ESTIMATING ABOVE-GROUND BIOMASS AND CARBON STOCK OF INDIVIDUAL TREES IN UNEVEN-AGED ULUDAG FIR STANDS

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ABSTRACT

Data related to carbon storage capacities of forests have become very important through global warming. After Kyoto Protocol, countries need to see carbon storage abilities of their forests to perform true declarations. So, we aimed to set allometric biomass and carbon equations suitable for predicting above-ground biomass and carbon amounts and conversion of standing stem volume to stored carbon values of above-ground tree components for Uludağ Fir trees. Based on data obtained 34 sample trees which symbolized diameter classes (4-60 cm), above-ground biomass development of Uludağ fir was modeled according to tree components. Carbon concentrations of tree components were established with the help of samples taken from sample trees. The biomass and sequestered carbon were modeled from the standing stem volume of single trees, in order to allow calculation of the carbon sequestered in stands. The study tested different models in determining biomass as a function of DBH or DBH and H. Appropriate functions were chosen and used in the estimation of biomass. Carbon concentrations were found to be lowest in branch barks, with a ratio of 47.0% and highest in needles, with a ratio of 53.5%. The present study make it possible to attain –above-ground biomass and sequestered carbon values safely and without any auxiliary operation by using the standing stem volume, which is the most practical element in management plans.

KEYWORDS: *Abies bornmüleriana Matff.*, above-ground biomass, stem volume, carbon storage, allometric equations.

1 INTRODUCTION

It is acknowledged that any increase in the level of atmospheric carbon dioxide and other greenhouse gases also increases atmospheric temperature. Carbon dioxide is the most effective greenhouse gas and the steady increase in the amount of carbon dioxide in the atmosphere may be attributed to the use of fossil fuels and deforestation across the world [1]. The Kyoto Protocol raised a demand for biomass data to calculate the carbon sequestering potential of forests. Forests have great potential to sequester atmospheric carbon dioxide in the mid-term [2]. It is needed to conduct continuous researches the influence of the climate change on the forest ecosystems and effects of this change during the establishment of new forests [3].

In order to understand the carbon sequestration process and carbon cycle, it is necessary to obtain data on tree biomass. Some recent remote-sensing techniques (LIDAR etc.) enable detailed assessment for above-ground biomass, but their accuracy depends on calibration with field data [4, 5]. In addition, linear programming is usable to model and to analyze in long term monitoring of forest ecosystem values such as carbon sequestration, but this way needs evaluation with a number of performance indicators, such as standing timber volume, harvested volume, ending forest inventory, areas harvested and basal area [6]. Thus, allometric equations are an effective way in the estimation of tree level or stand level above-ground biomass stocks [7-11]. The determination of tree biomass is a challenging, time consuming and costly process, due to operations such as cutting, uprooting, drying, and weighing of tree matter. Alternative techniques have been developed, for the estimation of biomass from easily measured tree characteristics. Within the literature, the estimation of biomass values has generally used allometric equations. These techniques show the relationship between above-ground biomass and diameter at breast height and/or total height, below- ground biomass and diameter at breast height and / or total height, and above-ground biomass and below-ground biomass [12, 13]. Recent studies in Turkey have used allometric relationships to estimate the above-ground biomass for common tree species [14-16]. These studies allow the estimation of above - ground biomass according to stem, branch, and leaf components. However, without additional evaluation, such techniques do not enable the estimation of the amount of bark and above - ground biomass, which are commercially valuable and thus removed

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from the forest during harvest, as well as those with no commercial value, that are left in the forest. Furthermore, there are a limited number of studies on the carbon contents of tree components that may be used for the estimation of carbon storage capacities of forest ecosystems in Turkey.

The composition of vegetation carbon (C) is found by applying a carbon conversion factor to dry weight [17]. According to previous studies, the value of this factor varies between 43.7% and 55.7% and a deviation of 10% may occur in calculations [18-22]. As the size of deviation may be large, it would be beneficial to reduce the uncertainties in the calculation of biomass carbon components. In calculating the carbon cycle of forest ecosystems in Turkey, generally accepted factors for the conversion of biomass to carbon are used. As these factors may show considerable variation, the determination of carbon concentrations of tree components for common tree species is of utmost importance.

