high coefficients of determination (R^2). High R^2 values signify that the models are good impressions of how AGSB is related to the independent variables. Furthermore predicted values of the allometric models were plotted against the residual values to find out the exactness of the best fitted model of the selected species. One of the objectives of these plot is to find whether the collinearity existed in between the independent variables. Results from the scatter plot showed that linear regression model no. 15 for *A. chaplasha*, and nonlinear (power) model no. 16 for *A. auriculiformis* did not suffer from colinearity problem. Other models of this two species suffer more from an increase in variance with increasing values of independent variables than these two models (model no. 15 and model no. 16 for *A. chaplasha* and *A. auriculiformis* respectively). Although the best fitted model of *T. grandis* (M15) suffered from colinearity problem but it had been selected as the best fitted model because this models yielded highest R^2 value (R^2=0.94) and lowest AIC value among the developed allometric models. Generally, lower AIC value indicates the high percentage of significance of the models. Similarly, in case of estimated biomass versus predicted biomass plots R^2 value was highest for *A. auriculiformis* and *T. grandis* (R^2=0.725 and 0.715 respectively) (Annex 13 and 12). But in case of *A. chaplasha* R^2 value was found highest in non-linear model no 16 (R^2=0.897) rather than best fitted multiple linear regression model (R^2=0.582). But finally this model had been selected as the best fitted model because of its lower AIC and RSE value (Annex 11).

The R^2 values for total aboveground stem biomass equations were lower than those reported by Brown et al. (1989), Segura and Venegas (1999) and Chave et al. (2004, 2005). The differences may be due to overall small sample size, sampling method in this study. Diameter is the most common predictor in all biomass allometric models (Ter-Mikaelian and Korzukhin 1997), but adding tree height and wood density variable improve the prediction power with statistical significance. Wood density is an important predictive variable in all of these models. Its importance may not be obvious if one is interested in estimating the biomass in an old-growth forest dominated by hardwood species, spanning a narrow range of wood densities (Chave et al. 2004). However, Baker et al. (2004) have shown that ignoring variations in wood density should result in poor overall prediction of the stand AGB. Although the use of tree height as a predictive variable also improved the quality of the model but models using them should be applied in forests with caution.

Depending on the data available one of the eighteen models presented above should be used for AGSB estimation of selected species. If DBH, H and ρ are available for each tree, then the model using ρD^2H as a predictive compound variable can be used. If height of the trees is missing then a model using ρ and DBH as predictive variables can be used instead (Chave et al. 2005). Especially model no. 8 can be used in case of missing height of the tree because of its higher R^2 value, lower AIC and RSE value for the respective species. These models are the best fitted model for the selected species of SNP. However, application of this model for other species in this park or of the same species and/or other species for the rest of national park in Bangladesh should be exerted with caution since these models are valid for DBH ≥0.10m. The current established equations may allow a rapid estimate of available biomass and thus aid in planning for sustainable use of these species in the forests.

CHAPTER SIX: CONCLUSION

Conclusion

In this study eighteen sets of allometric equations were developed and tested for determination of aboveground stem biomass of *Artocarpus chaplasha*, *Tectona grandis* and *Acacia auriculifomis* as a function of DBH, height and wood density. Among the allometric equations, the linear model no. 15 ($\ln Y = \alpha + \beta \ln(DBH2.H.\ \rho)$) was the best fitted model for biomass estimation of *A. chaplasha* and *T. grandis*. Conversely, the non-linear (power) model 16 ($Y = (\alpha\ DBH^2)^{\beta}$) was the best fitted model for *A. auriculifomis*. Study results also imply that model as a function of DBH, height and wood density significantly improve the biomass estimation. These equations provide a useful tool for rapid estimation of aboveground stem biomass of the selected three species in Satchari National Park. Therefore, it is recommend that the individual tree size distribution for the area of interest should be evaluated first then compared with the values presented in this study to check the validity of these allometric models for other sites, since dendrometric parameters of these species may not be similar in all sites.

