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Research Article

Total carbon stocks and carbon accumulation in living tree biomass in forest ecosystems of Turkey

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Abstract: In this study, the carbon stocks of forests of Turkey were examined by taking the national forest inventory completed in 2004 as a basis. Furthermore, the annual accumulations of carbon in the above- and below-ground biomass of Turkey were also investigated according to the gain-loss methods of "Agriculture, Forestry and Other Land Use" (AFOLU), published in 2006. The results of estimates showed that the total stock in all carbon pools (above- and below-ground, dead wood, litter, and soil) in the forests of Turkey was 2251.26 Tg C in 2004. Of that total carbon stock, 74.78% was in soil, 21.32% in living tree biomass, and 3.90% in litter and dead wood. It was also found that the annual biomass carbon accumulation increased from 2.20 Tg C year^{-1} in 1990 to 6.82 Tg C year^{-1} in 2005 (an average increase of 4.50 Tg C year^{-1}), according to the gain-loss method. In the productive forests of Turkey, the carbon density in above- and below-ground biomass is 41.66 Mg ha^{-1}, and this is slightly lower than that in the forests of Europe, which is 43.90 Mg ha^{-1} according to the United Nations Economic Commission for Europe and the Food and Agriculture Organization of the United Nations (UN-ECE/FAO). The forests in Turkey absorbed 7.99% of anthropogenic CO_2 emissions, which was 312.31 Tg CO_2 year^{-1} in 2005. In order to increase the amount of carbon accumulated in the forest biomass of Turkey, first of all, the illegal cuttings need to be reduced. Furthermore, the degraded forests, making up about half of the forest area in Turkey, must be rehabilitated, and to increase carbon stock, the concept of carbon management must be adapted to the forestry sector.

Key words: AFOLU, carbon accumulation, carbon stock, forest, Turkey

Türkiye orman ekosistemlerindeki toplam karbon stoku ve canlı ağaç bitkisel kütlesindeki karbon birikimi

Özet: Bu çalışmada 2004 yılında tamamlanan ulusal orman envanteri temel alınarak Türkiye ormanlarındaki karbon stokları incelenmiştir. Ayrıca 2006 yılında yayınlanan "Tarım, Ormancılık ve Diğer Arazi Kullanımı" (AFOLU) kılavuzundaki kazanç-kayıp yöntemine göre Türkiye ormanlarında toprak üstü ve toprak altı bitkisel kütledeki yıllık karbon birikimleri de araştırılmıştır. Buna göre 2004 yılında Türkiye ormanlarındaki tüm karbon havuzlarındaki (toprak altı ve toprak üstü bitkisel kütle, ölü örtü, ölü odun ve toprak) toplam karbon stokunun 2251.26 Tg olduğu belirlenmiştir. Bu karbon stokunun % 74.78'i toprakta, % 21.32'si canlı ağaç kütlesinde ve % 3.90'ı ölü örtü ile ölü odundadır. Kazanç-kayıp yöntemine göre 1990 yılında 2.20 Tg C yıl^{-1} olan yıllık karbon birikiminin 2005 yılında 6.82 Tg C yıl^{-1}'a yükseldiği (ortalama 4.50 Tg C yıl^{-1}) bulunmuştur. Türkiye'de verimli ormanlarda bitkisel kütle karbon yoğunluğu 41.66 Mg ha^{-1}'dır ve bu değer Birleşmiş Milletler Avrupa Ekonomik Komisyonu-Birleşmiş Milletler Gıda ve Tarım Örgütü'ne (UN-ECE/FAO) göre 43.90 Mg ha^{-1} olan Avrupa ormanlarındaki bitkisel kütle karbon yoğunluğundan çok az düşüktür. Türkiye ormanları 2005 yılında 312.31 Tg CO_2 yıl^{-1} olan antropojenik CO_2 emisyonlarının % 7.99'unu absorbe etmektedir. Türkiye ormanlarında biriktirilen karbon miktarını arttırmak için öncelikle kaçak kesimlerin azaltılması gerekmektedir. Ayrıca Türkiye ormanlarının yarısını oluşturan verimsiz ormanlar rehabilite edilmelidir ve karbon stoklarının arttırılabilmesi için karbon yönetimi konsepti ormancılığa adapte edilmelidir.

Anahtar sözcükler: AFOLU, karbon stoku, karbon akışı, orman, Türkiye

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Introduction

The effect of greenhouse gases, especially CO_2, on the warming of the atmosphere and the earth is of great importance. For this reason, studies are being conducted on certain measures such as limiting emissions in order to reduce the amount of CO_2 in the atmosphere. Forest ecosystems have a significant potential in this respect. Carbon can be stored in the biomass, soil, litter, and coarse woody debris pools in forest ecosystems. According to the Kyoto Protocol, the amount of carbon stocks in the forest ecosystems and the stock changes occurring in carbon pools must be determined. In accordance with this protocol, countries prepare the annual national inventory reports (NIR) of greenhouse gas emission and removal in some other sectors (energy, industrial processes, solvent and other product use, agriculture, etc.), as well, and submit them to the United Nations Framework Convention on Climate Change (UNFCCC). These inventories are arranged by the Good Practice Guidance for Land Use, Land-use Change, and Forestry (GPG-LULUCF), prepared by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2006). According to the GPG-LULUCF, the amount of carbon absorbed from the atmosphere and fixed in the biomass is determined indirectly. Generally, the changes in biomass stock or annual volume increment are used in determining the change in biomass carbon stocks in forests. However, determining the forest biomass appears to an important problem because the forest inventories are not generally designed to determine the carbon budget, but are focused mostly on determining the stem volume (Van Camp et al. 2004; Jalkanen et al. 2005). To make a carbon inventory, the stem volume has to be converted into the stem biomass first. This conversion can be done in 2 different ways. In the first method, the stem volume is multiplied by the basic wood density to calculate the stem biomass. The values of branch, foliage, and root biomasses are then required to be added to that value. For this purpose, the stem biomass value is multiplied by the coefficient called the biomass expansion factor (BEF) to obtain the above-ground biomass value. Then, by using the root to shoot ratios (R), the below-ground biomass value is calculated from the above-ground biomass values. After that, the coefficient called the carbon factor (CF) is used to determine the carbon stock in the total biomass (IPCC 2003). The second method, called Agriculture, Forestry, and Other Land Use (AFOLU), is recommended in the new version of GPG-LULUCF published in 2006. According to this method, the above-ground biomass is calculated directly from the stem volume by using the coefficients called the biomass conversion and expansion factors (BCEF), without using the wood density (IPCC 2006). The biomass factors used in calculating the above- and below-ground biomass are given in AFOLU separately for each climatic region, for the countries where these factors are not available (IPCC 2006).