For forestry practice in Turkey, stands within a forest ecosystem are classified according to tree species, diameter class and canopy closure. Standing stock is expressed as barked stem volume. In the determination of the amount of C which is sequestered in stands, biomass values of single tree components are first computed by biomass models for the related tree species, using median stand diameter values or median stand diameter - median stand height values. The resultant value is multiplied by the number of trees per hectare and thus the total biomass of the stand is found. Such procedures generally complicate the calculation process. The process may be facilitated considerably by the estimation of stand biomass from standing stem volumes.

The main objective of this study is to set allometric biomass and carbon equations suitable for predicting above-ground biomass and carbon amounts of Uludağ Fir trees. In Turkish forestry practice, it is a significant requirement to determine the amount of sequestered carbon from the standing stem volume. Therefore, establishing models that enable the determination of sequestered carbon amounts considering the values of standing stem volume is an additional objective. In accordance with objectives, this study examined the following: 1) The determination of commercially valuable above - ground biomass , which is removed from the forest during harvest as well as those with no commercial value, which are left in the forest. 2) The determination of carbon contents of above-ground tree components. 3) The development of appropriate models for the conversion of standing stem volume to biomass and stored carbon values of above - ground tree components.

2 MATERIALS AND METHODS

2.1 Study area

Sampling sites are located within the boundaries of the Department of Forestry of Abdipaşa (32° 32’ 35’’- 32° 47’ 30’E - 41° 35’ 25’’- 41° 24’ 55’’ N) and Department of Forestry of Arıt (32° 24’ 20’’- 32° 44’ 50’’E - 41° 33’ 90’’- 41° 45’ 70’’ N), where Uludağ fir grows very successfully. A typical Blacksea climate prevails in the study area. In this climate type, the summers are cool and rainfall, the winters are cold with rainfall. According to meteorological data, annual average temperature is 12.6 °C and average annual precipitation is 1027 mm. The elevation of the sampling sites is within the range 670 m to 1035 m.

2.2 Experimental design

Uludağ fir forms uneven-aged and multi-storey stands. Thus, allometric above-ground biomass models have performed at tree level. For this, sample trees in different diameter classes (4-60 cm) were analyzed in order to determine above-ground biomass development. A total of 34 sample trees were measured from various diameter and height groups. Some characteristics of sample trees are as shown in Table 1. As forest stands in Turkey are defined on the

TABLE 1 - Some characteristics about sample trees.

Sample no	DBH (cm)	Height (m)	Site class	Altitude (m)	Exposure	Sample no	DBH (cm)	Height (m)	Site class	Altitude (m)	Exposure
1	22	19.9	3	1000	SW	18	56	26.5	3	700	NW
2	21	19.4	3	670	NW	19	8	30.1	3	1035	SW
3	21	19.5	3	705	NW	20	9	5.6	3	1010	SW
4	23	22.09	3	700	NW	21	12	7.85	3	980	SW
5	52	27.73	2	710	NW	22	8	8.05	3	1020	SW
6	50	28.2	3	680	NW	23	18	5.9	3	980	SW
7	36	20.35	3	685	NW	24	16	13.5	3	1015	SW
8	28	19.55	3	705	NW	25	9	14.1	3	1030	SW
9	34	21	3	695	NW	26	8	8.9	3	1015	SW
10	40	24.15	3	670	NW	27	18	6.45	3	1035	SW
11	25	18.25	4	680	NW	28	16	13.1	3	1015	SW
12	36	23.5	3	715	NW	29	12	15.1	3	1000	SW
13	31	19.5	3	700	NW	30	6	7.85	3	1020	SW
14	48	23.3	3	705	NW	31	7	3.3	3	1035	SW
15	35	24.2	3	685	NW	32	19	4.47	3	995	SW
16	24	17.2	3	720	NW	33	7	12.6	3	1020	SW
17	45	19.9	3	680	NW	34	14	4,01	3	1025	SW

Mean annual temperature (^{o}C): 12.625; Long term mean P (mm) (Annual rainfall): 1027.

basis of tree species, diameter and canopy closure, the principle of determining the biomass development as a function of diameter or diameter and tree height, rather than age function, was adopted, in order to provide a practical means of assessing biomass and energy potential. After choosing sample trees, diameter (to the nearest mm and bidirectional) and height were measured in all trees.