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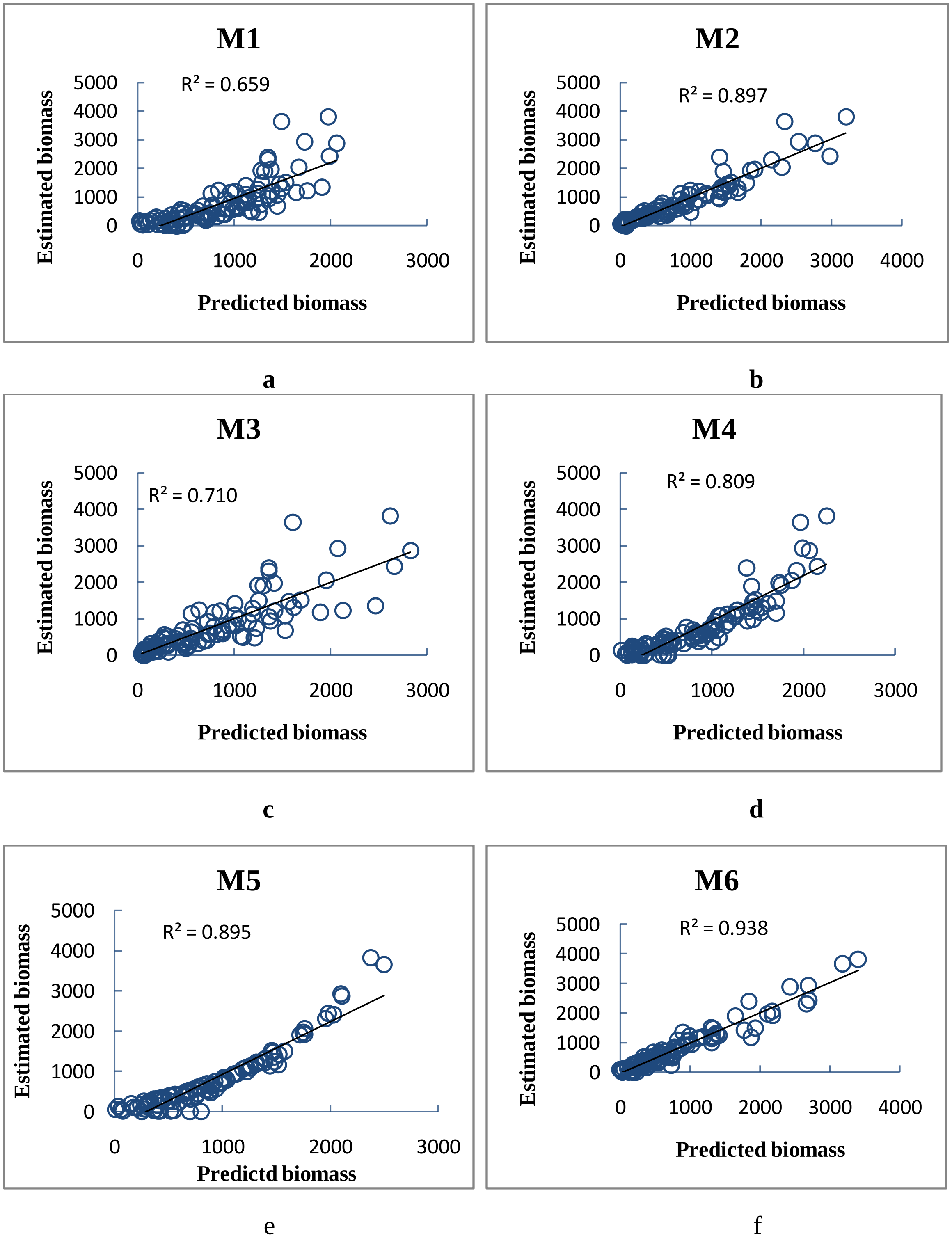
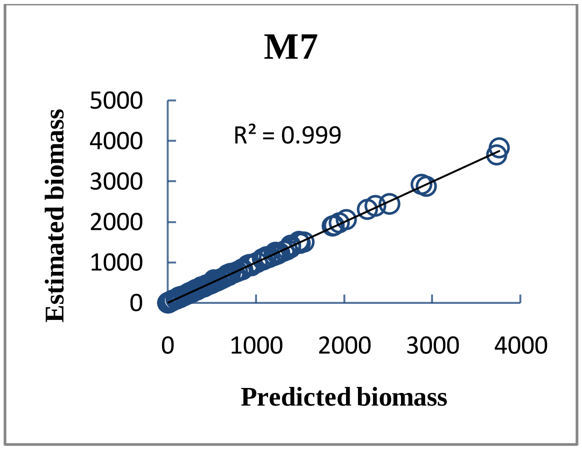
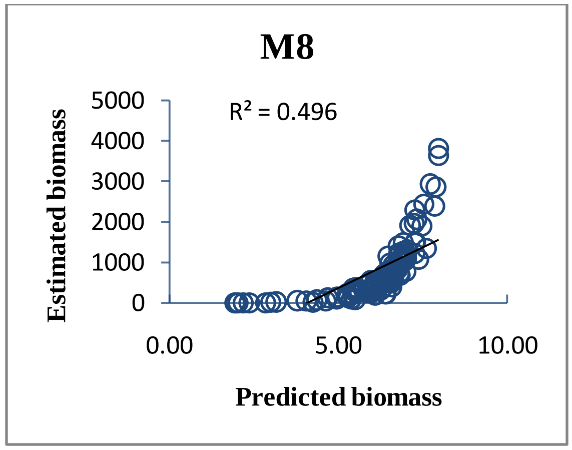
Annex 1. Predicted versus estimated biomass (kg) plots of *Artocarpus chaplasha*



Annex 1. Relationship between estimated and predicted mass (a)**,** (b)**,** (c)

Relationship between estimated and predicted mass (d), (e), (f)





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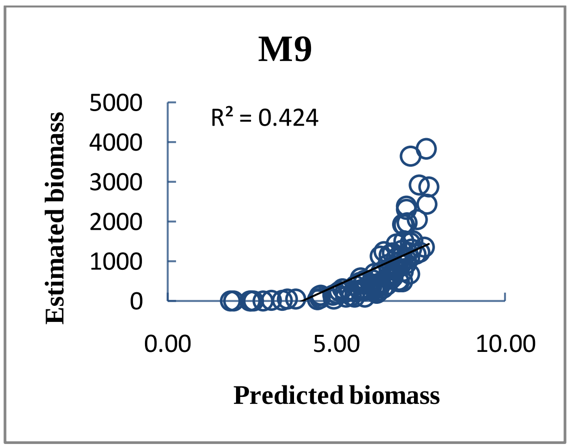
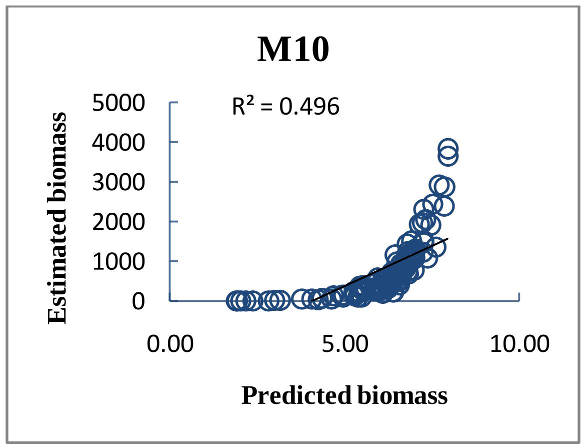
h





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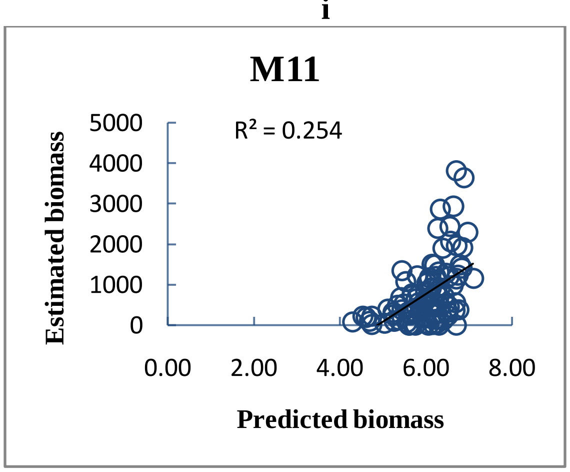
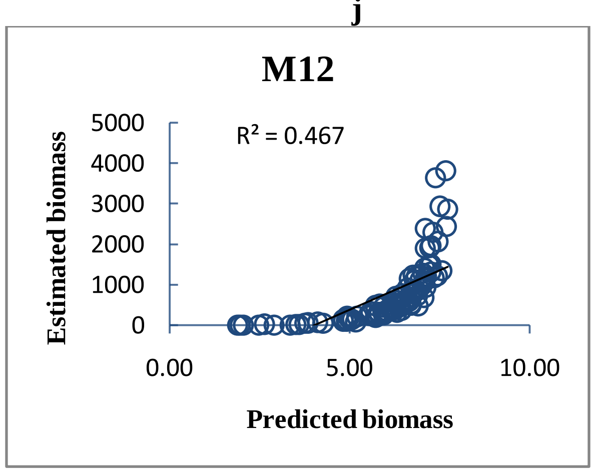
j

