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# Sustainable forest management for bioenergy

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**Abstract:** Biomass from the forest sector can be an important source of renewable energy and can contribute to climate change mitigation and bioenergy development. However, the removal of biomass from forests can have significant impacts on the forest ecosystems and therefore requires a thorough analysis. The purpose of this work is to compare different alternatives of sustainable forest management with the aim of minimizing greenhouse gases emission. The model used for the analysis, CO2FIX, describes the flows of carbon per unit area of biomass, soil storage and bioenergy products. The model was applied to the forests of the Italian region of Lombardy. We identified four macro-categories: coniferous, deciduous, mixed coniferous and deciduous forests, short rotation forests. For each macro-category, we ran a simulation, with an annual time step for a hundred years horizon, of various management policies: no harvest activities, maintenance of a constant stock, different rotation lengths, maximization of harvested biomass. We identified the most efficient management policy for each macro-category in terms of carbon emissions saved and carbon sequestered. Over the entire region, it emerges that the potential contribution to climate change mitigation amounts to about 1.5 million tons of $CO_{2eq}$ per year, equal to about 15% of the total reduction needed to meet Kyoto Protocol targets in the region.

***Keywords**:* Bioenergy; Carbon sequestration; Forest management; CO2FIX; Climate change mitigation.

## 1. INTRODUCTION

To mitigate global climate change our society will have to rely both on low carbon technologies and on maximizing the capacity of the biosphere to sequester carbon from the atmosphere. Even though the sequestration capacity of both soil and vegetation alone will not be enough to compensate the increase of carbon concentration, in the next years their contribution will be crucial. The carbon balance of terrestrial systems has therefore gained more attention because of the connection with global climate change.

Within terrestrial systems, forests play a major role as recognized in Article 3.3 of the Kyoto Protocol, where afforestation, reforestation and deforestation accountings are made mandatory. Countries can also choose to include management activities of existing forests as an addition to their carbon sinks. Furthermore, the use of forest biomass in substitution of more energy-intensive products, such as fossil fuels or other materials, is another major contribution that forests can provide [Brown et al., 1996; Nabuurs et al., 2008].

Globally, forests represent a significant carbon stock. They store 283 Gt of carbon in the biomass, 38 Gt in dead wood and 317 Gt in soils (top 30 cm) and litter. The total content of 638 Gt (for 2005) is more than the amount of carbon in the entire atmosphere. This standing carbon is combined with a gross terrestrial uptake, which was estimated at 2.4 Gt of carbon a year, a good deal of which is sequestration by forests [UNFCCC, 2010].

Management can strongly affect this carbon balance. Forests of new formation sequester carbon and store it in their biomass until an upper limit is reached; at this point, carbon losses due to respiration, mortality, external causes of disturbances and other utilizations may overcome the photosynthetic activity [Odum, 1969]. A recent study that involved boreal and temperate forests [Luyssaert et al., 2008], showed that forests between 15 and 800 years of age accumulate carbon and have a positive net system productivity (including trees and soil), even though there is an age-related decline. This carbon accumulation is explained with the different rates at which tree mortality and decomposition occur: the first is much faster than the second. Consequently, old-growth forests with tree losses do not necessarily become carbon sources. However, this process strongly depends on the stand structure and the disturbances forests have been subject to.

The biomass extracted and transformed in wood products is itself a limited reservoir of carbon. If a forest has been used to extract biomass or if a forest is lost because of natural events, its pool of carbon will disperse; the same happens when degraded woody products are not replaced by analogous products. On the contrary, the benefits that derive from the replacement of fossil fuels with energy from biomass can be considered irreversible: when energy is produced in substitution of any given fossil fuels, a defined amount of greenhouse gases will be permanently avoided [Tuskan et al., 2001].

Clearly, forests provide a number of other important ecosystem services, such as soil erosion control, wildlife habitat and diversity, as well as relevant economic contribution to sectors like tourism. This paper concentrates only on the carbon biogeochemical cycle to analyse how much the management of forest for the production of substitute of energy-intensive products and the preservation of carbon sinks can contribute to the regional carbon budget.