All measured sample trees were harvested. Each sample tree was cut very close to soil level after cleaning the surrounding area. The whole length of cut trees, crown heights up to the fresh and dry branches, and crown diameter were measured. The branches of the cut sample trees were then removed from the stem, the branches were grouped as thinner than 4 cm (non-commercial) and thicker than 4 cm (with commercial value) and they were weighed. Then, samples were taken from each group. The stem was divided into 2.05 m sections and the diameters of sections at both ends and the root collar diameter and height of the end piece were measured in order to determine the stem volume. Each section was weighted and 5-cm-thick stem samples were taken from the middle of these sections. All samples were then labeled and preserved in plastic bags.

2.3 Laboratory procedures

Stem, branch and needle samples were brought to the laboratory; needles were separated from the shoots; bark was separated from the wood and fresh weights were determined. Samples were first air dried, then oven dried at 65±3 ^{0}C until the weight stabilized, and the final dry weights were determined.

Dried samples were first weighed, then divided into small pieces and then converted into powder as appropriate for carbon analysis. Samples were dried again in order to prevent the effect of moisture, and carbon contents were determined via a CN analyzer as the amount of C for a dry weight of 100 g (%).

2.4 Statistical methods

The biomass of tree components such as the stem, branches, leaves, bark, coarse root and fine root are generally estimated using different allometric regression models, based on DBH or DBH and H [7-9, 23-28]. The present study tested different models in determining biomass as a function of DBH or DBH and H. Appropriate functions were chosen and used in the estimation of biomass.

The use of allometric models covers many decisions on the selection of extant models or the development of a local model, the predictor variables included in the selected model [29]. We have tried different extant models and selected most appropriate models due to decision criteria. During the determination of the most appropriate models, five different compliance measures were utilized. These measures are as follows: coefficient of determination (R^2), standard error of estimate (S_e), mean deviation ($\overline{D}$), absolute mean deviation ($\left|\overline{D}\right|$) and total error (TE(%)). Average difference, average absolute difference, standard error, total error and average absolute error values should be small and coefficient of determination value should be large in order to obtain a reliable model. However, a volume function providing reliable results according to one or more of these values may give inconsistent results according to other variables. In this situation, a "success range", comprising all of the measured values should be prepared in place of comparing biomass functions according to measure values [30]. All of these measures were taken into consideration in the selection of appropriate models in this study.

3 RESULTS

3.1 Above-Ground Biomass Equations

The models using the diameter at breast height ($d_{1.3}$) as an independent variable were tested and those providing the most appropriate results in accordance with compliance measures were determined. Within the biomass equations, the following units of measurement were used: Oven dry weight = kg; diameter at breast height (d) = cm; tree height (h) = m. The models that were found to be appropriate (1….,9) are as shown in Table 2.

TABLE 2 - Models using Diameter at Breast Height ($d_{1.30}$) as an Independent Variable

Single-Tree Biomass Equations:	
$S = -28.6553+(0.372705d_{1.30}^2)$	1
$SB = 0.042861+(0.04161d_{1.30}^2)$	2
$CB = -723.008+(213.8092 \ln d_{1.30})$	3
$CBB = -115.128+(36.83597 \ln d_{1.30})$	4
$NB = -44.1821+22.23076 \ln d_{1.30}$	5
$NBB = -13.965+7.211039 \ln d_{1.30}$	6
$N = -11.6672+1.275487d_{1.30}+0.015577d_{1.30}^2$	7
$TC = -37.568+3.757374d_{1.30}+0.0495d_{1.30}^2$	8
$WT = 24.7765+0.525998d_{1.30}^2$	9

(S: Stem biomass, SB: Stem bark biomass, CB: Commercial branch biomass, CBB: Commercial branch bark biomass, NB: Non-commercial branch biomass, NBB: Non-commercial branch bark biomass, N: Needle biomass, TC: Total crown biomass, WT: Whole tree biomass)

The models that use diameter at breast height ($d_{1.3}$) and tree height (h) as independent variables were tested and the models providing the most appropriate results according to compliance measures were determined. The models that were considered appropriate (10….,18) are given in Table 3.

3.2 Single Entry Volume Equation

In order to model the relationship between standing stem volume and biomass and carbon storage capacities, a volume equation is required. For forestry practice in Turkey, standing stem volumes are determined on the basis of diameter at breast height. Therefore, the function of volume was determined on the basis of diameter at breast height. For this purpose, various models were checked according to compliance criteria and the following model was adopted:

TABLE 3 - Models that use Diameter at Breast Height (*$d_{1.3}$*) and Tree Height (*h*) as Independent Variables.

