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Spatial Distribution and Temporal Change of Carbon Storage in Timber Biomass of Two Different Forest Management Units

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Abstract Forests make up large ecosystems and can play an important role in mitigating the emissions of CO_2, the most important greenhouse gas. However, they are sources of atmospheric carbon when they are disturbed by human or natural causes. Storage of carbon through expansion and adaptive management of forest ecosystems can assist in reducing carbon concentrations in atmosphere. This study proposes a methodology to produce spatially explicit estimates of the carbon storages (aboveground plus belowground) depending on land use/cover changes in two different forest ecosystems during various periods. Carbon storages for each forest ecosystem were projected according to inventory data, and carbon storages were mapped in a geographic information system (GIS). Results showed that total carbon stored in above and belowground of both forest ecosystems increased from one period to other because of especially increase of productive forest areas and decline of degraded forest areas as well as protection of spruce forests subject to insect attacks.

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1 Introduction

Rapid population growth together with faster industrial development and unrestricted utilization of natural resources has been causing drastic changes in vital ecological processes of the Earth. The greatest crisis ever faced by mankind is global warming, caused due to increased greenhouse gases, the major sources being from burning of fossil fuels, forest degradation and destruction, forest fires and accelerated decay of organic matter in the soil (Backéus, Wikström, & Lämås, 2005). In this context, terrestrial ecosystem carbon sequestration can reduce the rate of build up of greenhouse gases in the atmosphere and therefore can contribute to a better human adaptation to current and future environmental changes.

Forest ecosystem carbon sequestration is of particular interest to researchers and policy makers because, at global scales, forests account for 80–90% of terrestrial plant carbon and 30–40% of soil carbon (Harvey, 2000; Landsberg & Gower, 1997). Forests and forest soils have large capacities to both store and release carbon (Cannell, Dewar, & Thornley, 1992; Dixon et al., 1994), and detailed forest ecosystem carbon budgets are helpful for improving our understanding of the terrestrial carbon cycle and for supporting the decision-making process in forest management (J. Liu, S. Liu, & Loveland, 2006).

Estimating large-scale forest ecosystem carbon budget is complicated because of the difficulty of quantifying the impacts of both natural environmental variability and human disturbances. Different management regimes affect the ability of forests to sequester carbon. Forest biomass changes as a result of succession; direct human activities such as silviculture, harvesting, and clearing for conversion to non-forest use; natural disturbances caused by wildfire or pest outbreaks; and changes in climate and atmospheric pollutants. Human beings are accelerating the rate of increase in atmospheric CO_2 concentration through fossil fuels burning, land use, land-use changes, and forestry activities resulting in global warming and climate change during the recent times. The direct effects of land use and land-use changes have been estimated to cause a net emission of 1.7 ± 0.8 Gt carbon/year and 1.6 Gt carbon/year during the 1980s and 1990s (Houghton, 1999; Houghton et al., 2000; Upadhyay, Sankhayan, & Solberg, 2005). As a major indicator of human disturbances, land use and land cover change information, if available, needs to be incorporated into both retrospective and predictive carbon budget calculations (Liu et al., 2006). A number of reviews are available relating to modeling of land-use changes and their effects on forest and soil degradation. However, a few studies have addressed land use changes and its effects on forest vegetation, biomass and carbon storage (Adger & Brown, 1994; Burrows et al., 2003; Houghton, 1999; Kerr, Hendy, Liu, Brown, & Pfaff, 2004; Kerr, Liu, Pfaff, & Hughes, 2003; Kerr, Pfaff, & Sanchez-Azofeifa, 2002; Upadhyay et al., 2005).

Forest biomass is a useful measure for assessing changes in forest structure and a useful measure for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions (Backéus et al., 2005; Brown, Sathaye, Cannell, & Kauppi, 1996). Forest monitoring provides clues to the effects of human related disturbances (Cote & Ouimet, 1996; Covington et al., 1997). These forests also serve as references for evaluating the success of forest regeneration, growth rates, and structural changes following timber harvesting (Crowell & Freedman, 1994; Gore & Patterson, 1986; Martin & Hornbeck, 1990; Reiners, 1992; Roberts & Gilliam, 1995). Forest biomass also provides valuable information for many global issues. At present, the best approach for estimating forest biomass on a national or regional scale is to use existing data from national forest inventories (Brown, Schroeder, & Kern, 1999). This is an appropriate method for broad scale studies because inventory data are generally collected at regional scales from the population of interest and are designed to be statistically valid. Forest volume inventories have provided the basis for several national-level carbon budgets (Birdsey, 1992; Krankina, Harmon, & Winjum, 1996; Kurz & Apps, 1993). However, inventories report only the commercially valuable wood and exclude non-merchantable species and other important components such as branches, twigs, bark, stumps, foliage, roots, and seedlings and saplings. Methods and factors have been developed for converting inventoried forest volume to total biomass for a range of forest types (Brown, 1997; Cairns, Brown, Helmer, & Baumgardner, 1997; Schroeder, Brown, Mo, Birdsey, & Cieszewski, 1997).