The approach followed in this study is composed by two main steps. The first is the formulation of a method to compare different management policies and to identify the optimal ones, with the objective of maximizing avoided greenhouse gas emissions and the carbon fixed by the forest system (trees and soil). The second is to assess the environmental benefits that can be derived from the adoption of those policies identified in the first step, over the Region of Lombardy in Northern Italy.

## 2. STUDY REGION

Forests in the Lombardy region extend over an area of 665,702 hectares, more than one quarter of the overall regional area (24,000 km$^2$). The largest fraction of this area (58%) is covered by deciduous forests, followed by conifer forests (17%) and by mixed forests (13%); the remaining part is not classified into any of these categories [INFC, 2005; ERSAF, 2007]. The most widespread deciduous forests are chestnuts, hornbeams, and ash trees; the most common conifer is the Norway spruce forest. About two thirds of the forest area is public property, while the remaining is privately owned. Only one quarter is classified as a protected or naturalistic area.

About 20% of the total has natural origin, while the vast majority are semi-natural forests derived from sylvicultural and afforestation interventions, which for a small share, was made by replanting of indigenous species. According to the data recently collected by the National Forest Inventory, about 8% of forest can be considered in a juvenile stage, 61% in an adult stage and the remaining 31% in an old stage.

Lombardy forests generally lay in a partially abandoned condition that followed centuries of overexploitation, with consequences of aging and degradation. Removal of woods from the forest sharply decreased after the end of World War II; however a slight resurgence was observed after the 1980s. The removed quantity varies consistently from year to year and ranged between a minimum of 0.8 Mm$^3$ in 2004 to a maximum of 1.8 Mm$^3$ in 1999 [ISTAT, 2006].

## 3. THE MODELLING APPROACH

Different management strategies directly affect carbon pools and flows, both in trees and soil, and are determined by rotation length, whole-tree or conventional harvesting, thinning intensity, age-class distribution of the forests and many other factors. To compute the carbon budget, we adopted the CO2FIX V 3.1 model [Schelhaas et al., 2004; Masera et al., 2003], which has been widely used for studying, for example: the consequences of forest management policies [Kaipainen et al., 2004], the carbon profile according to forest types [Nabuurs and Schelhaas, 2002], the emissions from silvicultural activities [Markewitz, 2006] and the carbon credit accounting of Italian forest stands [Scarfò and Mercurio, 2009]. This model allowed us to design and compare alternative management policies. We then applied these management policies to the Lombardy forests to estimate how much forest management can contribute to bioenergy production and to climate change mitigation.

### 3.1 The CO2FIX model

The CO2FIX model describes a forest with a set of modules that represent what happens in the biomass, in the soil and to the wood products (Figure 1). Each of these modules assesses the incoming and outgoing flows of carbon. Finally, there is a fourth module that calculates the overall carbon balance, accounting for all flows, with respect to the atmosphere.

The Biomass module describes the forest biomass growth from the carbon that is absorbed via photosynthesis; the module distinguishes different sections for leaves, branches, logs and roots. Each of these sections is regulated by a set of defined equations that describe growth, mortality, turnover and cutting of the biomass. Mortality, turnover and harvest residues that are left on the soil are the input of the Soil module; this module describes biomass decomposition and the respective carbon flows that depend on climatic conditions and litter quality and composition. The raw material that is harvested is the input of the Products module that describes the various uses of biomass, such as manufacturing of sawn wood, board and panels, pulp and paper, and wood fuels. The biomass used to produce energy is finally described in the Bioenergy module that takes into account the carbon emission flows avoided thanks to the substitution of fossil fuels in electric or thermal energy production. The final module Carbon in the Atmosphere describes the balance of all these flows with respect to the atmosphere. The model has been validated for several climatic regions, including central Europe [Masera et al., 2003].

CO2FIX is a flexible tool that can be applied to several forestry species. For example, the Biomass module, through the cohort model, can describe mono-cultures and mixed forests and can deal with age-structured stands.

All variables are expressed in terms of carbon per hectare (tC/ha) for a single homogeneous stand of forest. The measure of carbon per hectare can be converted, according to the appropriate parameters, into units of weight (dry t/ha) or of volume ($m^3$/ha) of the biomass. The time step used for the simulation of the forest dynamics is one year.