A large number of studies have been carried out in various countries on the biomass factors or equations, and in Turkey, biomass studies have increased in recent years. Biomass equations have been developed in Turkey for some coniferous trees, such as *Pinus sylvestris* L. (Uğurlu et al. 1976; Atmaca 2008; Çömez 2010; Tolunay 2010), *Pinus brutia* Ten. (Sun et al. 1980; Ünsal, 2007), *Picea orientalis* (L.) Link (Özkaya 2004), and *Pinus nigra* Arnold (Çakıl 2008). For the deciduous trees, biomass tables have been developed for *Fagus orientalis* Lipsky (Saraçoğlu 1998), *Alnus glutinosa* (L.) Gaertn. (Saraçoğlu 2000), *Quercus* sp. (Durkaya 1998), and *Castanea sativa* Mill. (İkinci 2000). All of these studies, however, have been made on local or regional scales.

Turkey signed the United Nations Framework Convention on Climate Change in 2004 and the Kyoto Protocol in 2009. The emissions of greenhouse gases in Turkey were observed to increase from 170.06 Tg CO_2 in 1990 to 312.31 Tg CO_2 in 2005, representing an increase of 83.06% (NIR Turkey 2007). A great portion of the greenhouse gas emissions originates from the energy sector, 77.30% of total greenhouse gas emissions. In Turkey, during the period of 1990-2005, sectors other than forestry have caused greenhouse gas emissions (NIR Turkey 2007).

National greenhouse gases inventory reports for Turkey were prepared for 2004 and 2005 (UNFCCC 2009). In these reports, an attempt was made to calculate the amount of carbon stored in the forests annually by using the annual volume increment values. In converting the annual volume increment values into biomass and amount of carbon, some of the biomass factors given in GPG-LULUCF and the BEF values obtained from a small number of biomass studies (Uğurlu et al. 1976; Sun et al. 1980; Durkaya 1998; Saraçoğlu 1998; İkinci 2000; Saraçoğlu 2000) in Turkey were used. Recent increases in biomass studies and recent changes in carbon inventory methodologies require the recalculation of the carbon stocks and accumulations in Turkey's forests.

The study aimed, by using the methods stated in AFOLU (IPCC 2006) and recalculated coefficients, to: 1) determine the carbon stocks in the above-ground and below-ground biomass according to the 2004 National Forest Inventory; 2) estimate the carbon stocks in dead wood, litter, and forest soil; 3) calculate the amount of carbon accumulated in the living biomass annually in Turkey's forests by using the gain-loss method; and 4) determine the amount of carbon removed from the forests by the production of industrial roundwood and fuelwood, forest fires, and illegal cuttings.

Materials and methods

Forest inventory data

There were 2 national forest inventories published in Turkey, in 1972 and 2004. These forest inventories do not pertain to a short period but cover a period of many years. The 1972 inventory included the period of 1963-1972, while the 2004 inventory included the period of 1973-2004. In this study, the data of both forest inventories were used (OGM 1980; OGM 2006). The distribution of the area, stand volume, and increment values of coniferous, deciduous, and coppice forest, as determined by these inventories, are shown in Table 1.

Determination of carbon stocks

The carbon stocks in the biomass were calculated using the following formula:

$$C = (V \times BCEF_I) \times (1 + R) \times CF \qquad (1)$$

where V is the growing stock volume (m^3), $BCEF_I$ is the factor for conversion and expansion of stem volume to above-ground biomass ($Mg\ m^{-3}$), R is the root to shoot ratio (dimensionless), C is the carbon stock (Mg), and CF is the carbon factor. According to AFOLU, if the merchantable stem volume is determined in the National Forest Inventory (NFI), the $BCEF_S$ (conversion and expansion factor to convert the merchantable stem value to above-ground biomass) must be used in these calculations. However, $BCEF_I$ was used in this study because the whole stem volume was measured instead of merchantable stem volume in Turkey's NFI. $BCEF_I$ is basically obtained by multiplying wood density (WD) by BEF. Thus, first the BEF coefficients specific to each tree species were calculated from the previous biomass studies carried out for Turkey's forests. Species-specific BCEF coefficients were then obtained by using WD and calculated BEFs (Table 2). Some studies also indicated

Table 1. Comparison of area and growing stock values of Turkey's forests in the forest inventories of 1972 and 2004 (OGM 1980; OGM 2006).