The main goal of this paper is to produce spatially explicit estimates of the carbon storage (aboveground plus belowground) depending on two different forest ecosystems (Artvin and Camili forest ecosystems) inventory databases during various periods. We converted these volume data to estimates of aboveground biomass. Belowground biomass was estimated from a fixed converting factor relating belowground biomass to aboveground biomass. Carbon storages were mapped in a geographic information system (GIS) by each forest ecosystem. Total above and belowground carbon storages of each forest ecosystem in various periods were evaluated in context of land use and forest cover type changes as well as growing stocks for hardwood and softwood species.

2 Materials and Methods

2.1 Forest inventory data

2.1.1 Artvin Forest Planning Unit

One of the study areas is the Artvin Forest planning unit (AFPU) surrounding the city of Artvin and characterized by a dominantly steep and rough terrain with an average slope of 62% and an altitude from 400 to 2,220 m above sea level. It extends along

UTM ED 50 datum 37. zone 731,000–743,000E and 4,556,000–4,570,000N on the northeastern Black Sea region of Turkey. The total area is 5,221.2 ha. The vegetation type is forest vegetation and the dominant tree species of the vegetation are *Picea orientalis* (L.) Link, *Pinus sylvestris* L., *Abies nordmanniana* (Stev.) Spach subsp. *nordmanniana*, *Fagus orientalis* Lipsky, *Quercus petraea* (Maattuschka) Liebl. subsp. *iberica* (Steven ex Bieb.) Krassiln., *Carpinus betulus* L., *Ostrya carpinifolia* Scop., and *Pinus pinea* L. *Pinus pinea* community is locally distributed in the study area as a Mediterranean enclave (Varol, Karaer, Terzioğlu, & Kutbay, 2003). Mean annual temperature of the study area is 11.9°C, and mean annual precipitation is 719.7 mm. Main soil types are sandy clay loam, clay loam and sandy loam. In this study, 1972 and 2002 forest inventory data was used to estimate forest timber biomass in Artvin forest. Inventory data includes area and growing stocks per hectare of each forest stand type. Volume and area data of each forest stand type were obtained from Artvin forest management plans carried out in 1972 and 2002 (Anonymous, 1972, 2002).

2.1.2 Camili Forest Planning Unit

The other study area is the Camili Forest planning unit (CFPU) that covers 25,395.3 ha. It is situated in the mountain ranges of the Artvin City in the northeastern corner and Georgian border of Turkey. The study area consists of all forests, UTM European 50 datum 37. zone 736,000–757,000E, 4,581,000–4,602,000N. The altitude ranges from 360 to 2,000 m above sea level. During the summer period, the study area is often shrouded by fog, winters are mild and wet and, the average annual precipitation is 705 mm and the average temperature is 11.9°C. Local residents are scattered in lower, but in summer in higher altitudes of the area.

CFPU includes some of the regions' last pristine and natural mixed forest, dominated by *Fagus orientalis*, *Picea orientalis*, *Tilia rubra* subsp. *caucasica*, *Abies nordmanniana* subsp. *nordmanniana*, *Alnus glutinosa* subsp. *barbata*, *Castanea sativa*, *Carpinus betulus*, *Quercus pontica*, *Quercus petraea* subsp. *iberica* and *Q. hartwissiana*. The research area is one of the biodiversity rich areas in Turkey and many ancient, rare, endangered and endemic plant and animal species are found here (Başkent et al., 2004). As well, the study area included by the region which has been classified as one of the Conservation International's 39 world biodiversity hotspots (biologically the richest and the most endangered terrestrial ecoregion; Mittermeier et al., 2004). It is also categorized as temperate forests of the Caucasus as one of the 200 priority ecoregions of the Earth (WWF & IUCN, 1994). In 2005, the Camili area became a member of the International Network of Biosphere Reserves by the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2005). From the plant geographical point of view, the study area is located in Colchis sector of Euxine province of Euro–Siberian region. In this study, 1984 and 2005 forest inventory data was used to estimate forest timber biomass in the Camili forest. Inventory data includes area and growing stocks per hectare of each forest stand type. Volume and area data of each forest stand type were obtained from Camili forest management plans carried out in 1984 and 2005 (Anonymous, 1984, 2005).