The output of the model is given in the form of two indicators. The first quantifies the annual average amount of greenhouse gases sequestered by the forest (standing biomass and soil). The second quantifies the annual average carbon emissions avoided by using biomass instead of a fossil fuel to produce energy.

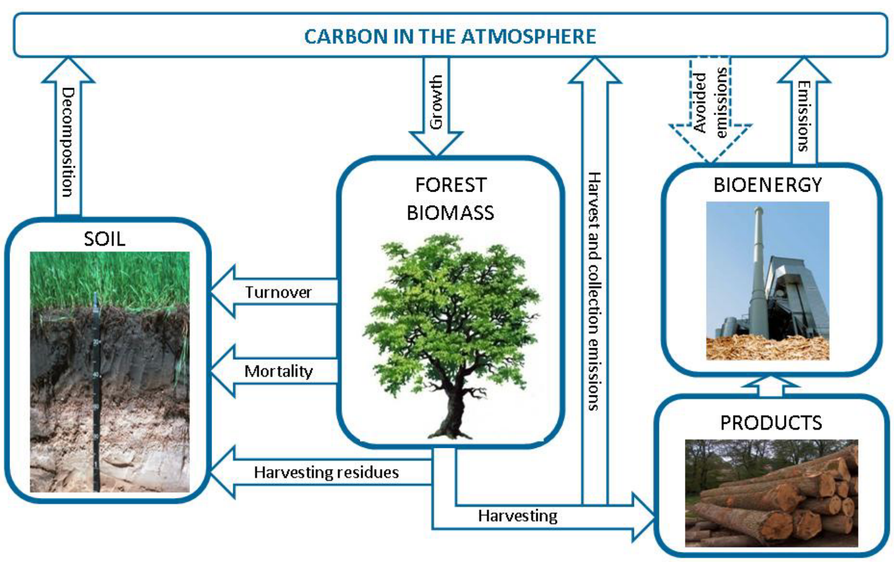


**Figure 1.** Structure of the CO2FIX model.

### 3.2 Applying the CO2FIX model to the forests of Lombardy

To study different alternatives for the management of the forests of Lombardy with CO2FIX, we considered four major forest macro-categories: conifer forests, deciduous forests, conifer and deciduous mixed forests, arboriculture tree plantations. These macro-systems are also used in the land use digital cartography of the region [ERSAF, 2007].

Therefore, this correspondence allows to connect the management policies of the macro-categories with their spatial extension and sites by applying GIS software.
Because of their fully different management, arboriculture plantations should be considered separately from the others forests categories. In fact, in this case we assume to grow biomass in short rotation cycles (3 years) that, therefore, have very high yields (up to 33 $m^3$/ha/y) [Fiorese and Guariso, 2010]. Arboriculture has an old tradition in the region and is presently constituted mainly by poplars and some other fast growing species, such as willows and robinia. These areas are all located in the southern flat and fertile part of the region. The figures given by arboriculture are useful to compare its potential with other forestry sectors.
CO2FIX simulations were run for each of the four macro-categories assuming single cohort, even-aged forest stands. For the parameters of the Biomass module (see Table 1), we used values of the stand carrying capacity, annual rate of growth, turnover and mortality derived from a national study by APAT [2002]. For the parameters of the Soil module, the initial soil carbon content and its evolution over time were elaborated from a recent study that covers the region and that estimates the organic content of the soil at various depth [Progetto Kyoto Lombardia, 2008]. The soil carbon dynamics depends also on the local climatic conditions that regulate the moisture and the chemical, physical and biological processes that occur within the soil. In the Product module, we assumed that all the log is used for energy production and that a fraction of leaves and branches (10% for arboriculture and 30% for the other macro-categories) is left on the soil [Masera et al., 2003]. Finally, in the Bioenergy module, it is necessary to define how the biomass will be converted into energy (e.g., electricity or heat and with which conversion efficiency) and what fossil fuel it will substitute. It is assumed here that biomass is used to produce only thermal energy in a plant with 80% efficiency. This thermal energy substitutes that produced by a natural gas plant (assumed to have a 85% efficiency). The avoided emissions are thus estimated with respect to natural gas for all the GHG gases with the appropriate heating value and emission factors for biomass (LHI 16 $MJ/kg_{biomass}$; 0.0 $gCO_2/kg_{biomass}$; 0.48 $gCH_4/kg_{biomass}$; 0.06 $gN_2O/kg_{biomass}$) and for natural gas (LHI 42.62 $MJ/kg_{gas}$; 3853 $gCO_2/kg_{gas}$; 0.88 $gCH_4/kg_{gas}$; 0.08 $gN_2O/kg_{gas}$). It is possible to choose different conversion options, such as the use of biomass to generate electricity instead of heat. In this case, the conversion efficiency is more favourable for natural gas (whose conversion efficiency is about 55%) than for biomass (24%). The choice of the energy conversion should, in any case, also depend on local energy demand. Typically in mountainous areas, such as those of the Alps of Lombardy, biomass is mostly used locally in small thermal plants (from hundreds of $kW_t$ up to 20 $MW_t$).
Throughout the analysis, we assumed an average carbon content of 0.5 tC per dry ton of biomass and a lower heating value of 16 MJ/kg for all the macro-categories. The dry wood mass density ($kg/m^3$), on the other hand, varies from species to species (Table 1). All other parameters for the simulations have been set as advised in the manual of the model [Schelhaas, et al., 2004]