Productivity	Group of species	1972			2004			Difference		
		Area	Growing stock	Volume increment	Area	Growing stock	Volume increment	Area	Growing stock	Volume increment
		(10^6 ha)	(10^6 m^3)	(10^6 m^3)	(10^6 ha)	(10^6 m^3)	(10^6 m^3)	(10^6 ha)	(10^6 m^3)	(10^6 m^3)
Productive	Coniferous	4.56	548.70	15.59	7.08	818.56	22.24	2.52	269.86	6.65
	Deciduous	1.61	210.03	5.20	1.86	310.01	7.67	0.25	99.98	2.47
	Coppice	2.68	117.73	4.81	1.68	70.46	3.93	-1.00	-47.27	-0.88
	Subtotal/mean	8.85	876.46	25.60	10.62	1199.03	33.84	1.77	322.57	8.24
Degraded	Coniferous	3.95	44.42	1.09	5.69	51.07	1.17	1.74	6.65	0.08
	Deciduous	0.81	9.94	0.25	0.81	14.37	0.35	0.00	4.43	0.10
	Coppice	6.59	45.51	1.11	4.07	23.65	0.93	-2.52	-21.86	-0.18
	Subtotal/mean	11.35	99.87	2.45	10.57	89.09	2.45	-0.78	-10.78	0.00
Total/mean		20.20	976.33	28.06	21.19	1288.12	36.28	0.99	311.79	8.24

Table 2. Wood density, BEF, and BCEF coefficients calculated after reevaluation of the biomass studies in Turkey.

Tree species	Number of sample trees	Diameter at 1.3 m height range (cm)	Wood density [b] ($Mg\ m^{-3}$)	BEF_I	$BCEF_I$ ($Mg\ m^{-3}$)	Reference
Pinus sylvestris	10	19.5-31.0	0.426	1.242 ± 0.092	0.529 ± 0.039	Uğurlu 1976
Pinus sylvestris[a]	33	17.0-66.0		1.198 ± 0.032	0.510 ± 0.014	Atmaca 2008
Pinus sylvestris	13	6.1-10.9		1.263 ± 0.050	0.535 ± 0.043	Tolunay 2010
Pinus sylvestris	55	7.1-63.2		1.279 ± 0.106	0.545 ± 0.058	Çömez 2010
Total/ weighted mean	111			1.243 ± 0.086	0.530 ± 0.037	
Pinus brutia	14	9.0-39.8	0.478	1.225 ± 0.062	0.586 ± 0.029	Sun et al. 1980
Pinus brutia[a]	33	8.0-52.0		1.349 ± 0.022	0.645 ± 0.011	Ünsal 2007
Total/ weighted mean	47			1.319 ± 0.064	0.630 ± 0.031	
Pinus nigra[a]	44	12.0-60.0	0.470	1.071 ± 0.026	0.503 ± 0.012	Çakıl 2008
Picea orientalis[a]	30	20.0-52.0	0.358	1.132 ± 0.009	0.405 ± 0.003	Özkaya 2004
Quercus sp.	32	10.0-31.0	0.570	1.324 ± 0.157	0.755 ± 0.089	Durkaya 1998
Fagus orientalis[a]	32	11.0-46.0	0.530	1.228 ± 0.072	0.651 ± 0.042	Saraçoğlu 2000
Castanea sativa[a]	34	15.0-37.0	0.400	1.320 ± 0.068	0.528 ± 0.027	İkinci 2000
Alnus glutinosa[a]	86	7.0-30.0	0.407	1.103 ± 0.051	0.449 ± 0.020	Saraçoğlu 1998

[a] Calculated for the measurement diameter at 1.3 m height range in the field using the equations and tables developed for the estimation of biomass values.
[b] As et al. (2001).

that there were practical benefits in using common coefficients for coniferous and deciduous tree groups instead of species-specific coefficients in carbon inventories (Asan 1995; Raev et al. 1997). The WD, BEF, and BCEF coefficients specific to coniferous and deciduous groups were therefore obtained by calculating the weighted mean according to the growing stock values (Tables 3 and 4). The *R* and *CF* values used in the Eq. (1) were taken from AFOLU (Table 5). $BCEF_S$ was only used in the conversion of coppice forest tree volumes into above-ground biomass values. $BCEF_S$ were taken from NIR Turkey (2007) (Table 4).

Carbon densities per unit area, which were calculated by Tolunay and Çömez (2008) through a survey of studies from 1959-2008, were used in the calculation of carbon stocks in litter and soil. As there were not many studies on degraded forests, carbon densities of maquis areas were used for those areas (Table 6).

There have not been many studies in Turkey on dead wood carbon stocks. However, in the Forest Management Regulations, it is stated that 1 or 2 dead trees need to be left per hectare in order to preserve biological diversity. Therefore, in the calculation of dead wood carbon stocks, it was assumed that about 1% of the growing stock per hectare was dead wood.

Annual carbon accumulations in the living biomass

The gain-loss method (IPCC 2006) was used in this study to determine the annual carbon accumulation in Turkey's forests. In this method, the annual changes in the amount of carbon accumulated in the biomass in forests are calculated by means of the following formula:

$$\Delta C_B = \Delta C_G - \Delta C_L \quad (2)$$

where ΔC_B is the annual change in biomass carbon stocks ($Mg\ C\ year^{-1}$), ΔC_G is the annual increase in carbon stocks due to biomass growth ($Mg\ C\ year^{-1}$), and ΔC_L is the annual decrease in carbon stocks due to biomass loss ($Mg\ C\ year^{-1}$).

The following formula is used in calculating the annual increments in the carbon stocks in the tree biomass:

Table 3. Wood densities (WD), growing stock volume (V), and stem biomass over bark of tree species.