2.2 Estimation of biomass and carbon

In this paper, carbon storages of hardwood and softwood species were estimated separately. Biomass for each forest types was calculated using allometric equations from the literature (Asan, Destan, & Özkan, 2002; Keleş & Başkent, 2006; Yolasığmaz, 2004). To estimate aboveground biomass, timber volume of softwoods and hardwoods were multiplied by species-specific conversion factors. These conversion factors were 1.25 for hardwoods and 1.2 for softwoods (Asan et al., 2002). Equations that compute fresh-weight biomass were multiplied by species-specific conversion factors to yield dry-weight biomass. The conversion factors were 0.64 for hardwoods and 0.473 for softwoods (Asan et al., 2002). The root biomass was estimated according to the aboveground biomass. For this reason, the aboveground biomass was multiplied by predetermined root to shoot ratios. These ratios are 0.15 for hardwoods and 0.20 for softwoods (Asan et al., 2002). Total dry weight biomass of a tree was converted to total stored carbon by multiplying by 0.45 (Asan et al., 2002). All conversion factors used in this study are also coefficients proposed for Turkey by Near East Region Convention application guidelines (General Directorate of Forestry, Turkey, 2005).

2.3 Mapping carbon storage

The GIS presentation of above- and belowground carbon storage in Artvin and Camili was accomplished using the following GIS data; forest cover type maps for Artvin (1972 and 2002) and Camili (1984 and 2005). Source scale of these maps was 1:250,000, based on the National Map Accuracy Standard for 1:250,000 maps. Forest cover type maps of case study areas (Artvin and Camili) were firstly digitized and processed using Arc/Info version 8.3 GIS with a maximum root mean square (RMS) error under 10 m and spatial database established. Spatial database consists of stand type, crown closure, forest development stages and stand type area. Given the initial spatial database, the stand type volume was