$S = 47{,}5306+(-8{,}90955d)+(0{,}468435dh)+(0{,}167333d^2)+(0{,}003735d^2h)$ 10
$\ln ySB = -3{,}63636+(1{,}36184\ln d)+(0{,}874147\ln h)$ 11
$CB = -2929{,}16+(92{,}98339d)+(-6{,}54215dh)+(-0{,}25893d^2)+(171{,}9641h)+(0{,}047813d^2h)$ 12
$CBB = -2058{,}02+(103{,}1452d)+(-3{,}94196dh)+(-1{,}13604d^2)+(77{,}00917h)+(0{,}004455d^2h)$ 13
$\ln NB = -14{,}3735+(9{,}548516\ln d)-(1{,}29489\ln^2 d)+(0{,}051463\ln h)+(0{,}020457\ln^2 h)$ 14
$\ln NBB = -15{,}6255+(9{,}893857\ln d)-(1{,}41229\ln^2 d)-(0{,}04206\ln h)+(0{,}097988\ln^2 h)$ 15
$N = -6{,}91358+(0{,}432661d)+(-0{,}01342dh)+(0{,}077531d^2)+(-0{,}00145d^2h)$ 16
$TC = 18{,}65024+(-6{,}08655d)+(0{,}0502275dh)+(0{,}540787d^2)+(-0{,}01259d^2h)$ 17
$WT = 84{,}61739+(-20{,}9204d)+(0{,}599125dh)+(0{,}930834d^2)+(-0{,}0114d^2h)$ 18

$V=0.095+(-0.017d_{1.30})+(0.0012\ d_{1.30}{}^2)$ ($R^2=0.98$)
V: Stem volume (m^3)
$d_{1.3}$: Diameter at breast height (cm)

3.3 Carbon Concentrations of Tree Components

Carbon contents of components are shown in Table 4 as minimum, maximum and mean values.

TABLE 4 - Carbon Concentrations of Tree Components.

Tree components	Min. (%)	Max. (%)	Mean (%)
Stem wood	46.5	49.9	47.8
Stem bark	47.3	50.4	48.5
Commercial branch	47.7	53.4	50.2
Commercial branch bark	46.8	48.9	48.0
Non-commercial branch	47.8	51.5	49.0
Non-commercial branch bark	46.8	49.7	48.1
Needle	48.9	53.5	51.1

3.4 The relationship between standing stem volume and biomass

Various models were tested in order to enable the determination of biomass amounts from standing stem volumes and those that yielded the best results with regard to compliance criteria were identified. In Tables 5 and 6 the models (19...,27) enabling the determination of biomass amounts from standing stem volumes on single tree and stand basis and the compliance criteria for these models are given.

TABLE 5 - Biomass Models using the Standing Stem Volume (V) as an Independent Variable.

$S = 9.2885+(391.44V)$ 19
$SB = 4.6815+(43.084V)$ 20
$CB = 0.8084+(44.934V)$ 21
$CBB = 12.54097+(5.887663V)$ 22
$NB = 14.92174+(10.89325V)$ 23
$NBB = 5.330885+(3.341475V)$ 24
$N = 7.205382+(36.82928V)$ 25
$TC = 19.38104+(110.8624V)$ 26
$WT = 33.35209+(545.3821V)$ 27

(S: Stem biomass, SB: Stem bark biomass, CB: Commercial branch biomass, CBB: Commercial branch bark biomass, NB: Non-commercial branch biomass, NBB: Non-commercial branch bark biomass, N: Needle biomass, TC: Total crown biomass, WT: Whole tree biomass)

TABLE 6 - Compliance Measures of Biomass Models that were Considered Appropriate.