Tree species	Wood density ($Mg\ m^{-3}$)	Growing stock volume ($10^6\ m^{-3}$)	Stem biomass over bark (WD*V) (Tg)
Pinus brutia	0.478[a]	270.09	129.10
Pinus nigra	0.470[a]	296.72	139.46
Pinus sylvestris	0.426[a]	117.78	50.18
Pinus pinea	0.470[b]	1.14	0.54
Pinus halepensis	0.480[c]	0.02	0.01
Pinus pinaster	0.440[d]	4.41	1.94
Pinus radiata	0.380[e]	0.00	0.00
Abies sp.	0.350[a]	93.46	32.71
Picea orientalis	0.358[a]	50.67	18.14
Cedrus libani	0.430[a]	27.36	11.76
Juniperus sp.	0.460[a]	7.94	3.65
Other coniferous	0.431[f]	0.02	0.01
Fagus orientalis	0.530[a]	263.77	139.80
Quercus sp.	0.570[a]	137.74	78.51
Carpinus sp.	0.630[d]	1.31	0.82
Alnus sp.	0.407[a]	5.80	2.36
Populus sp.	0.350[d]	0.12	0.04
Castanea sativa	0.480[d]	5.94	2.85
Fraxinus sp.	0.562[g]	1.69	0.95
Other deciduous	0.550[h]	2.13	1.17

[a] As et al. (2001); [b] Erten and Sözen (1997a); [c] Erten and Sözen (1997b); [d] IPCC (2003); [e] Topaloğlu (2005); [f] Mean of coniferous; [g] Gürsu (1971); [h] Mean of deciduous.

Table 4. Recalculated common WD, BEF, and BCEF coefficients for coniferous and deciduous trees.

Group of species	WD ($Mg\ m^{-3}$)	BEF_I	BEF_S[a]	BEF_R	$BCEF_I$ ($Mg\ m^{-3}$)	$BCEF_S$ ($Mg\ m^{-3}$)	$BCEF_R$[b] ($Mg\ m^{-3}$)
Coniferous	0.446	1.195	1.240	1.378	0.533	0.553	0.614
Deciduous	0.541	1.230	1.260	1.400	0.665	0.682	0.757

[a] NIR Turkey, 2007; [b] Calculated by dividing $BCEF_S$ by 0.9 (IPCC 2006).

$$\Delta C_G = I_v \times BCEF_I \times (1 + R) \times CF \qquad (3)$$

where I_v is the annual volume increment ($m^3\ year^{-1}$).

Leibniz's formula is used in the calculation of annual increment (Kalıpsız 1988):

$$I_i = I_f \times [1 + (p / 100)]^n \qquad (4)$$

where I_i and I_f represent the amount of volume increment ($m^3\ year^{-1}$) at the beginning and end of the period, respectively; *p* represents the rate of increment (%); and *n* is the length of the period.

The amount of increment values given for the years between 1990 and 1995 by Raev et al. (1997) are used in the calculation of *p*. For this period, *p* was found to be 0.565%. In addition, p was calculated as 1.515% over the period between 1995 and 2004.

Annual losses in carbon stocks are calculated by the following formula:

$$\Delta C_L = L_W + L_F + L_D \quad (5)$$

where L_W is the annual carbon loss due to industrial roundwood removals (Mg C $year^{-1}$), L_F is the annual biomass carbon loss due to fuelwood removals (Mg C $year^{-1}$), and L_D is the annual biomass carbon loss due to disturbances (Mg C $year^{-1}$).

The L_W and L_F values were calculated by means of the following equation:

$$L_i = H \times BCEF_R \times (1 + R) \times CF \quad (6)$$

where L_i is L_W or L_F, H is the annual volume of industrial roundwood or fuelwood removals (m^3 $year^{-1}$), $BCEF_R$ is the biomass conversion and expansion factor for conversion of removals in merchantable volume to above-ground biomass removals (including bark) (Mg m^{-3}), and $BCEF_R$ is found by dividing $BCEF_S$ by 0.9 (IPCC 2006).

The following equation was used in determining the amount of carbon in the areas subjected to disturbances by insects, fire, etc.:

$$L_D = A \times (B_w - B_s + R) \times CF \quad (7)$$

where A is the area affected by disturbances (ha $year^{-1}$), and B_w and B_s are the average above-ground and stem biomass over bark of forest areas affected by the disturbances (Mg ha^{-1}).

The amounts of wood removed from the forests by the harvest of wood and by illegal cuttings, and the amount of forests burned by fire during the years 1990-2005, are given in Table 7. Using this data, the amount of carbon removed from forests annually was estimated. Certain presumptions, however, were used in these estimations. These presumptions were as follows:

Table 5. Default root to shoot ratio and carbon factor given in AFOLU for temperate zone forests (IPCC 2006).

Group of species	Above-ground biomass (Mg ha^{-1})	Root to shoot	Carbon factor
Coniferous	<50	0.40	0.51
	50-150	0.29	
	>150	0.20	
Deciduous	<75	0.46	0.48
	75-150	0.23	
	>150	0.24	

Table 6. Carbon density (Mg ha^{-1}) in litter and soil in Turkish forests (Tolunay and Çömez 2008).

Group of species	Litter		Soil[a]	
	Number of samples	Mg ha^{-1}	Number of samples	Mg ha^{-1}
Coniferous	591	7.46	996	76.56
Deciduous	371	3.75	193	84.82
Maquis	41	1.70	45	79.60
Total/weighted mean	1003	5.86	1234	77.96

[a] Soil organic carbon stock to a depth of 100 cm.

Table 7. Forest areas damaged by fire and amounts of industrial roundwood, fuelwood, and illegal cuttings, 1990-2005.