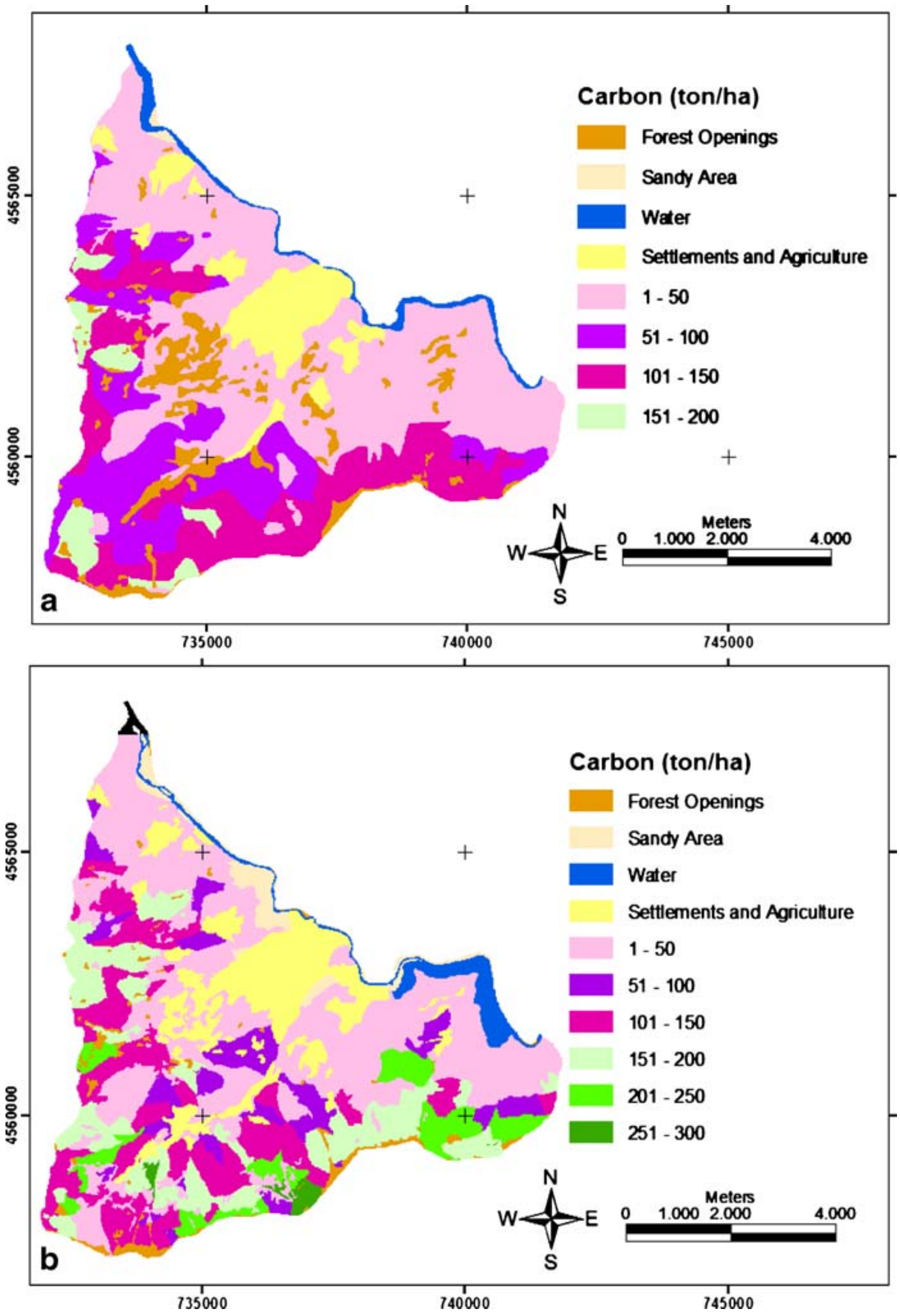

Figure 1 Maps of carbon storage (above- plus belowground) of Artvin Forest planning unit in **a** 1972 **b** 2002.

added to the database. Above- and belowground carbon storages were calculated using the GIS database including these stand type volumes and produced above- and belowground carbon storage maps (m^3/ha) in 1972 and 2002 for Artvin and, 1984 and 2005 for Camili by reclassifying a map of the forest cover type maps.

3 Results and Discussion

3.1 Spatial distribution and temporal change of carbon storage in AFPU

As of 1972, using the methodology in this article, it was estimated that forest ecosystems in AFPU contain 250,181.3 tons of carbon above and below the ground. Though 211,800.6 tons of whole carbon storages in forest ecosystem are aboveground, the rest (38,380.7 tons) are belowground. However, it was estimated that forest ecosystems contain 355,627.7 tons of carbon with 293,016.4 tons aboveground and 62,611.3 tons of carbon belowground in 2002. As shown, carbon storages increased 105,446 tons during a 30-year period. Distributions of carbon storages of AFPU in the years of 1972 and 2002 are shown in Figure 1.

The area of AFPU forests was 4,206.8 ha in 1972. The amount of forestland has decreased by approximately 143 ha between 1972 and 2002 because of population growth and agricultural expansion. The most important change between 1972 and 1985 is the extension of the city boundary towards the northern direction. Such enlargement of settlements has progressively continued up to the year 2002. The most important reason in this city expansion is the rural migration to Artvin city from 1970 to 2000. The population of Artvin has increased nearly two times over 30 years (Republic of Turkey, State Institute of Statistics, 1950–2000). Here, human interventions have been effective in conversion of forested areas to non-forest area. Thus, non-forest areas including agriculture and settlements increased from 593.9 ha in 1972 to 1046.3 ha in 2002.

Even though these changes represent a decrease in forestation of approximately 4%, total carbon storages have increased. This result can be explained to land cover changes in forest planning unit. Namely, degraded forests decreased from 1,597.6 ha in 1972 to 1,144.8 ha in 2002. Forest openings also decreased from 420.4 ha in 1972 to 112.1 ha in 2002. In addition, productive forests increased by 309 ha between 1972 and 2002. Approximately 35% of whole forest area in planning unit is dominantly spruce stands. The first insect attacks started in 1966 and penetrated into the region from the adjacent country of Georgia. The most destructive insects in the region are *Ips typographus, Ips sexdentatus* and *Dendroctonus micans* (Güner, Tüfekçioğlu, & Öztürk, 2004). Mechanical controls against these insects were implemented in 1985. Diseased trees were generally chased and removed from the area. However, these efforts were unable to stop the insect outbreaks, and therefore, biological struggles have started since 1985. For these reasons, some activities relating insect outbreaks as well as forest harvesting were made in the planning area. In