Single-Tree Biomass Equations:

	R^2	F	S_e	TE(%)	$\overline{D}$	$\lvert\overline{D}\rvert$
S	0.99	3535	31.2	0.000119	0.00031	17.84
SB	0.95	557	8.6	-0.000102	0.000033	5.41
CB	0.41	6	47.3	-0.000009	-0.000006	26.9
CBB	0.08	0.78	17.5	-0.000017	-0.0000037	12.6
NB	0.19	7,47	18,9	0.000027	0.0000059	14.97
NBB	0.18	7.25	5.88	0.0000028	0.00000021	4.77
N	0.78	114	16.3	-0.000011	-0.0000033	11.37
TC	0.75	96	53	-0.000018	-0.000016	33.19
WT	0.97	1232	73.3	0.0000025	0.0000098	47.6

3.5 The relationship between standing stem volume and carbon

For forestry practice in Turkey, it is a significant requirement to determine the amount of sequestered carbon from the standing stem volume. Therefore, models that enable the determination of sequestered carbon amounts considering the values of standing stem volume were established. These models (28….,36) (Table 7) and relevant compliance criteria (Table 8) are given below. Relations between standing stem volume and tree components are as shown in Figure 1.

TABLE 7 - Carbon Models using Standing Stem Volume (*V*) as an Independent Variable.

$S = 3.4339+(189.7663V)$ 28
$SB = 2.2612+(20.9869V)$ 29
$CB = -0.951+(23.558V)$ 30
$CBB = 6.0929+(2.772V)$ 31
$NB = 7.311283+(5.405102V)$ 32
$NBB = 2.565427+(1.602309V)$ 33
$N = 3.77156+(18.95956V)$ 34
$TC = 9.423534+(56.10787V)$ 35
$WT = 15.11856+(266.8612V)$ 36

(S: Stem carbon, SB: Stem bark carbon, CB: Commercial branch carbon, CBB: Commercial branch bark carbon, NB: Non-commercial branch carbon, NBB: Non-commercial branch bark carbon, T: Twig carbon, N: Needle carbon, TC: Total crown carbon, WT: Whole tree carbon)

TABLE 8 - Compliance Measures of Carbon Models that were Considered Appropriate.

Single-Tree Biomass Equations:						
	R^2	F	S_e	TE(%)	$\overline{D}$	$\lvert\overline{D}\rvert$
S	0.99	3517	15.1	0.0000034	0.0000043	9.14
SB	0.94	539	4.3	0.000046	0.0000072	2.61
CB	0.44	6.98	23.5	-0.00013	-0.000048	13.78
CBB	0.08	0.77	8.3	0.0054	0.000576	5.98
NB	0.19	7.5	9.3	0.0000013	0.00000014	7.37
NBB	0.18	7.19	2.8	0.0000035	0.00000012	2.29
N	0.78	111	8.5	-0.000011	-0.0000017	5.86
TC	0.76	99	26.1	-0.000004	-0.0000018	16.3
WT	0.97	1198	36	0.0000106	0.000019	23.17