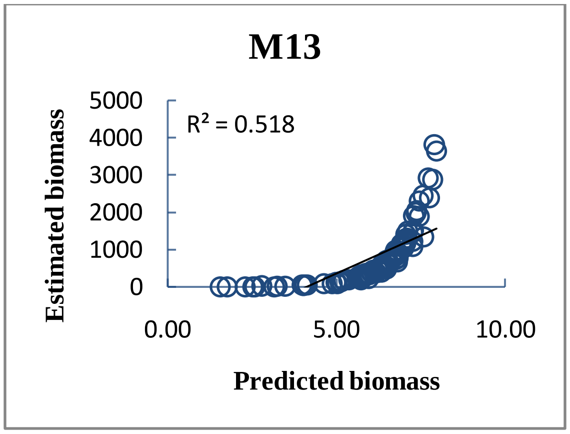


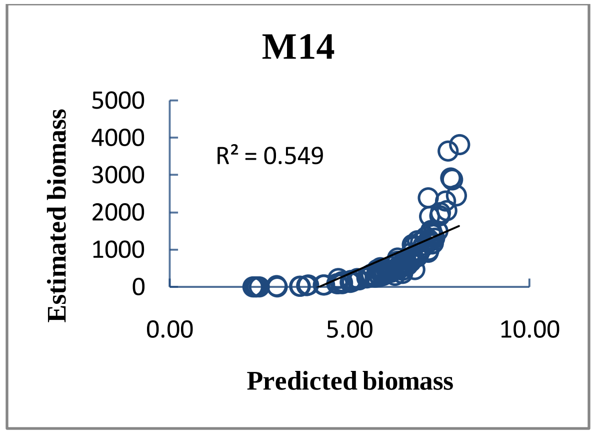


k

l

Annex 1. Relationship between estimated and predicted mass (g), (h), (i), Relationship between ln estimated and predicted mass (j), (k), (l)





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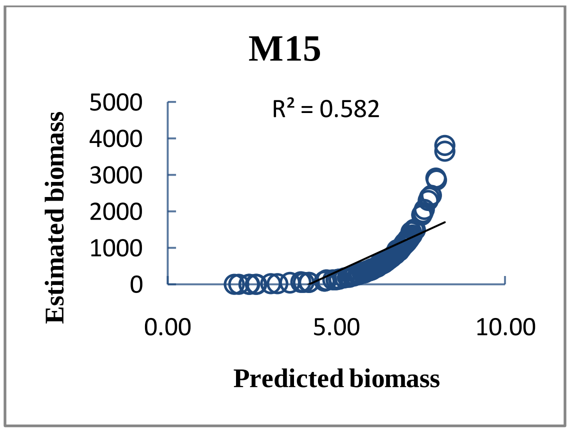
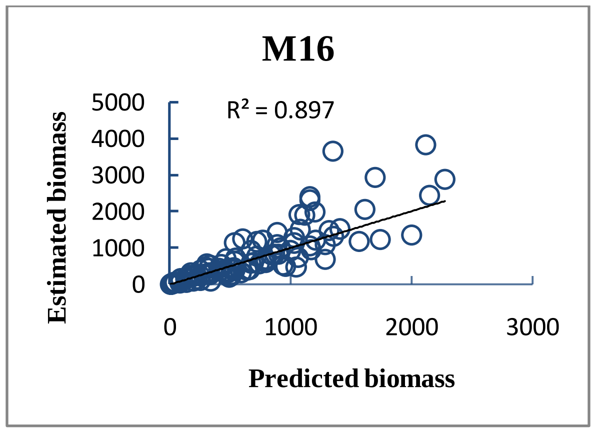
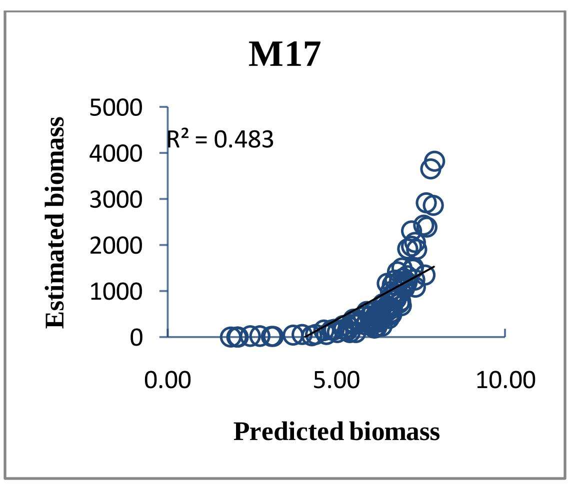
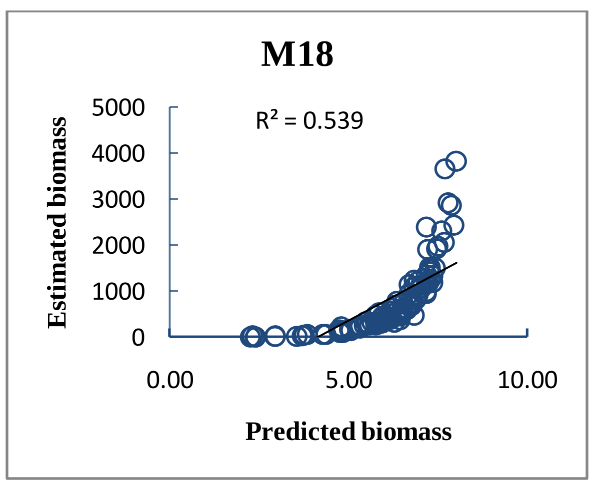




o

p





q

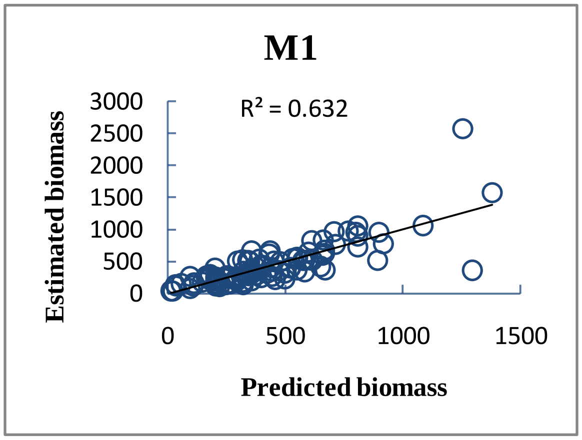
r

Annex 1. Relationship between ln estimated and predicted mass (m), (n), (o)