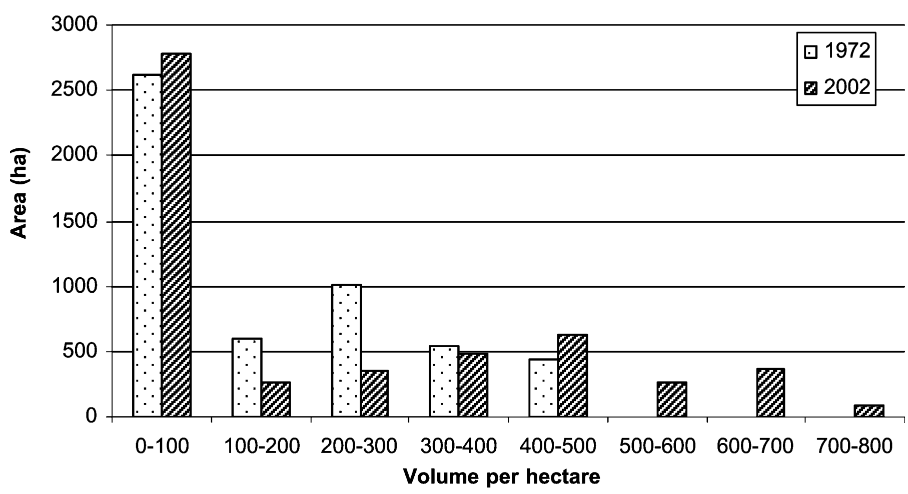

Figure 2 Distribution of areas by volume per hectare of Artvin Forest planning unit in the years of 1972 and 2002.

AFPU, harvest schedule has been prepared to generate maximum wood production up to 1985. After that year, intensive wood production has been interrupted in the forests around the city of Artvin. This means that the area of stands with high growing stocks has increased (Figure 2). Further, the quality of forest ecosystem structure during a 30-year period has increased through light silviculture made in planning unit since 1990. For example, the area of over mature stands (average dbh>36 cm) increased from 540 ha in 1972 to 713 ha in 2002. These findings show that forest ecosystems in planning unit have improved since 1972, and resulted in an increase of 234,324 tons of biomass.

3.2 Spatial distribution and temporal change of carbon storage in CFPU

It is estimated that forest ecosystems in CFPU contain 1,175,117.8 tons of carbon aboveground and

