THE IMPACT OF AFFORESTATION ON CARBON STORAGE - A REVIEW

I. DUTCĂ[1] **I.V. ABRUDAN**[1] **V. BLUJDEA**[2]

Abstract: *This paper reviews the main aspects regarding the carbon storage that occurs after afforestation. By afforestation the initial changes that happen consist in carbon emissions from both removing the existing biomass and disturbing the soil. As the plantation is growing, carbon accumulates in biomass and also in soil. The most important amount of carbon stored by afforestation is in aboveground biomass. The rate of carbon storage in biomass depends on biomass growth rate. Although soil can stock an important amount of carbon, the rate of storage in soils is smaller than the rate of storage in forest biomass.*

Key words: *carbon storage, afforestation, plantation biomass, soil organic carbon.*

1. Introduction

The carbon dioxide (CO_2) emissions from land use change during the last 150 years were estimated at about 136 (±55) Gt (i.e. 1 Gt = 10^9 tons), which is approximately one third of the total emissions in the atmosphere [25]. These emissions resulted predominantly from forest vegetation removal (about 87% after Houghton, 1999). The annual emissions from land use change were estimated at 1.7 (±0.8) Gt yr^{-1} for 1980 to 1989 and at 1.6 (±0.8) Gt yr^{-1} for 1989 to 1998 [25].

The main possibilities to reduce greenhouse gases in the atmosphere are: reduction of emissions (with direct repercussions on the economy) and CO_2 storage in ocean, vegetation and soil. The storage of carbon in vegetation is a result of the photosynthesis process. Therefore, forests are a very important sink for CO_2, storing large amounts of carbon in wood [13].

At the global level, forest plantations represent less than 10% of deforested areas and tree planting currently compensates about 0.3% of the carbon released by deforestation [5]. Forest plantations across the world totalize approximately 130×10^6 ha, and annual rates of establishment are about 10.5×10^6 ha. The total carbon storage in forest plantations is nowadays approximately 11.8 Gt with an annual increase of 0.178 Gt yr^{-1} [24]. The estimations made by Houghton and Goodale (2004), regarding the carbon storage in plantations during the 1990s, indicated a global level rate of 0.19 Gt yr^{-1}. They also estimated the annual carbon storage rate in the tropical plantations - 0.11 Gt yr^{-1} and in the temperate and boreal plantations - 0.081 Gt yr^{-1}.

Plantations are defined as "forest stands that have been established artificially, either on land that has not supported forests in the last 50 years (i.e. ***afforestation***), or on land that has supported

[1] Dept. of Forest Sciences, *Transilvania* University of Braşov.
[2] Forest Research and Management Planning Institute, Bucharest.

forests in the past, but where the original vegetation has been replaced by forests (i.e. ***reforestation***)" [3].

The afforestation has the potential to contribute to carbon storage, directly through accumulation in biomass and soil and indirectly, by providing an alternative to fossil fuel [7]. The use of biomass as a renewable source of fuel can create a mechanism for offsetting increased atmospheric CO_2 and also provides an incentive for improving forest management [4]. In this way the addition of CO_2 from burning fossil fuel in the global CO_2 cycle could be reduced.

Depending on the type of vegetation, terrestrial ecosystems could be a source or a sink for atmospheric CO_2 [8]. The tropical biome is considered to be a net source of CO_2, while the boreal is a sink for CO_2 [22]. The boreal ecosystems hold their highest stocks of carbon in soils, whereas, moist tropical forests in general have large stocks of carbon in the trees [25].

The Gross Primary Production (GPP) represents the total amount of biomass resulted from the photosynthesis process. The GPP is expressed in Gt of CO_2 used and is estimated to be about 120 Gt yr^{-1}. But the losses from respiration lead to a Net Primary Production (NPP) of only 60 Gt yr^{-1}. Through decomposition of dead organic matter, global ecosystem loses other 50 Gt yr^{-1} resulting a Net Ecosystem Productivity (NEP) of 10 Gt yr^{-1}. NEP is usually affected by disturbances (e.g. fire, wind-throw, drought, pests, and human activities). These disturbances translate NEP into a Net Biome Productivity (NBP) which was estimated to be about 0.7 (±1) Gt yr^{-1} [25]. The NBP is actually the resulting net imbalance of the terrestrial ecosystem from a CO_2 perspective.

The dynamics of CO_2 storage through afforestation is detailed further at the following different levels: aboveground biomass, belowground biomass and soil.