Relationship between estimated and predicted mass (p)

Relationship between ln estimated and predicted mass (q), (r),

Annex 2. Predicted versus estimated biomass (kg) plots of *Tectona grandis*



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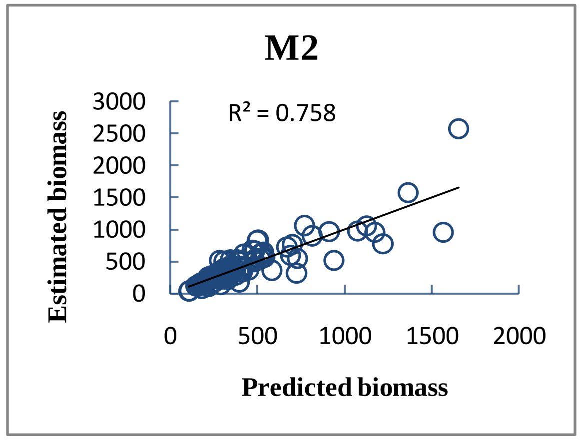

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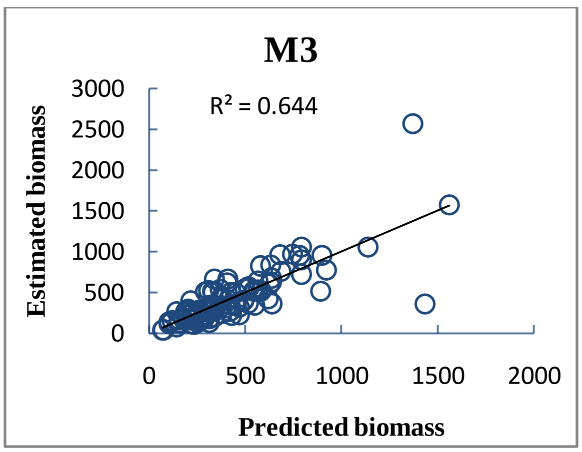

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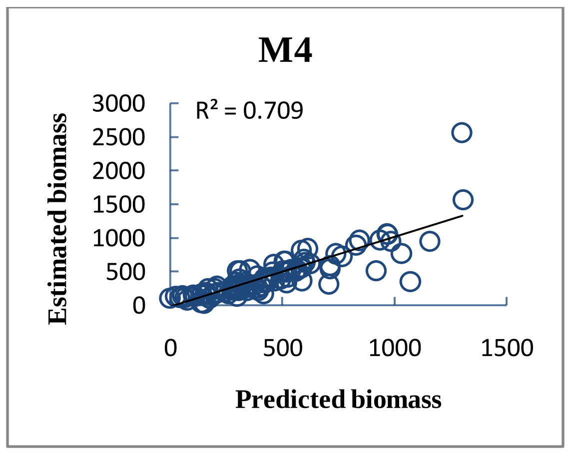

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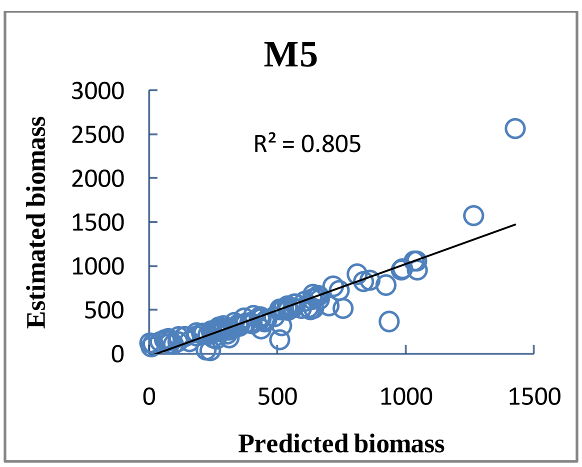

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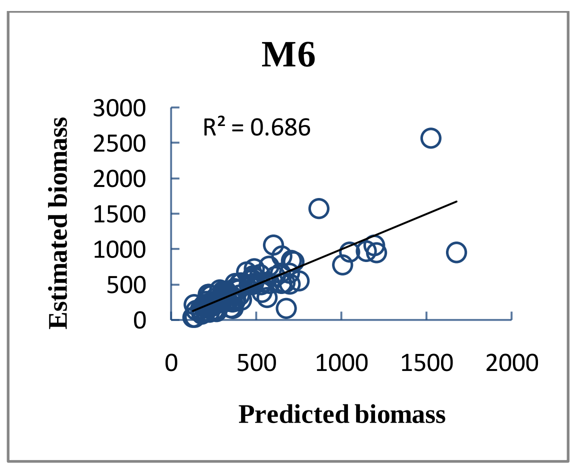
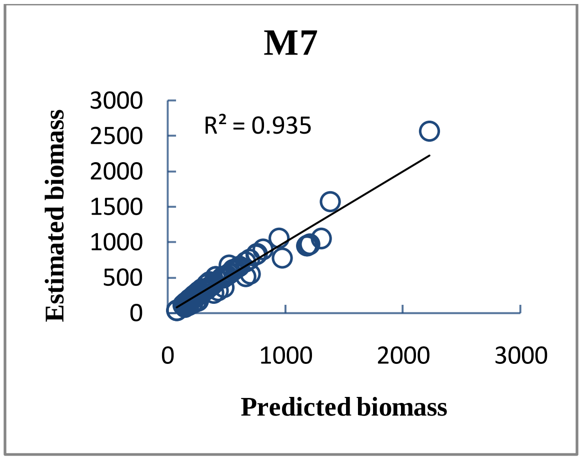


f

Annex 2. Relationship between estimated and predicted mass (a)**,** (b)**,** (c)