**Table 1.** Initial values of forest simulation (regional averages).

| Forest macro-category | Dry wood mass density[a] [$kg/m^3$] | Carrying capacity[b] [$m^3$/ha] | Standing biomass[a] [$m^3$/ha] | Carbon content [tC/ha] | Organic C in soil 100 cm deep[c] [tC/ha] |
|---|---|---|---|---|---|
| Conifer forests | 526 | 339 | 321 | 84 | 154,7 |
| Deciduous forests | 705 | 183 | 160 | 56 | 126,1 |
| Mixed forests | 615 | 261 | 241 | 74 | 137,2 |
| Arboriculture plantations | 515 | - | 115 | 30 | 108,0 |

[a] INFC, 2005; [b] APAT, 2002; [c] elaborated from Progetto Kyoto Lombardia, 2008.

### 3.3 Definition of forest management policies

The management of forests can be defined as sustainable when it – at least – maintains the system biodiversity, productivity, capacity of renewal, vitality, and when it does not compromise the capacity of supplying, now and in the future, ecosystem services [APAT, 2002]. In this study, sustainability is defined only in terms of biomass: the stand biomass at the end of the management horizon is constrained not to be lower than the initial one. However, since this may determine some initial and final transients that are due to the specific initial conditions (and thus to the management of the past 20-30 years), we will refer in the following only to the average performances, transients excluded.

For each forest macro-category, the optimal management problem can be formalized with the objective of maximizing the sum of the average annual $CO_2$ fixed by the forest ($I_f$) and the average annual $CO_{2,eq}$ avoided by the substitution of natural gas with biomass for heat production ($I_a$). These in turn depend on the biomass *B*, whose dynamics is obviously determined by the management policy *u*.

The optimal management policy is thus the solution of the following optimal control problem:

$$\max_u \frac{1}{N}\sum_{t=1}^{N}\left(I_f(t)+I_a(t)\right) \quad (1)$$

$$B(t+1)=f(B(t),u) \quad (2)$$

$$I_f(t)=g'(B(t)), \quad I_a(t)=g''(B(t)) \quad (3)$$

$$B(N)\geq B(0) \quad (4)$$

where constraints (2)-(3) are implemented through CO2FIX, and the time horizon *N* considered in this study is 100 years.