2. Aboveground Biomass Accumulation

The rate of carbon storage in forest biomass depends on tree growth rate: the more biomass is added through photosynthesis the more carbon is stored. Following afforestation, this rate (i.e. storage rate) increases in time, up to a maximum and then decreases. It depends on tree species, site conditions, planting density (i.e. number of trees per area) and rotation (i.e. the number of years required to grow a stand to a desired size or maturity). Fast growing species are the most efficient for carbon storage. Studies in tropical forests by Silver et al., (2000) indicates that aboveground biomass increased at a rate of 6.2 t ha^{-1} yr^{-1} during the first 20 years after afforestation and only at a rate of 2.9 t ha^{-1} yr^{-1} over the first 80 years, because of slower growth rate of older forests. Although in over-mature forests growth rate approaches to zero, CO_2 may continue to be stored in soils by decomposition of dead leaves and branches from trees [25].

Another study conducted in a plantation chrono-sequence of oak and Norway spruce from Denmark, Sweden and Netherlands, showed that the rate of carbon stored in biomass was 3.7 (range between 2.7 and 4.6) t ha^{-1} yr^{-1} for stands younger than 45 years with no clear influence of different site characteristics [23]. The authors explained this lack of site influence on carbon storage as a legacy of former agricultural use (i.e. the soil enrichment with fertilizers). This rate is close to the rate of 4.1 t ha^{-1} yr^{-1} reported by Winjuma et al. in 1997 as a potential carbon storage rate for temperate forests.

Based on existing literature, Nilsson and Schopfhauser (1995) suggested the following rates of aboveground carbon accumulation in plantations: 10 t ha^{-1} yr^{-1} for coniferous plantations in Australia and New Zealand; 1.5…4.5 t ha^{-1} yr^{-1} in coniferous temperate plantations of Europe and the United States; 0.9…1.2 t ha^{-1} yr^{-1} in Canada and the former Soviet Union, and 6.4…10.0 t ha^{-1} yr^{-1} in tropical Asia, Africa, and Latin America.

In pastures, carbon accumulation (i.e. combined aboveground and below-ground NPP) is about 3.4 t ha^{-1} yr^{-1} in tropical humid savannas, 0.7 t ha^{-1} yr^{-1} in tropical dry savannas and 0.5 t ha^{-1} yr^{-1} in temperate steppe [16].

Increases in atmospheric carbon may lead to a higher GPP due to intensification of the photosynthesis process. However, some models indicate that the increase in CO_2 concentration will not necessarily lead to a higher NPP, because respiration is expected to continue to increase with the rise in air temperature [25].

3. Belowground Biomass Accumulation

Belowground biomass is represented by root and litter biomass. The development of the roots depends on soil type, tree species and bedrock. Some figures regarding the biomass stored in roots in different types of ecosystems is presented in Table 1.

Table 1

The estimation of the carbon stored in root biomass in different regions of the world [15]

Region	Carbon stored in root biomass [%]	Carbon stored in roots [t/ha]
Boreal	20	11.0
Temperate	19	17.1
Tropical	20	14.0
Agro-forestry	10	3.0

The belowground biomass represents 10 to 25% of the aboveground biomass [15]. Cooper (1983), found that the percentage of roots out of the total crop biomass was 17% in coniferous forests and 20% in hardwood forests, of which the share of fine roots accounts for 15%. A study of Murphy and Lugo, 1986 showed that roots represent 8 to 50% of plant biomass in dry forests (with roots' NPP of 22-24%) and less than 5 to 33% in rainforests.

The litter fall, according to Nilsson (1995) for boreal coniferous ecosystems, is estimated to be about 0.3 t ha^{-1}, with a litter duration of approximately 353 years. By contrast, in the tropical forests litter fall is estimated at 6.0 t ha^{-1} with a litter that resists less than a year. The carbon stored in litter was estimated to be about 0.5 t ha^{-1} for boreal forests, 2.8 t ha^{-1} for temperate forests and 3.7 t ha^{-1} in tropical forests [15].

4. Changes in Soil Carbon

The soil carbon consists in soil organic carbon (SOC) and inorganic carbon. The SOC is comprised of detritus - decomposed plants, animals and microbes [21].

Each soil has a maximum carbon storing capacity, depending on the nature of the vegetation, precipitation and temperature [8]. This capacity represents the equilibrium between carbon inflow and outflow from the soil carbon pool. When land use is changed this equilibrium is disturbed, a new equilibrium being reached later, after the new ecosystem is established.