Year	Amount of burnt area (10^3 ha)	Industrial roundwood[a] (10^6 m^3)			Fuelwood[a] (10^6 m^3)			Illegal cuttings[b] (10^6 m^3)	Total cuttings (10^6 m^3)
		Coniferous	Deciduous	Total	Coniferous	Deciduous	Total		
1990	13.74			6.58			9.11	7.67	23.36
1991	8.08			6.51			8.63	7.43	22.57
1992	12.23			6.90			8.36	7.19	22.45
1993	15.39			7.01			8.13	6.96	22.10
1994	38.13			6.71			6.28	6.74	19.73
1995	7.68			8.05			7.15	6.52	21.72
1996	14.92			7.53			7.80	6.31	21.64
1997	6.32			6.97			6.93	6.11	20.01
1998	6.76			7.05			6.28	5.92	19.25
1999	5.80			7.07			6.13	5.73	18.93
2000	26.35	5.76	1.57	7.33	1.89	4.00	5.89	5.48	18.70
2001	7.39	5.16	1.62	6.78	1.90	3.79	5.69	5.21	17.68
2002	8.51	6.31	1.70	8.01	1.93	3.76	5.69	4.95	18.65
2003	6.64	5.62	1.70	7.32	2.05	3.81	5.86	4.65	17.83
2004	4.88	6.34	1.91	8.25	2.14	3.95	6.09	4.35	18.69
2005	2.82	6.26	1.84	8.10	2.15	3.60	5.75	4.05	17.90
Mean	11.60	5.91	1.72	7.26	2.01	3.82	6.86	5.95	20.08

[a] OGM (2009); [b] DPT (2001) and DPT (2007).

1) Deciduous and coniferous group distribution of the produced wood in Turkey has been recorded only since 2000. Before 2000, the records were only in terms of roundwood and fuelwood (Table 7). In order to estimate the amount of carbon removed due to wood production, the deciduous and coniferous group distribution of the wood must be known. Besides, in coppice forests, the roots do not die after the cutting, and they reproduce buds. Therefore, R in Eq. (6) must be taken as 0 in the calculation of the carbon loss caused by the wood production in coppice forests. The deciduous and coniferous wood production ratios were determined for 2000-2005 in order to make these calculations. The deciduous and coniferous distribution of wood produced in 1990-1999 was determined by using these ratios. Wood is assumed to be produced at the full annual increment rates while calculating the amount of wood produced from the coppice forests. Eq. (4) was used in the calculation of the increment of coppice forests. Thus, p was calculated as -0.615% between the years 1972 and 2004.

2) A significant amount of illegal fuelwood cutting is being done in Turkey. There are not very reliable data available on illegal cuttings. There is, however, some estimation made on the subject. Data given in DPT (2001) and DPT (2007) were used in this study (Table 7). It was assumed that the amount of illegal cuttings was the same in deciduous, coniferous, and coppice forests.

3) There are no reliable data in Turkey on the biomass losses occurring in forests due to damage by insects and fungi. All of the trees damaged are cut, and the amounts of wood cut in this way are also entered in the records for industrial or fuelwood. Therefore, in the calculations made here, it was assumed that there was no damage due to insects or fungi.

4) With regard to forest fires, only the amount of forest area burned by fire could be obtained. Fire-damaged trees were used as fuelwood, similar to trees damaged by insects and fungi. For this reason, the amount of fire-damaged trees was given as roundwood or fuelwood. It was accepted that only

branches and foliage burned to account for carbon losses via forest fires. The average biomass density for all forest ecosystems was used to calculate the losses that occurred in the biomass due to forest fires.

Results

Total carbon stock in Turkey's forests

The total carbon stock in Turkey's forests was calculated as 2251.26 Tg C in 2004. An important portion of total carbon stock was in the forest soils. The carbon stock in the living biomass was calculated as 479.87 Tg C, and 92.20% of carbon stock in the living biomass belonged to the productive forests, while the remaining 7.80% belonged to the degraded forests (Table 8).

The biomass carbon density was also found, calculated as 22.65 Mg C ha^{-1}. According to the forest inventory of 2004, the total biomass carbon density in productive forests was calculated as 41.66 Mg C ha^{-1}. The majority of this total biomass density, 32.44 Mg C ha^{-1}, belonged to the above-ground biomass, while the remaining 9.22 Mg C ha^{-1} belonged to the below-ground biomass (Table 9). The carbon density was the highest in deciduous forests, with a value of 154.66 Mg C ha^{-1} (Table 9). As for living biomass carbon stock, the highest value was in the *Pinus nigra*, *Fagus orientalis*, and *Pinus brutia* forests, with values of 104.54, 104.26, and 102.79 Tg C, respectively (Figure 1).

Table 8. Carbon stocks (Tg) in the forest carbon pools of Turkey in 2004.

Productivity	Group of species	Above-ground	Below-ground	Total living biomass	Litter	Dead wood	Soil	Grand total
Productive	Coniferous	222.51	64.53	287.04	52.84	2.28	542.31	884.48
	Deciduous	98.96	22.76	121.72	6.96	0.99	157.49	287.15
	Coppice	23.07	10.61	33.68	6.30	0.22	142.58	182.79
	Total	344.53	97.90	442.43	66.11	3.50	842.38	1354.42
Degraded	Coniferous	13.88	5.55	19.44	9.67	0.14	452.87	482.12
	Deciduous	4.59	2.11	6.70	1.38	0.05	64.48	72.60
	Coppice	7.74	3.56	11.31	6.92	0.08	323.82	342.12
	Total	26.21	11.22	37.44	17.96	0.26	841.18	896.84
Grand Total		370.74	109.12	479.87	84.07	3.76	1683.56	2251.26
%		16.47	4.85	21.32	3.73	0.17	74.78	100.00

Table 9. Carbon density (Mg ha^{-1}) in the forest carbon pools of Turkey in 2004.