Additionally, we restrict the set U of possible policies to only six alternatives, which closely resemble those followed in the past. Thus, their social acceptability is guaranteed. The considered management policies are:

- **Complete protection**: the forest is left evolving according to its natural cycle, without any intervention or biomass removal.
- **Conservation**: each year, biomass is removed from the forest in such an amount that guarantees a constant stock of carbon; the annual net productivity is therefore removed each year.
- **Long, medium and short rotation cycle**: with the first biomass harvest, the forest density is set at a value that allows for maximum growth, therefore guaranteeing a high biomass yield in the following years; after the first cut, biomass is harvested at regular intervals, every 20, 10 or 5 years.
- **Maximum sustainable yield (MSY)**: with the first harvest, the forest density is set at the value that allows the maximum growth from one year to the next; the annual net productivity is then removed each year.

## 4. RESULTS

The values of the two components of the objective for each policy are listed in Table 2 for deciduous forests. Within all the management policies analysed, the optimal policy is the short rotation cycle that, for this macro-category, allows for both the highest carbon sequestration and a high amount of avoided emissions. Table 3 lists the optimal results for all the forest macro-categories.

In order to estimate the potential contribution to climate change mitigation of forest biomass in the region, once the optimal management policy has been defined for each macro-category, it is necessary to estimate the extension of such a macro-category. Land use cartography [ERSAF, 2007] has been used for this purpose and figures are listed in Table 4. However, not all the forest area can be managed because of natural or technical constraints (for example, slope limits the accessibility of the forest by machineries and, at the same time, prevents from extracting biomass from parts of the forests where erosion might be more severe).

**Table 2.** Value of the indicators for each management policy for deciduous forests.

| | $I_f$ | $I_a$ | $I_f + I_a$ |
|---|---|---|---|
| | | [$tCO_{2,eq}$/y] | |
| Protection | -1.06 | 0.00 | -1.06 |
| Conservation | 0.51 | 0.72 | 1.24 |
| MSY | 0.71 | 3.38 | 4.09 |
| Long cycle | 0.16 | 3.41 | 3.57 |
| Medium cycle | 0.23 | 3.31 | 3.54 |
| Short cycle | 0.93 | 3.25 | 4.18 |

**Table 3.** Optimal policy and value of the indicators for each forest macro-category.

| Forest macro-category | Optimal management | Harvested biomass [$m^3$/ha/y] | $I_f$ | $I_a$ [t $CO_{2,eq}$/y] | $I_f + I_a$ |
|---|---|---|---|---|---|
| Conifer forests | Long cycle | 5.52 | 0.25 | 3.93 | 4.19 |
| Deciduous forests | Short cycle | 3.40 | 0.93 | 3.25 | 4.18 |
| Conifer and deciduous mixed forests | MSY | 5.32 | 0.74 | 4.43 | 5.17 |
| Arboriculture plantations | SRF | 33.51 | -0.41 | 23.36 | 22.95 |

**Table 4.** Regional extension of each forest macro-category, its manageable part and estimated reduction of greenhouse gases according to the optimal policy.

| Forest macro-category | Regional forest area [ha] | Manageable area [ha] | Avoided emissions [kt$CO_{2,eq}$/y] | $CO_2$ sequestered [kt$CO_2$/y] |
|---|---|---|---|---|
| Conifer forests | 134,352 | 10,647 | 41,8 | 2,7 |
| Deciduous forests | 340,137 | 97,253 | 316,1 | 90,4 |
| Conifer and deciduous mixed forests | 91,555 | 14,989 | 66,4 | 11,1 |
| Arboriculture plantations | 39,323 | 39,323 | 918.6 | -16.1 |
| **Total** | **605,367** | **162,212** | **1343.0** | **88.1** |


**Figure 2**. Forests in Como province, a part of Lombardy (green areas represent forests that can presently be managed; dark brown areas forests that could be managed if new roads are built; light brown areas forests that can not be managed because of high slope).

We assumed to manage only forest land with a moderate slope (lower than 30%) and close enough to the existing road network (distance less than 200 m). This constraint guarantees that the harvested biomass can be collected and transported to the conversion facility at reasonable costs. These constraints were applied to the forest areas through simple GIS operations on the land use map. Table 4 shows that the extension of the forest that satisfies these two manageability constraints is a small share (27%) of the overall forest area.