In agricultural land, by far, the highest amount of carbon is stored belowground. The agricultural activities (e.g. plowing, planting and harvesting) lead to an enhanced oxidation of organic matter within the soils. As a result of this process, carbon dioxide is released into the atmosphere [1].

During the first years after afforestation, the soil loses carbon. This loss is a result of the reduced input of biomass (above- and below-ground) to the soil, the change in soil moisture and temperature regimes (which accentuate the rate of organic matter decomposition), and also due to the tillage induced perturbations which reduce physical protection of the soil and promote soil erosion [11]. The most important factors influencing the change in soil carbon are: previous land use, the climate and the type of forest installed [20]. For example, Guo and Gifford (2002) showed that planting broadleaf trees into pasture had little effect on soil carbon stock. In contrast, conifer trees reduce soil carbon stocks by 12% [8]. Considering climate factor, the conversion from pasture to forest has little effect in the lower rainfall areas (i.e. <1200 mm yr^{-1}) but significantly reduced soil carbon stocks in higher rainfall areas. This is valid especially in the areas with precipitation higher than 1500 mm yr^{-1}, where this reduction reached 23% [8].

According to Guo and Gifford (2002) the dynamics of soil carbon is also a function of the type of land use change (Table 2). The type of transition with the highest rate of SOC storage in the soil is from agricultural crop to forest and the one with the highest loss in SOC is from pasture to agricultural crop. In addition, the type of transition with the lowest impact on SOC change is pasture to plantation and plantation to pasture. Additionally, the same authors showed that, when pastures are converted to conifer plantations, SOC declines, while when they are converted to either broadleaf tree plantations or naturally regenerated secondary forest, SOC is unaffected [8].

Table 2

Soil carbon inputs (positive values) and outputs (negative values), by the type of transition, based on data from 74 publications [2]

Before	After	Carbon stock
pasture	plantation	−10%
forest*	plantation	−13%
forest*	crop	−42%
pasture	crop	−59%
forest*	pasture	+8%
crop	pasture	+19%
crop	plantation	+18%
crop	forest*	+53%

*Mature forest

Studies by Paul et al. (2002), found that plantations established on agricultural lands lost soil carbon during the first 5-10 years. However, the initial carbon balance of the agricultural land was restored after 30 years.

The most susceptible part of the soil to lose carbon is the top layer, which also contains the highest amount of SOC. This layer, during the first years after afforestation, will receive relatively little input from above-ground litter, while SOC from agricultural residues will continue to decompose. As a result the overall SOC may decrease. However, during this time, at higher soil depths the SOC may increase as a result of root decomposition [18]. Several studies have shown that the highest soil carbon losses occur during the first year, affecting the soil up to a depth of 40 cm. Also, according to Nilsson (1995), the highest rates of carbon loss are in the areas with the highest rates of land use change: the tropical and subtropical regions.

5. Conclusions

In terrestrial ecosystems the amount of carbon stored in soil is greater (about 1550 Gt in the first meter of the soil) than the amount in living vegetation (about 600 Gt) and atmosphere (about 700 Gt) [2], [12], [19], [21]. Therefore, it is important to understand the dynamics of soil carbon cycle to adopt the appropriate management strategy for carbon preservation.

By afforestation, the amounts of carbon lost or gained by soil are generally small compared with accumulation of carbon in tree biomass [17]. Because at global level, the rate of carbon emissions from the soil is much higher than the storage rate, the main strategy regarding the soil carbon pool should seek the preservation of the existing reserves and also the sequestration of new SOC.

In the pastures, the herbs' leaves and

stems die at the end of each growing season and therefore, almost all carbon stored in aboveground biomass is transferred into the soil through biomass decomposition. By contrast, the forest enriches the soil in carbon by litter decomposition while another important amount is stored in wood. Therefore carbon storage in woody biomass is an important alternative for atmospheric carbon mitigation. However, through burning or decomposition the amount of carbon stored in wood is released back into the atmosphere. Therefore, to maintain these reserves, the wood should be transformed in long-life wood products. This will help reduce the emissions in the atmosphere of the carbon previously stored in biomass.