Relationship between estimated and predicted mass (d), (e), (f)



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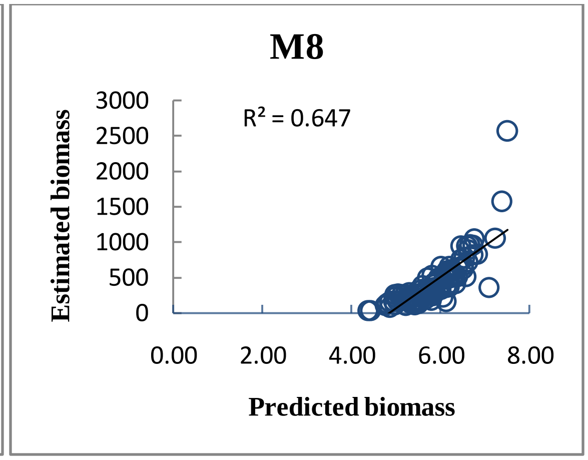

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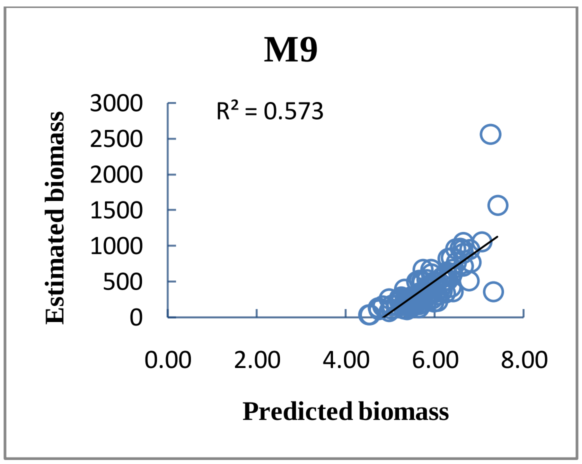

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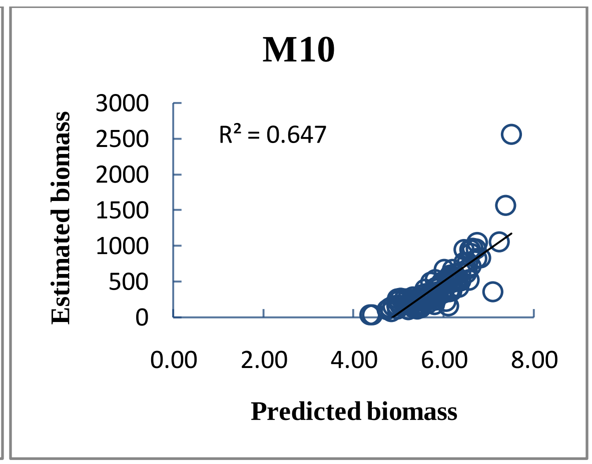

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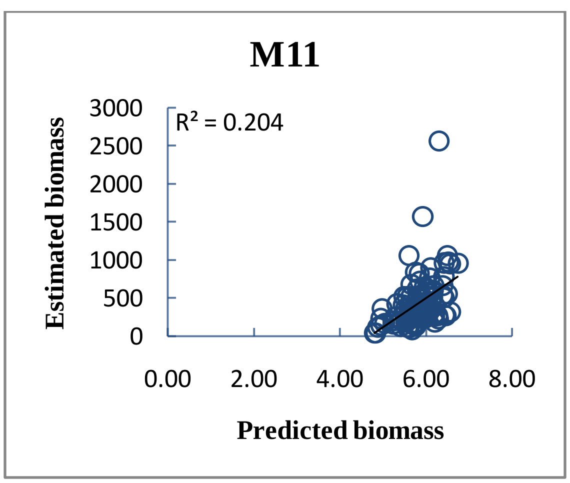

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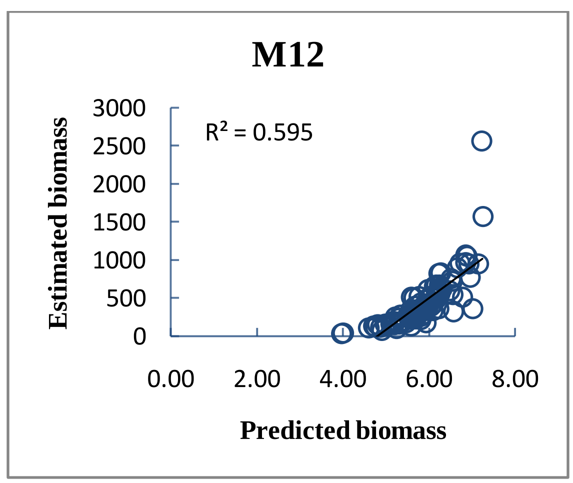
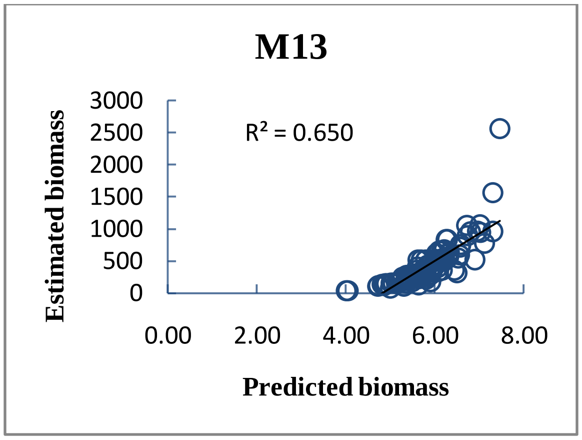
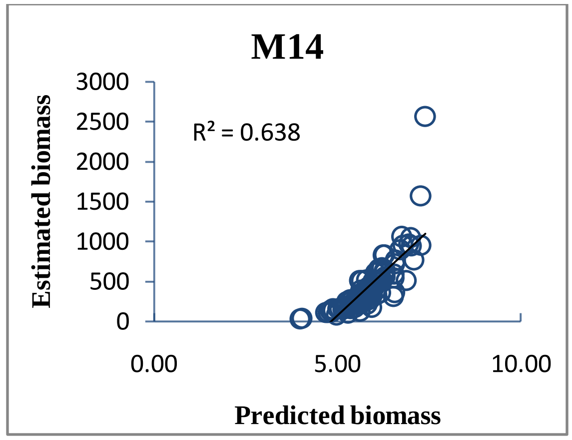


l

Annex 2. Relationship between estimated and predicted mass (g), (h), (i)