The management of forests over this area under the proposed policies leads to a decrease of $CO_2$ of about 1.43 Mt/y from avoided emissions and from sequestration in the forest system (trees and soil). The greatest contribution to the avoided emissions is given by arboriculture plantations; at the same time, however, this forest macro-category is a source of $CO_2$ from the forest ecosystem (0.016 Mt). This happens because arboriculture plantations are composed by young trees (completely harvested every three years, with a small litter) and thus cannot exploit carbon storage in the soil. On the contrary, for the other forest macro-categories only a part of the biomass is harvested (for example the net primary productivity in the MSY alternative) and a larger fraction of this is left on the soil. The dynamics of carbon in the soil thus plays a major role in determining if the forest can be considered as a source or a sink of GHG.

The amount of biomass that can be harvested could be increased by extending the area of the managed forests. Under the assumptions made on slope and road vicinity, the manageable area could be increased for example by constructing more roads into the forests (which may be positive also for other activities such as fire fighting, but may also have negative impacts, such as habitat fragmentation). The maximum potential area that can be managed over the entire region, could be increased in this way from 162 to 262 thousand hectares, resulting in a 30% increase of carbon sequestration and substitution. The map of the province of Como (a part of Lombardy) in Figure 2 shows all the forest area, the part that can be managed and the part that could potentially be managed.

## 5. DISCUSSION AND CONCLUSIONS

Historical harvests from the forest of Lombardy have covered about 11,000 hectares and have produced an average of little less than one million cubic meter of wood per year, corresponding to about 90 $m^3$ per hectare and year - quite higher than any sustainable policy.

According to the management policies proposed in this paper, harvesting could cover a larger surface of 35,000 hectares, with a total harvest of about half a million cubic meter of wood per year, i.e. an average of about 14 $m^3$ per hectare per year. A substantial contribution to these figures is given by arboriculture that accounts for 74% of the wood production (even if only 24% of the area is presently grown with this macro-category). The suggestion is thus to shift from the overexploitation of only a small area, to a more sustainable harvesting of all the forests, each with its own best policy.

From the figures above, it clearly emerges that the role of forest as bioenergy suppliers is quite more important than their being carbon sinks, but there is no contradiction between these two functions. On the contrary, there might be a positive synergy. In fact, in the absence of harvesting, our forests are not bound to increase their productivity/growth or their carbon sequestration. Indeed, this analysis shows that if forests are let evolving according to their own dynamics, without any intervention (complete protection policy), they might become a source of carbon, instead of being a sink. The difference between the overall sequestration under the optimal solution and the sequestration under such a protection policy, can be considered the “price”, in terms of missing sequestration, that society pays for the lack of proper management of forests.

Moreover, the current abandonment of the Lombardy forests constitutes a form of pressure as well, that may not just impact on the carbon sequestration aspect, but also on the other ecosystem services, such as for instance the spreading of wildfires or the diffusion of parasites. A sustainable set of management operations may contribute to provide healthier forests with a higher capacity of sequestering carbon from the atmosphere and provide wood products.

The management policies proposed in this paper could contribute to the GHG reduction goal set in the Kyoto Protocol. Forests in Lombardy may contribute with a reduction corresponding to about 15% of the total expected reduction in the region [Progetto Kyoto Lombardia, 2008]. Furthermore, this can be achieved in a sustainable way, i.e. without compromising the future biomass production of the forests and even without modifying current land cover.

The model adopted in this study has the single objective of optimizing $CO_2$ reduction. This approach overlooks all the other relevant issues that should be considered to define a sustainable forest management policy such as, for example, forests biodiversity, that depends on standing biomass and on litter quality as well. Our future research will thus focus on investigating policies that consider other ecosystem services as objectives of the optimal forest management problem. Other improvements might regard the emissions caused by the harvest and transport operations and other life cycle emissions of forest biomass with respect to the equivalent life cycle emissions of natural gas. However, previous works [e.g., Fiorese and Guariso, 2010] have shown that the emissions due to logistic operations contribute only to a few percent of the overall balance of the bioenergy systems. Moreover, we plan to evaluate the robustness of the results by adopting other carbon budget models, such as, for example, FORMICA [Böttcher et al., 2008] that has been developed for regional scale studies, or GORCAM [Schlamadinger and Marland, 1996] that accounts not only for the carbon mitigation potential of biomass, but also for possible land use changes.