Productivity	Group of species	Above-ground	Below-ground	Total living biomass	Litter	Dead wood	Soil	Grand total
Productive	Coniferous	31.41	9.11	40.52	7.46	0.32	76.56	124.86
	Deciduous	53.30	12.26	65.55	3.75	0.53	84.82	154.66
	Coppice	13.72	6.31	20.03	3.75	0.13	84.82	108.74
	Total	32.44	9.22	41.66	6.22	0.33	79.31	127.52
Degraded	Coniferous	2.44	0.98	3.42	1.70	0.03	79.60	84.74
	Deciduous	5.66	2.60	8.27	1.70	0.06	79.60	89.62
	Coppice	1.90	0.88	2.78	1.70	0.02	79.60	84.10
	Total	2.48	1.06	3.54	1.70	0.02	79.60	84.87
Grand Total		17.50	5.15	22.65	3.97	0.18	79.46	106.25

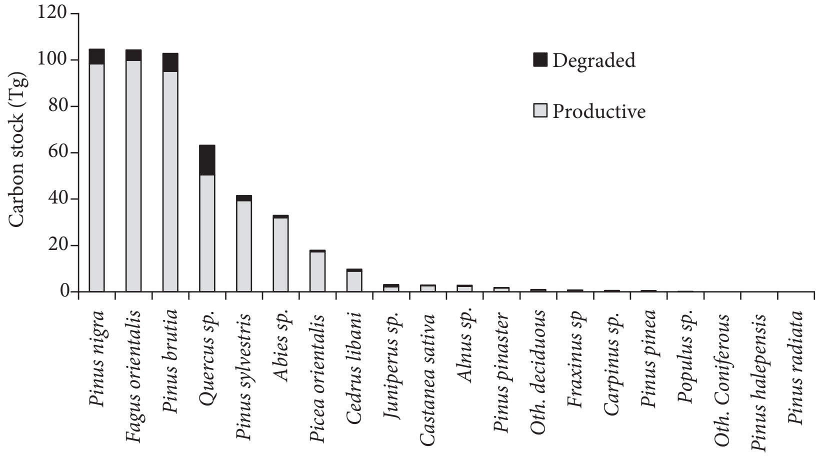

Figure 1. Distribution of carbon stocks of living tree biomass in productive and degraded forest areas, according to the Turkish National Forest Inventory of 2004.

Annual net carbon accumulation

Using the gain-loss method, Turkey's forests were found to have absorbed 13.68 Tg C year^{-1} from the atmosphere in 2004. The majority of that amount, 12.63 Tg C year^{-1}, belonged to the productive forests, while the remaining 1.05 Tg C year^{-1} portion belonged to the degraded forests (Table 10). Carbon accumulated in the forests due to volume increment, however, is removed from the forests through the fuelwood and industrial roundwood production. During 1990-2005, an average cutting amount of 7.26 million m^3 year^{-1} was done for industrial roundwood production, while an average amount of 6.86 million m^3 year^{-1} was done for fuelwood production. Illegal cuttings have also occurred in Turkey's forests. The illegal cuttings were estimated at an average of 5.95 million m^3 year^{-1} for the 15-year period. A volume of 18.69 million m^3 year^{-1} is removed from the volume increment, which reached 36.28 million m^3 year^{-1} by cuts in Turkey's forest in 2004. Furthermore, the forest area damaged by fires in Turkey is reported to be 11,600 ha year^{-1} on the average for the period of 1990-

Table 10. Annual volume and biomass carbon increments of Turkish forests in 2004.

Productivity	Group of species	Annual volume increment		Annual biomass carbon increment			
		10^6 m^3	m^3 ha^{-1}	AB	BB	Total	Mg ha^{-1}
Productive	Coniferous	22.24	3.14	6.04	1.75	7.79	1.10
	Deciduous	7.67	4.13	2.45	0.56	3.01	1.62
	Coppice	3.93	2.34	1.25	0.58	1.83	1.09
	Total	33.83	3.19	9.74	2.89	12.63	1.19
Degraded	Coniferous	1.17	0.20	0.32	0.13	0.45	0.08
	Deciduous	0.35	0.44	0.11	0.05	0.16	0.20
	Coppice	0.93	0.23	0.3	0.14	0.44	0.11
	Total	2.45	0.23	0.73	0.32	1.05	0.10
Grand Total		36.28	1.71	10.47	3.21	13.68	0.65

AB = Above-ground biomass; BB = Below-ground biomass.

2005 (Table 7). The amount of biomass carbon removed from Turkey's forests through industrial and fuelwood productions, illegal cuttings, and forest fires during 1990-2005 was calculated as 2.95, 2.60, 2.41, and 0.10 Tg C year^{-1} on average, respectively (Table 11). Hence, it is understood that, as an average figure, an amount of 4.50 Tg C year^{-1} was stored in the biomass during a period of 15 years. However, the annual carbon accumulation in the biomass showed an increasing trend during that period. Accordingly, the net annual carbon accumulation, which was 2.20 Tg C year^{-1} in 1990, had increased to 6.82 Tg C year^{-1} by 2005 (Table 11).

Discussion

According to data from UN-ECE/FAO (2006), in 2005, there was a carbon stock of 282.7 Pg C (or 71.5 Mg C ha^{-1}) in the global forest ecosystems. In research carried out on the European forests by taking 1990 as a basis of evaluation, the biomass carbon stocks were found to vary from 5.5 to 9.0 Pg C, depending on the different number of countries included in the evaluation and hence the different size of the forest areas involved (Table 12). In another study of 47 European countries for 2005, the European forests were reported to have a carbon stock of 43.93 Pg C (UN-ECE/FAO 2006). The biomass carbon densities in European forests were found to range from 32.0 to 53.2 Mg C ha^{-1} (Table 12). According to UN-ECE/FAO (2006) data, the average biomass carbon density in European forests is 43.9 Mg C ha^{-1}. In Turkey, having a forest area of 21.2 million ha, an amount of 22.65 Mg C ha^{-1} was found to be stored in the forest biomass as of 2004. This value is quite lower than the average value for Europe. In the productive forests, however, the biomass carbon density is 41.66 Mg C ha^{-1}, which is slightly lower than the average value for Europe. Karjalainen et al. (2003) reported that the biomass carbon densities in northern and southern European forests are lower than those of central European forests, due to northern Europe's cold climate and drought in southern Europe. In Turkey, the biomass carbon density values of

Table 11. Biomass carbon amounts removed by cuttings and annual carbon storage in Turkish forests, 1990-2005 (Tg C year^{-1}).