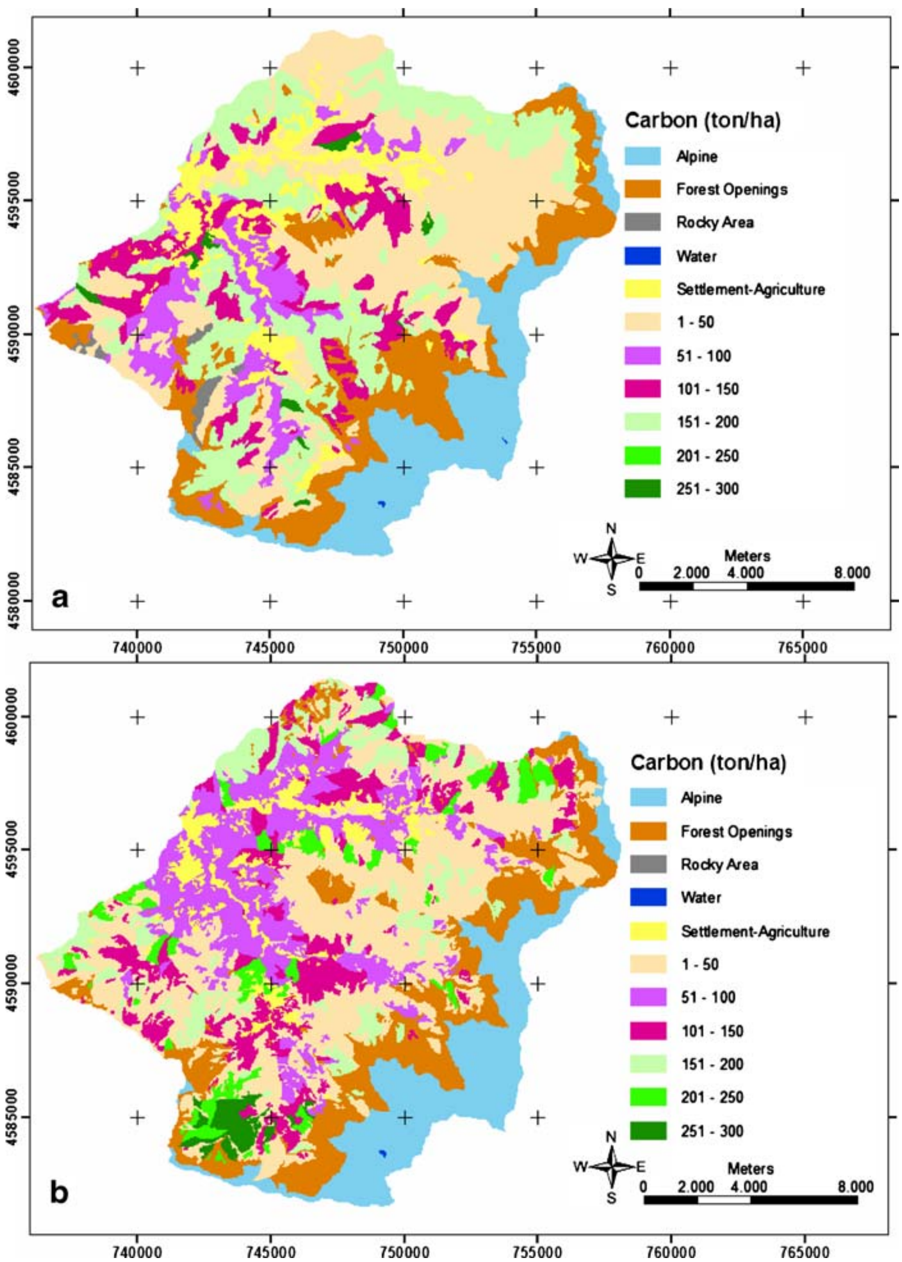

Figure 3 Maps of carbon storage (above- plus below-ground) of Camili Forest planning unit in **a** 1984 **b** 2005.

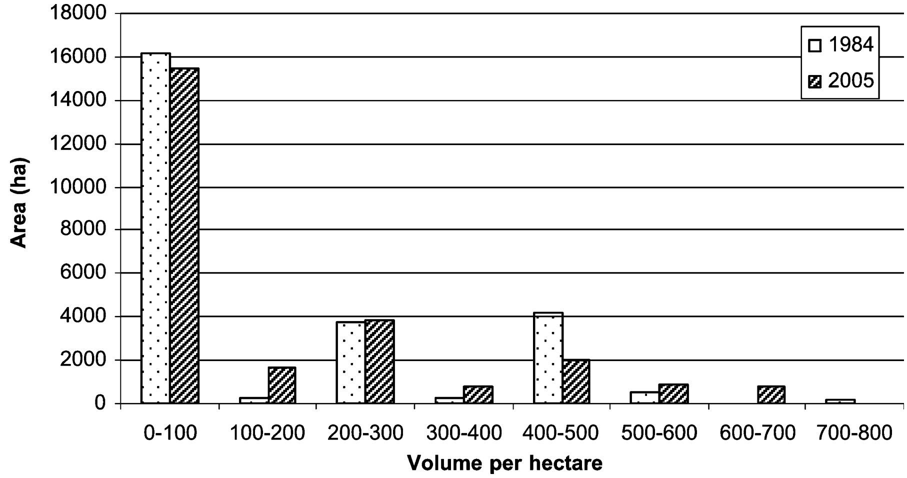

Figure 4 Distribution of areas by volume per hectare of Camili Forest planning unit in the years of 1984 and 2005.

176,267.6 tons of carbon belowground in 1984. Carbon storages above and belowground in 2005 are also estimated 1,190,529.1 and 182,409.6 tons, respectively. Consequently, carbon storage increased by 21,553 tons between 1984 and 2005. Distributions of carbon storages of CFPU in the years of 1984 and 2005 are shown in Figure 3.