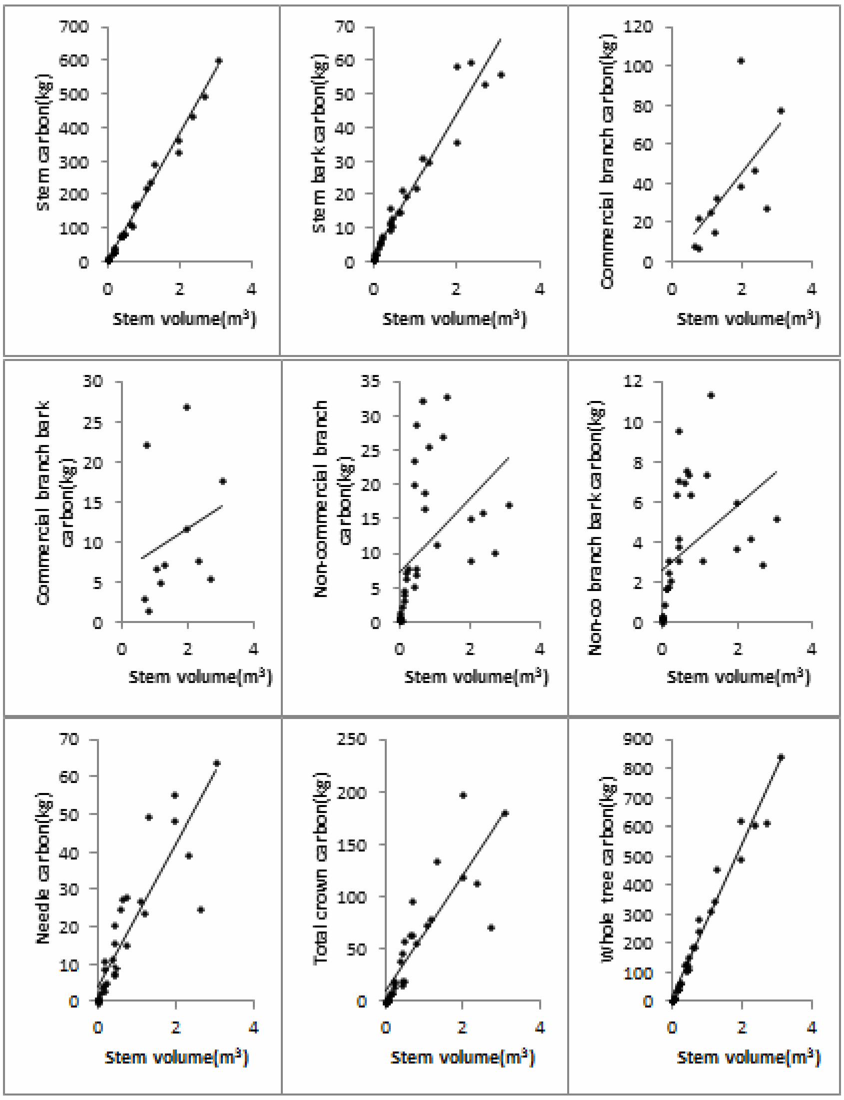

FIGURE 1 - Relations between standing stem volume (m^3) and tree components.

4 DISCUSSION

Mass-based carbon concentrations are widely used for the conversion of biomass to the amount of stored carbon. A previous study by Zhang et al. [22] found the average amount of carbon in the stem to be 49.9% ± 1.3 (mean + SE) for 10 different species, varying between 43.7% and 55.6% according to species. A study by Lamlom and Savigne [20] of 41 species reported this value in the range of 46.3% to 55.2%. The generally accepted method is to determine the amount of stored carbon by multiplying total dry weight of trees by a coefficient of 0.5 [1]. In the present study, the carbon content of stem wood was found to be an average of 47,8 %. Carbon concentrations were found to be lowest in stem wood (47.8%) and highest in needles (51.1%). When carbon concentrations are evaluated as a whole, it is seen that these values are quite close to the generally accepted level of 50% [31]. McPherson et al. [32] conducted a literature review of the conversion of fresh biomass to dry biomass and adopted an average coefficient of 0.56 for deciduous trees and 0.48 for coniferous trees. According to the results of the present study, the conversion factor from fresh weight to dry weight for Uludağ fir species was calculated as an average of 0.51 for above-ground components. This coefficient is higher than that predicted for coniferous species.

Previously, numerous models of single tree and stand biomass have been set in Turkey. Once the large number of forest tree species is taken into account, the number of studies is inadequate to reliably predict biomass and carbon amounts. In these studies generally oven dry and fresh weight values for single tree or stand are given as stem, crown (branches and leaves) and whole above-ground tree weight. In the present study, additionally commercial and non-commercial parts of trees were determined.

In branch equations of Uludağ fir, the correlation of biomass with independent variables is relatively low. It is probable that these differences occurred due to various crown developments arising from non-standard stand treatments and due to natural stands sampled.

5 CONCLUSIONS

In order to accurately determine the amount of carbon sequestered in forests, it is more appropriate to carry out an individual study for each species, rather than basing calculations on non-specific conversion factors. As seen in the literature, carbon concentrations differ considerably according to various tree species and components.

For forestry practice in Turkey, the definitions of stands are made on the basis of tree species, tree diameter class and canopy closure. Tree diameter classes are termed “development ages” and represent a considerably wide range of diameters. Therefore, it is not possible to utilize biomass and carbon models on the basis of tree diameter or height alone by only using data in the management plan. Therefore, additional studies are required. As the results of the present study make it possible to attain–above-ground biomass and sequestered carbon values safely and without any auxiliary operation by using the standing stem volume, which is the most practical element in management plans.

Within the scope of this study, –above-ground modeling was performed, whereas no study of –below-ground carbon sequestration capacities was carried out due to lack of study opportunities. If these shortcomings are addressed in future studies, a major knowledge-gap will be filled.

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Received: June 12, 2012
Revised: August 16, 2012
Accepted: August 28, 2012

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