Years	Annual C loss					Annual C storage	
	Roundwood	Fuelwood	Illegal cutting	Forest Fire	Total	Before harvest	After harvest
1990	2.72	3.50	3.11	0.11	9.44	11.64	2.20
1991	2.70	3.29	3.01	0.07	9.07	11.70	2.63
1992	2.85	3.18	2.91	0.10	9.04	11.77	2.73
1993	2.90	3.08	2.82	0.13	8.93	11.83	2.90
1994	2.69	2.37	2.73	0.31	8.10	11.90	3.80
1995	3.30	2.70	2.64	0.06	8.70	11.97	3.27
1996	3.12	2.95	2.55	0.12	8.74	12.15	3.41
1997	2.84	2.62	2.47	0.05	7.98	12.33	4.35
1998	2.84	2.37	2.39	0.06	7.66	12.52	4.86
1999	2.84	2.31	2.32	0.05	7.52	12.71	5.19
2000	2.95	2.22	2.22	0.22	7.61	12.90	5.29
2001	2.71	2.14	2.11	0.06	7.02	13.10	6.08
2002	3.21	2.15	2.00	0.07	7.43	13.30	5.87
2003	2.94	2.21	1.88	0.05	7.08	13.50	6.42
2004	3.34	2.30	1.76	0.04	7.44	13.68	6.24
2005	3.25	2.18	1.64	0.02	7.09	13.91	6.82
Mean	2.95	2.60	2.41	0.10	8.05	12.56	4.50

Table 12. Comparison of results of studies conducted on the biomass carbon stock and annual carbon flux in the forests of the world, Europe, and Turkey.

Region	Years	Forest area (Mha)	Total C stock in biomass (Tg C)	C density in biomass (Mg C ha^{-1})	Total biomass C flux before harvest		Total biomass C flux after harvest		Reference
					(Tg C year^{-1})	(Mg C ha^{-1})	(Tg C year^{-1})	(Mg C ha^{-1})	
World	1987-90	4165	359000	86			-900	-0.22	Dixon et al. 1994
World	1990	4077	299181	73.4					UN-ECE/FAO 2006
World	2005	3952	282651	71.5			-1102	-0.28	UN-ECE/FAO 2006
Europe (47 countries)	1990	989	42004	42.5					UN-ECE/FAO 2006
Europe (47 countries)	2005	1001	43928	43.9			128.3	0.13	UN-ECE/FAO 2006
Europe	1990	182	7300	40.1					Fang et al. 2006
Europe (30 countries)	1990	135.8	6148.28	45	216.5	1.59	76.7	0.56	Schelhaas and Nabuurs 2001
Europe (30 countries)	1990	149	7700	51.7	210	1.41			Goodale et al. 2002
Europe (15 countries)	1980s	149	7929	53.2			101.3	0.68	Nabuurs et al. 1997
Europe (15 countries)	1990s	110.1	5505	50			63.2	0.57	Liski et al. 2000
Europe	1987-1990	283	9000	32			90-120	0.32-0.42	Dixon et al. 1994
Europe	1995	339			363	1.07			Janssens et al. 2003
Europe (27 countries)	1995	128.6	6489	50.5			81.9	0.64	Karjalainen et al. 2003
Turkey	1995	20.559			21.70	1.06			Asan 1999
Turkey	1990	5.466	246.18	45	5.32	0.97	2.51	0.46	Schelhaas and Nabuurs 2001
Turkey	1995	20.559					3.7	0.18	Raev et al. 1997
Turkey	1996	9.954	399.78	40.16	7.93	0.80			UN-ECE/FAO 2000.
Turkey	1996	20.713	429.00	20.71	15.10	0.73	7.87	0.38	Evrendilek 2004.
Turkey	2005	21.189			18.54	0.88	13.10	0.62	NIR Turkey 2007
Turkey	2005	21.189	479.87	22.65	13.91	0.66	6.82	0.32	Current study

productive forests are higher than those of countries like Portugal, Albania, Croatia, and Macedonia, which are located in a similar climatic zone (Karjalainen et al. 2003).

By the gain-loss method, the amount of carbon accumulated annually in the biomass in Turkey's forests was calculated to be 4.50 Tg C $year^{-1}$ (or 16.47 Tg CO_2 $year^{-1}$) on average during 1990-2005. During this period, the amount of carbon accumulated annually in the forests increased continuously, rising from 2.20 Tg C $year^{-1}$ (or 8.05 Tg CO_2 $year^{-1}$) to 6.82 Tg C $year^{-1}$ (or 24.96 Tg CO_2 $year^{-1}$). Increase of forest areas, decrease in the production of fuelwood, and decrease in illegal cuttings affected the carbon increase in biomass (Tables 7 and 11). The increase of migration from rural areas to urban areas in Turkey is very effective in increasing forest areas and decreasing illegal cuttings (Yeşil and Asan 2007). In addition, conversion of coppices to high forest, rehabilitation of degraded forests, and an increase of plantations led to an increase in carbon sequestration. For greenhouse gas emissions, 7.99% of the total amount, which was 312.31 Tg CO_2 as of 2005, was compensated for by the forests in Turkey. This value is somewhat less than that reported for Europe. For example, the rate of compensation of emissions by the amount of carbon accumulated in the European forests was reported to be 9.5% according to Nabuurs et al. (1997), 7% according to Liski et al. (2000), and 8.7% according to Pussinen et al. (2009). Liski et al. (2005) reported that the European land biosphere absorbed 7%-12% of European anthropogenic CO_2 emissions.