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## REFERENCES

APAT, Assorbimento e fissazione di carbonio nelle foreste e nei prodotti legnosi in Italia, Rapporti 21/2002, Roma, 2002.

Böttcher, H., A. Freibauer, and M. Obersteiner, E.D. Schulze, Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model, *Ecological Modelling, 213*(1), 45-62, 2008.

Brown, S., J. Sathaye, M. Cannell and P. Kauppi, Management of forests for mitigation of greenhouse gas emissions. In: Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of WG II to the II Assessment Report of the IPCC [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)], Cambridge Univ. Press, Cambridge-New York, pp. 773-797, 1996.

ERSAF, Destinazione d'Uso dei Suoli Agricoli e Forestali della Lombardia, 2007.

Fiorese G., and G. Guariso, A GIS-based approach to evaluate biomass potential from energy crops at regional scale, *Environmental Modelling & Software*, 25(6), 702-711, 2010.

IFNC, Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio, www.sian.it/inventarioforestale, 2005.

ISTAT, Utilizzazioni legnose totali e forestali, www.istat.it, 2006.

Kaipainen, T., J. Liski, A. Pussinen, and T. Karjalainen, Managing carbon sinks by changing rotation length in European forests, *Environmental Science & Policy, 7*(3), 205-219, 2004.

Luyssaert, S., E.D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law, P. Ciais, and J. Grace. Old-growth forests as global carbon sinks, *Nature, 455*, 213-215, 2008.

Markewitz, D., Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests, *Forest Ecology and Management, 236*(2-3), 153-161, 2006.

Masera, O., J.F. Garza-Caligaris, M. Kanninen, T. Karjalainen, J. Liski, G.J. Nabuurs, A. Pussinen, B.H.J. de Jong, and G.M.J. Mohren, Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modelling, 164*(2-3), 177-199, 2003.

Nabuurs, G.J., E. Thurig, N. Heidema, K. Armolaitis, P. Biber, E. Cienciala, E. Kaufmann, R. Makipaa, P. Nilsen, R. Petritsch, T. Pristova, J. Rock, M.J. Schelhaas, R. Sievanen, Z. Somogyi, and P. Vallet. Hotspots of the European forests carbon cycle, *Forest Ecology and Management, 256*(3), 194-200, 2008.

Nabuurs, G.J., and M.J. Schelhaas, Carbon profiles of typical forest types across Europe assessed with CO2FIX, *Ecological Indicators, 1*(3), 213-223, 2002.

Odum, E.P., The strategy of ecosystem development, *Science, 164*(3877), 262–270, 1969.

Progetto Kyoto Lombardia, Per vincere la sfida dei cambiamenti climatici e del controllo dei gas serra nella regione più industrializzata d'Italia, ed. Fondazione Lombardia per l'Ambiente, Milano, Italy, 2008.

Scarfò F., and R. Mercurio, Carbon credit accounting: the model CO2FIX v. 3.1 applied to a beech stand under Forest Management in southern Italy, *Forest@ 6*, 215-228, 2009.

Schelhaas, M.J., P.W. van Esch, T.A. Groen, B.H.J. de Jong, M. Kanninen, J. Liski, O. Masera, G.M.J. Mohren, G.J. Nabuurs, T. Palosuo, L. Pedroni, A. Vallejo, and T. Vilén, CO2FIX V 3.1 - description of a model for quantifying carbon sequestration in forest ecosystems and wood products. ALTERRA Report 1068. Wageningen, The Netherlands, 2004.

Schlamadinger, B., and G. Marland, The Role of Forest and Bioenergy Strategies in the Global Carbon Cycle, *Biomass and Bioenergy, 10*(5/6), 275-300, 1996.

Tuskan, G.A., and M.E. Walsh, Short-rotation woody crop systems, atmospheric carbon dioxide and carbon management: A U.S. case study, *The Forestry Chronicle,* 259-264, 2001.

UNFCCC. Land Use, Land-Use Change and Forestry, http://unfccc.int/methods_and_science/lulucf/items/4122.php, 2010.