Relationship between ln estimated and predicted mass (j), (k), (l)





m

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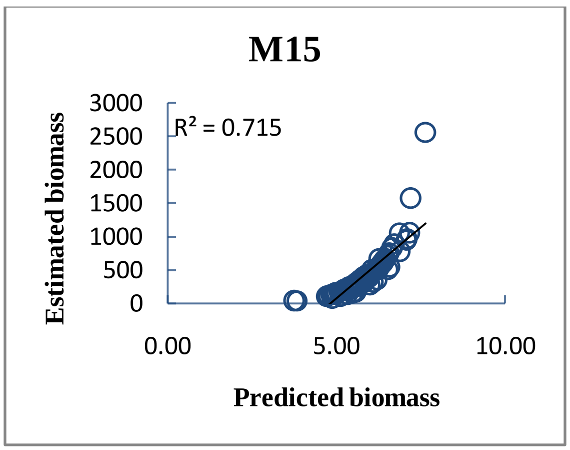

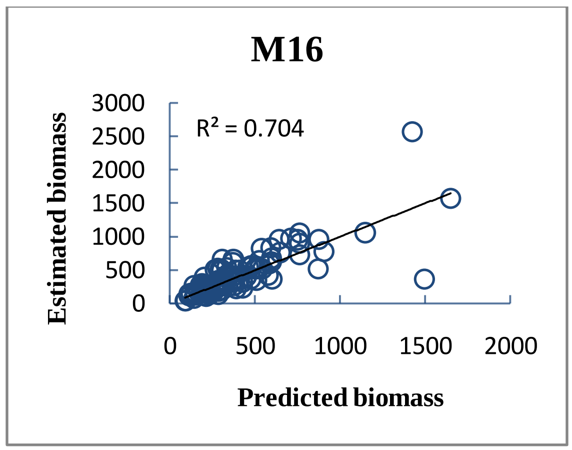

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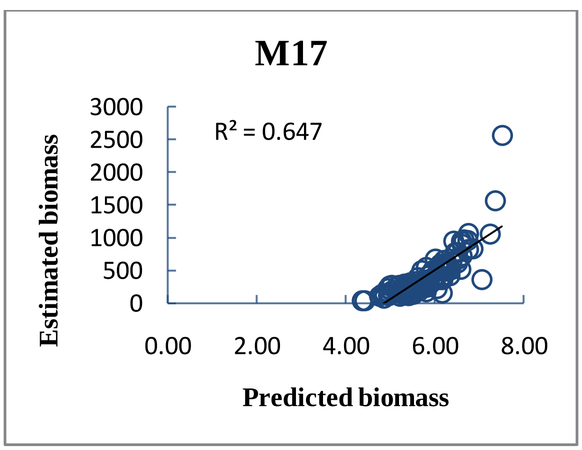
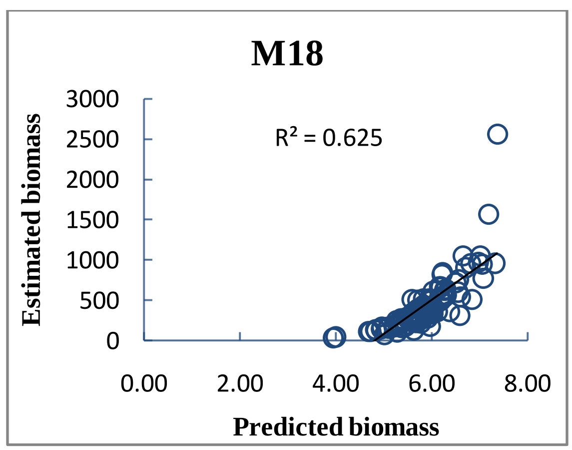




q

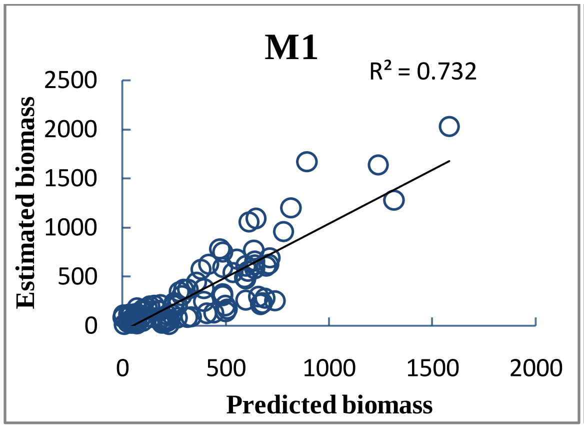
r

Annex 2. Relationship between ln estimated and predicted mass (m), (n), (o)

Relationship between estimated and predicted mass (p)

Relationship between ln estimated and predicted mass (q), (r)

Annex 3. Predicted versus estimated biomass (kg) plots of *Acacia auriculiformis*



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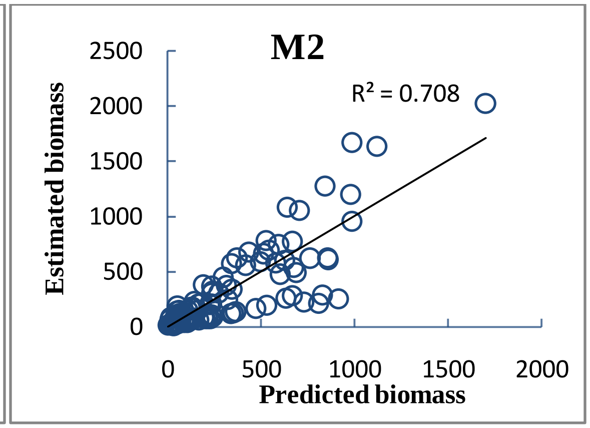