Differences exist between the results obtained in this study of biomass carbon stock or the annual carbon accumulation in Turkey's forests, and the results obtained in other studies carried out on Turkey's forests. Such differences are due to the differences in the amount of Turkey's forest area, differences in the methods of calculation used, differences between the accepted amount of carbon removed from the forests in different ways, the lack of sufficient data, and the differences in the years taken as a basis of evaluation. As an example, the amount of Turkey's forest areas was reported to be 9.954, 5.466, 20.559, 20.713, and 21.19 Mha according to UN-ECE/FAO (2000), Schelhaas and Nabuurs (2001), Raev et al. (1997), Evrendilek (2004), and NIR Turkey (2007), respectively (Table 12). This result is related to the definition of areas accepted as forest area (Nabuurs and Schelhaas 2003). The forest areas exhibiting a cover of less than 10%, which are called degraded forests in this study, are not accepted as forests by the FAO and Forest Resources Association (FRA). Therefore, different values for the amount of forest areas or for amounts of carbon calculated may be found in various studies conducted for this purpose. "Forest area" must be determined clearly for an accurate carbon inventory. There are 2 forest inventories available in Turkey, one completed in 1972 and the other in 2004. These inventories cover a period of about 10 years. Hence, they belong not to a certain year, but to a certain period of years, and therefore they fail to show the increases or decreases occurring annually in the forest areas. The amount of forest area cited in NIR Turkey (2007) and in this study are the same. There are, however, some differences in the calculations for carbon flux before and after cuttings. In this study, the annual carbon storage value before cuttings was calculated as 13.91 Tg C $year^{-1}$. This value is given as 18.54 Tg C $year^{-1}$ in NIR Turkey (2007). The difference between the findings of NIR Turkey (2007) and this study obtained on the C flux after cuttings is actually much more remarkable (Table 7). According to NIR Turkey (2007), carbon accumulation in the living biomass after harvest of Turkey's forests was estimated to be 13.10 Tg C in 2005. In this study, the net annual carbon accumulation was found to be half of the value calculated by NIR Turkey (2007). The reason for this might be the differences between LULUCF and AFOLU methodologies. This difference may be due to the use of BEF values obtained from a small number of locally conducted biomass studies by NIR Turkey (2007). Furthermore, oven-dry wood density (oven-dry weight divided by oven-dry volume) values were used instead of basic wood density (oven-dry weight divided by fresh volume) in the calculations made by NIR Turkey (2007). Additionally, the carbon factor (CF) used in converting the biomass into carbon value was taken as 0.50 in NIR Turkey (2007). In this study, the coefficients given by the IPCC (2006) for temperate zone forests were used. The CF value was accepted to be 0.51 for coniferous forests and 0.48 for deciduous forests.

In conclusion, in order to reduce uncertainties in Turkey's carbon inventory, there is a need to adapt the methods of carbon inventory to the methods of the national forest inventory presently used to determine the stem volume. For example, inventories based on the principal tree species are currently available in Turkey, but the amounts of mixed forests and secondary forest trees are not included in such inventories. No detailed information on the damage caused by insects, fungi, and forest fires is registered, either. The amount of wood cutting is cited only for conifer and broadleaf forests, and even this practice has started only after 2000. Therefore, the annual changes in forest area should first be determined in Turkey, and detailed records of the quality and quantity of forest damage should be kept. Furthermore, the factors of BEF, BCEF, R, or CF required for determining the forest biomass and carbon stocks need more biomass research. Emphasis should be given to research on carbon accumulation and stock in soil, litter, and coarse woody debris or dead wood, which are other important carbon pools in a forest ecosystem. In this study, carbon stocks of soil and litter were interpreted by reviewing former studies in Turkey. It covers a 50-year period, not the 2004-based carbon densities of soil and litter described by Tolunay and Çömez (2008). Values given by the authors were lower than the value of soil carbon, given as 96.2 Mg ha^{-1} (Janzen 2004), for temperate forests. Determination of carbon stocks of litter, soil, and dead wood for the same year of carbon inventory is essential. For this, more sensitive estimations of carbon stocks of litter, dead wood, and soil can be made based on 563 Level 1 sample plots in the context of the ICP Forests Program. Annual carbon fluxes of litter, dead wood, and soil were not determined in this study. Fluxes of these carbon pools were generally accounted for with modeling studies. Annual litterfall and fine root amounts, carbon stocks in litter and soil, decomposition rates of dead woods and litter, and carbon losses due to soil respiration were used in these modeling studies (Liski et al. 2005; Liski et al. 2006). Research on litter decomposition, carbon losses via soil respiration, or fine root masses has increased in the last years in Turkey (Sarıyıldız 2003; Tüfekçioğlu et al. 2004; Sarıyıldız et al. 2005; Tüfekçioğlu et al. 2005; Tüfekçioğlu and Küçük 2005; Akburak 2008; Sarıyıldız 2008). However, these studies were generally carried in northern Turkey, and research is needed in other regions. In addition to determining the accumulation of carbon in Turkey's forests, there is a need to adapt the carbon management approach to forest management (Başkent et al. 2008; Başkent et al. 2009). The principal aim of carbon management is to increase the amount of carbon accumulated in the forest ecosystems. Reduction of deforestation, forest fires, illegal cuttings, and afforesting are the main measures for increasing the carbon accumulation. In particular, the degraded forests, making up half of Turkey's forests, have to be rehabilitated. The carbon stocks may also be increased by taking various silvicultural measures.

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