Total forest area increased 679 ha (4%) during the 21-year period in CFPU, thus total biomass increased by 47,897 tons. However, non-forest areas in CFPU decreased from 5643.4 ha in 1984 to 4600.2 ha in 2005. In other words, the observed trends of increasing forest and decreasing agricultural and settlement areas in the Camili could be explained by the following reasons. First, among the general and main causes of deforestation are human population pressure and an increasing demand of land for agriculture and timber products from forests (Laurance, 1999; Lawrence, Peart, & Leighton, 1998; Ochoa-Gaona, 2001; Ochoa-Gaona & Gonza´lez-Espinosa, 2000; Rudel & Roper, 1997). In the Camili forests, human population decreased from 3303 to 1284 inhabitants in the period 1970–1997 (Republic of Turkey, State Institute of Statistics, 1950–2000). In other words, the population of Camili has decreased nearly three times over 27 years. Second, plantation establishment by the forest department on degraded forestlands and forest openings has contributed to the increase in forest area. Third, degraded forest, agriculture-settlement, and forest openings converted to forest areas due to protection by legal since the late 1970s and this situation contributed to the increase in forest cover.

Between 1984 and 2005, while degraded forest areas were decreasing 506 ha, productive forest areas increased by 1,185 ha. CFPU consists of two natural reserves which cover approximately 2,138 ha (9%). Natural reserves have been widely adopted to protect biodiversity/ecodiversity over the world. Also, these are insect outbreaks in spruce stands of management planning unit. For that reasons, light silvicultural and protective prescriptions instead of maximum wood production have been carried out in the planning unit. These land cover changes and management prescriptions have supported the increase in carbon storages of forest ecosystem. However, even though the increase in productive forest areas is very large, total carbon storages are low. This result can be explained by the fact that the increase of forested areas have resulted from transition of forest openings and non-forested areas into forested areas. Thus, large carbon storages have not occurred during 21-year period because of young stands and their low standing timber volumes (Figure 4).

4 Summary and Conclusion

In this paper, a methodology was demonstrated to document carbon storage, using existing databases and GIS technology. We produced the maps of the carbon storages of two forest planning units depending on their inventory database during various temporal scales. Maps provide a visual representation of the pattern of forest biomass densities over space that is useful for forest managers and decision makers, and as databases for verification of vegetation models. It was also described the effects land use/cover changes on timber carbon stocks in different forest ecosystems. The spatial and temporal change patterns of land use and mapping of carbon storage were made in the context of GIS. GIS can greatly facilitate the process because these systems or methods can be used in the collection, analysis and presentation of resource data. Such a system is useful for both visual assessments of natural resources dynamics occurring at a particular time and space as well as quantitative evaluation of land use/land cover changes overtime. Information generated by using GIS coupled with accounting of socioeconomic behavior and good databases for detailed land-use changes over time seems promising indeed for developing more comprehensive and useful models to analyze carbon storage or sequestration dynamics based on system analysis.

This study showed that carbon stored in AFPU (above and belowground) increased 105,446 tons between 1972 and 2002 because of increasing of productive forests and decreasing of degraded forests in as well as protection of spruce forests subject to insect attacks. On the other hand, the results showed that carbon stored in CFPU (above- and belowground) increased 21,553 tons between 1984 and 2005 because of increasing of forested and productive forest areas and decreasing of non-forest and degraded forest areas.

The greenhouse effect is one of our most severe current environmental problems. Forests make up large ecosystems and can play an important role in mitigating the emissions of CO_2, the most important greenhouse gas. Forests play an important role in regional and global carbon cycles because they store large quantities of carbon in vegetation and soil. However, they are sources of atmospheric carbon when they are disturbed by human or natural causes, and become atmospheric carbon sinks during regrowth after disturbance, and can be managed to sequester or conserve significant quantities of carbon on the land (Brown et al., 1996). Because of their importance in the global carbon cycle, there is an increasing need to improve the accuracy of estimates of the amount of carbon (Birdsey, 1992; Brown & Lugo, 1982).

Different management regimes affect the ability of forests to sequester carbon. It is important to investigate in what way we best can use forests to mitigate the greenhouse effect. Land cover change involving deforestation is a significant global concern due to losses of biomass and its corresponding carbon stocks. At the same time, changes in vegetation lead to modifications of the physicochemical characteristics of the soils, which can also induce changes in the soil organic reserves (Adger & Brown, 1994; Desjardins, Barros, Sarrazin, Girardin, & Mariotti, 2004; Neill et al., 1998). Land-use changes are mostly affected by complex interactions of ecological, biophysical, socioeconomic and institutional factors. As a major indicator of human disturbances, land use and land cover change information, if available, needs to be incorporated into carbon budget calculations.

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