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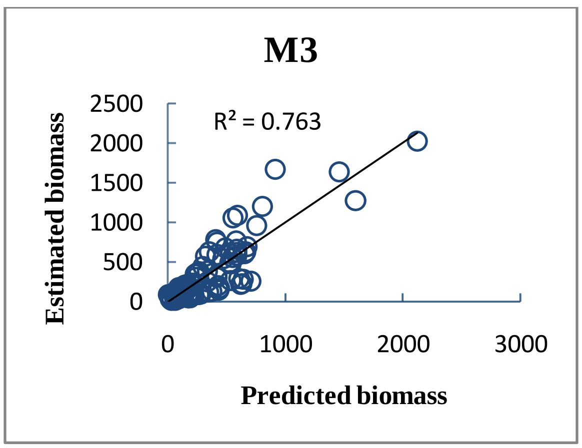

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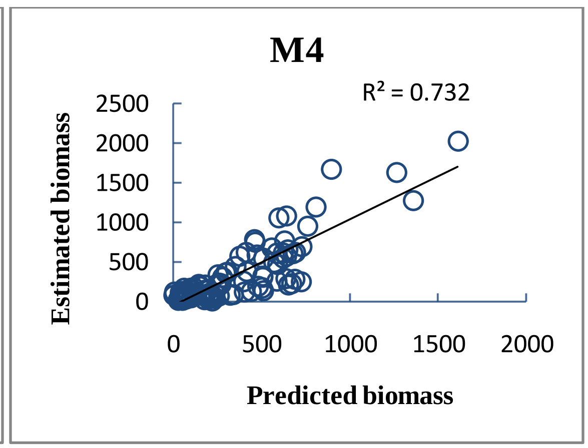

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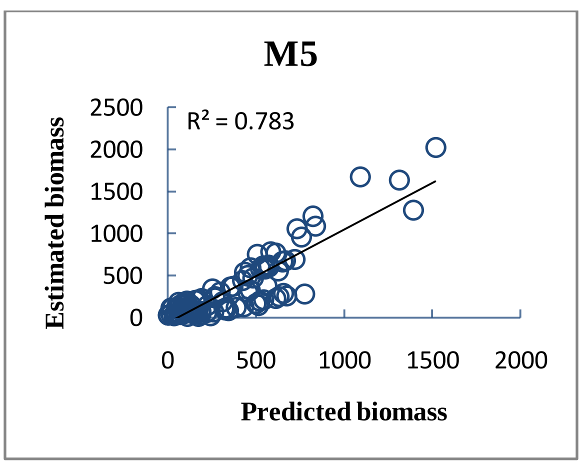

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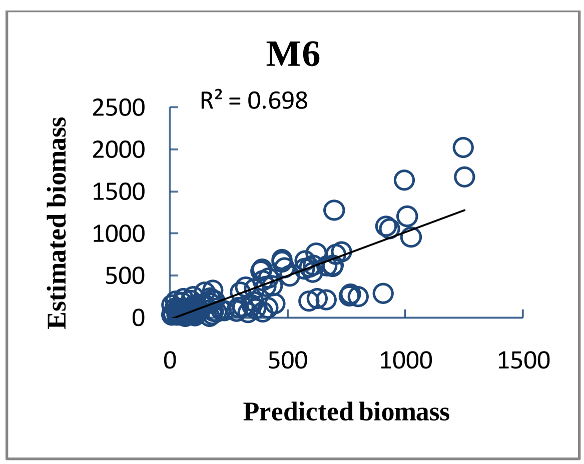
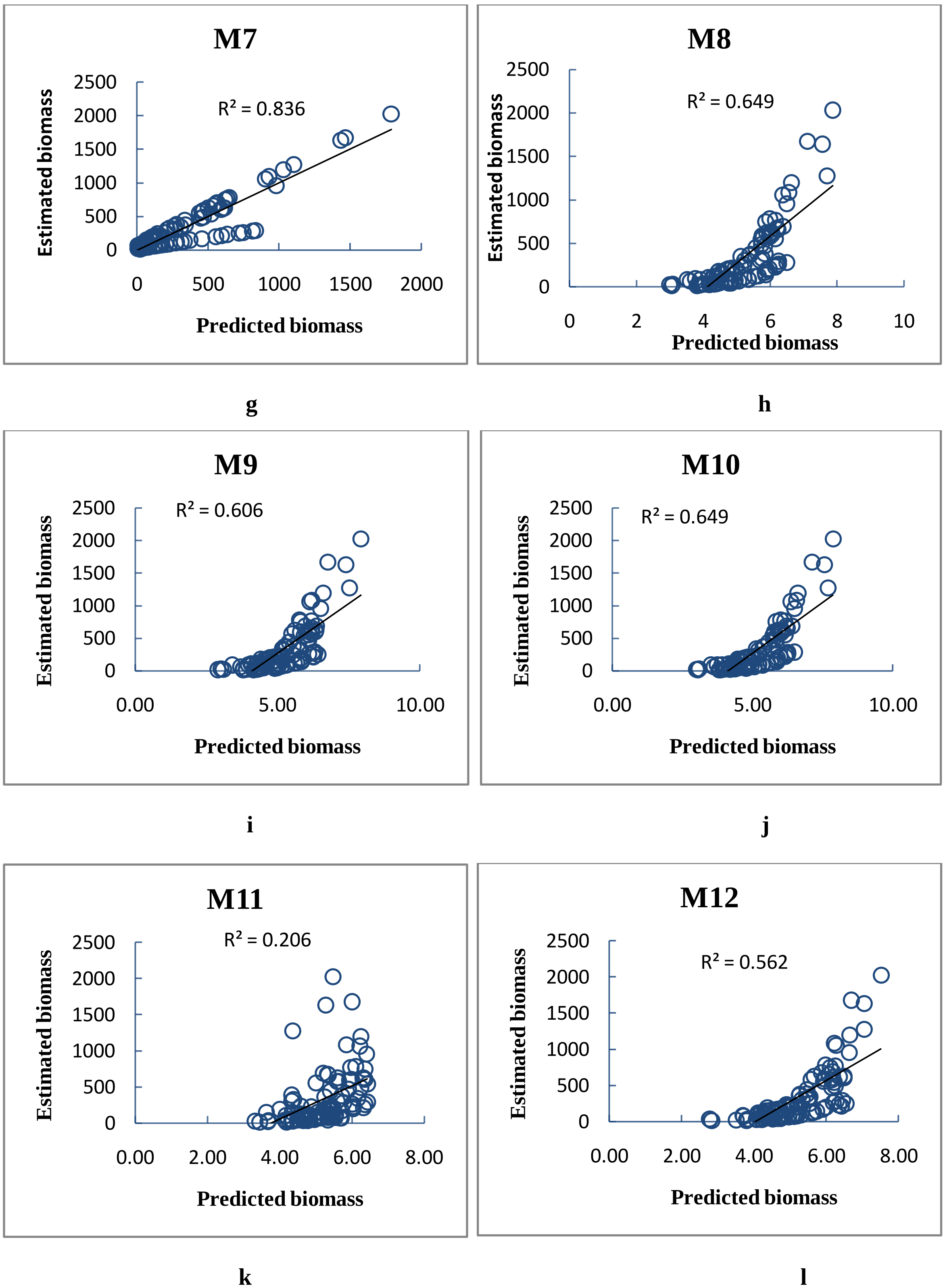