References

1. Baker, J.M., Ochsner, T.E., et al.: *Tillage and Soil Carbon Sequestration - What Do We Really Know?* In: Agriculture, Ecosystems and Environment **118** (2007), p. 1-5.
2. Bouwman, A.F.: *Soils and the Greenhouse Effect.* New York. John Wiley & Sons, 1990.
3. Brown, S., Lugo, A.E., Chapmen, J.: *Biomass of Tropical Tree Plantation and Its Implications for the Global Carbon Budget.* In: Forest Research **16** (1986), p. 390-394.
4. Brown, S., Sathaye, J., et al.: *Management of Forests for Mitigation of Greenhouse Gas Emissions*. In: *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses.* Watson, R.T., Zinyowerea, M.C., Moss, R.H. (eds). Cambridge University Press, Cambridge, 1996, p. 773-797.
5. Bruening, E.: *Conservation and Management of Tropical Rainforests: An Integrated Approach To Sustainability.* Wallingford. Oxon, CABI Publishing, 1996.
6. Cooper, C.F.: *Carbon Storage in Managed Forests.* In: Canadian Journal of Forest Research **13** (1983) No. 1, p. 155-166.
7. Fearnside, P.M.: *Amazonian Deforestation and Global Warming: Carbon Stocks in Vegetation Replacing Brazil's Amazon.* In: Forest Ecology and Management **80** (1996), p. 21-34.
8. Guo, L.B., Gifford, R.M.: *Soil Carbon Stocks and Land Use Change: A Meta Analysis.* In: Global Change Biology **4** (2002), p. 345-360.
9. Houghton, R.A.: *The Annual Net Flux of Carbon to the Atmosphere from Changes in Land Use 1850-1990.* In: Tellus **50B** (1999), p. 298-313.
10. Houghton, R.A., Goodale, C.L.: *Effects of Land-Use Change on the Carbon Balance of Terrestrial Ecosystems.* In: Global Change Biology **153** (2004), p. 317-327.
11. Lal, R.: *Forest Soils and Carbon Sequestration.* In: Forest Ecology and Management **220** (2005), p. 242-258.
12. Lal, R., Kimble, J.M.: *Conservation Tillage for Carbon Sequestration.* In: Nutrient Cycling and Agroecosystems **49** (1997), p. 243-253.
13. Montagnini, F.: *Evaluating the Role of Plantations as Carbon Sinks: An Example of an Integrative Approach from the Humid Tropics.* In: Environmental Management **22** (1998) No. 3, p. 459- 470.
14. Murphy, P.G., Lugo, A.E.: *Ecology of Tropical Dry Forests.* In: Annual Review of Ecology and Systematic **17** (1986), p. 67-88.
15. Nilsson, S., Wolfgang, S.: *The Carbon-Sequestration Potential of a Global Afforestation Program.* In: Climatic Change **30** (1995), p. 267-293.
16. Parton, W.J., Scurlock, J., Ojima, D.S., Schimel, D.S., Hall, D.O.: *Impact of*

Climate Change on Grassland Production and Soil Carbon Worldwide. In: Global Change Biology **1** (1995), p. 13-22.

17. Paul, K.I., Polglase, P.J., Nyakuengama, J.G, Khanna, P.K.: *Change in Soil Carbon Following Afforestation.* In: Forest Ecology and Management **168** (2002), p. 241-257.
18. Polglase, P.J., et al.: *Change in Soil Carbon Following Afforestation or Reforestation.* In: Technical Report No. 20, National Carbon Accounting System, Australian Greenhouse Office, Canberra, Australia, 2000.
19. Post, W.M., Peng, T.H., et al.: *The Global Carbon Cycle.* In: American Scientist **78** (1990), p. 310-326.
20. Post, W.M., Kown, K.C.: *Soil Carbon Sequestration and Land Use Change: Processes and Potential.* In: Global Change Biology **6** (2000), p. 317-327.
21. Schlesinger, W.H.: *Evidence from Chronosequence Studies for a Low Carbon Storage of Soils.* In: Nature **348** (1990), p. 232-234.
22. Silver, W.L., Ostertag, R., Lugo, A.E.: *The Potential for Carbon Sequestration through Reforestation of Abandoned Tropical Agricultural and Pasture Lands.* In: Restoration Ecology **8** (2000), p. 394-407.
23. Vesterdal, L., Rosenqvist, L., Van der Salm, C., Hansen, K., Groenenberg, B.J., Johansson, M.B.: *Carbon Sequestration in Soil and Biomass Following Afforestation: Experiences from Oak and Norway Spruce Chronosequences in Denmark, Sweden and The Netherlands.* In: Plant and Vegetation **1** (2007), p. 19-52.
24. Winjuma, J.K., Schroeder P.E.: *Forest Plantations of the World: Their Extent, Ecological Attributes and Carbon Storage.* In: Agricultural and Forest Meteorology **84** (1997), p. 153-167.
25. *** *IPCC Special Report: Land Use, Land-Use Change and Forestry*, 2000.