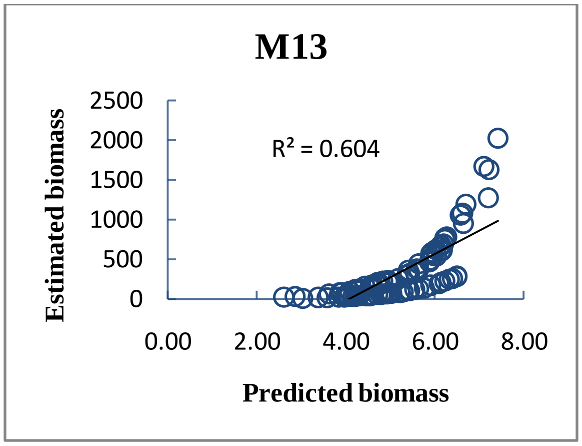
f

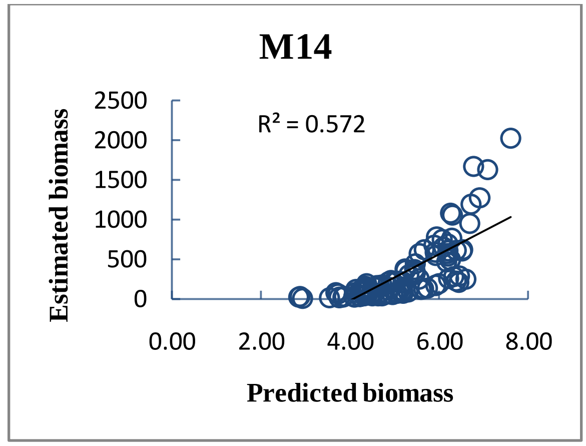
Annex 13. Relationship between estimated and predicted mass (a)**,** (b)**,** (c)

Relationship between estimated and predicted mass (d), (e), (f)

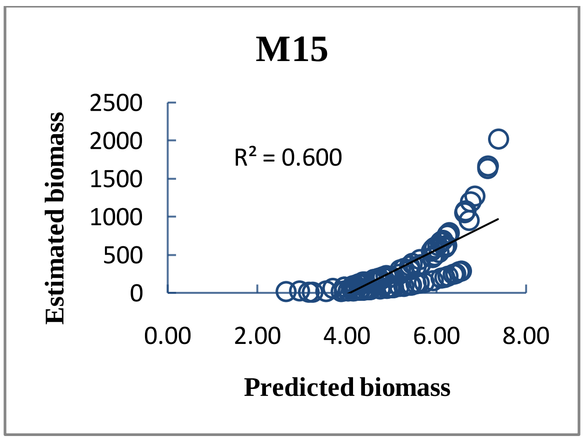


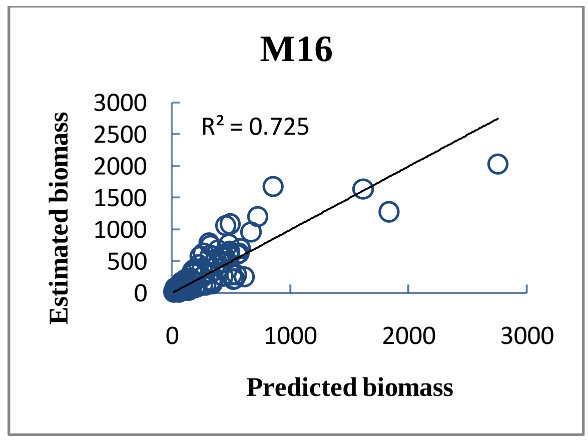
Annex 3. Relationship between estimated and predicted mass (g), (h), (i), Relationship between ln estimated and predicted mass (j), (k), (l)



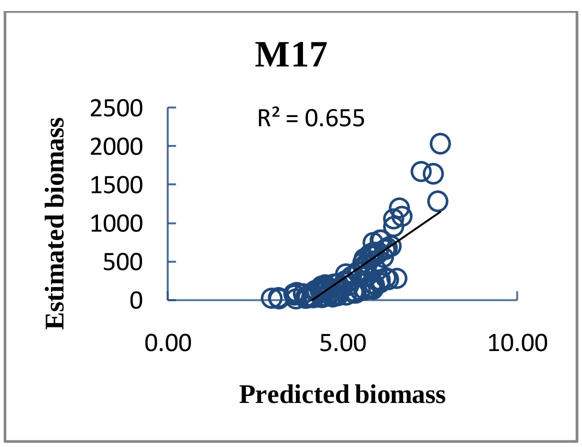


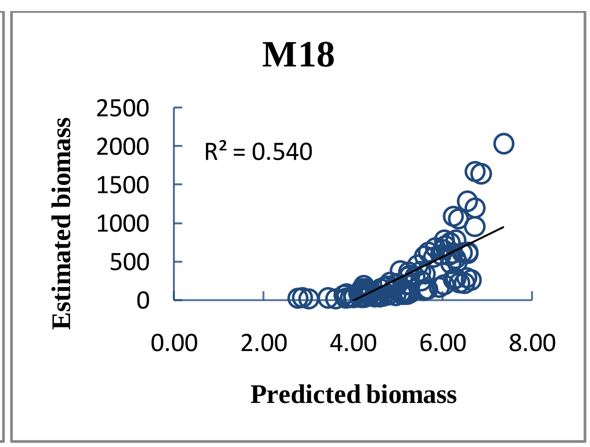
m **n**





o **p**





q **r**

Annex 3. (m), (n), (o), Relationship between ln estimated and predicted mass

(p) Relationship between estimated and predicted mass

(q), (r), Relationship between ln estimated and predicted mass