Abstract

Only 40% of the total CO_2 emitted by human activities and natural sources remain in the atmosphere, since the rest is taken up by plants and oceans. In particular temperate and boreal forests are usually significant sinks of carbon, even if they are very susceptible ecosystems and they might turn into sources in consequence of the predicted temperature increase. That is one of the reasons why a network of researches about Nordic ecosystem has been developed in the last years.

Actually some forests already act as sources of carbon, and this is the case of the ecosystem considered in this study: Norunda forest has been releasing carbon to the atmosphere since scientists started measurements in 1994, through a 100 meters tower. The aim of the project is to give an explanation of this particular behaviour, by analysing two hypotheses. The first one regards the morphology of the area of the tower, which is supposed to be an inflow area collecting Dissolved Organic Carbon (DOC) from the surroundings. The second one concerns the responsibility of forest soil in emitting CO_2 after human exploitation.

Topography of the area was analysed, then some of the streams and lakes in the catchment area have been sampled two times to get DOC content of the water, and discharge has been calculated. Role of the forest soil was analysed by using a simulation model, which gave responses to the drainage carried out at the beginning of the last century and to the repeated harvests occurring every one hundred years.

The source area of measurements was found not to be an inflow area. However analyses on DOC revealed that streams and lakes in Norunda drainage basin are supersaturated in carbon, which means that water directly releases CO_2 into the atmosphere. Moreover, a certain quantity of carbon has been found to flow out the basin during the sampling time, and if it will be confirmed by long term analyses this can be seen as another cause of carbon release.

The simulation model showed that draining and harvesting a forest site can strongly influence forest soils delicate balance, reached after thousands of years. Drainage, in fact, lowers the water table and places more oxygen at microorganism's disposal. Respiration and decomposition rate increase and then CO_2 is released to the atmosphere, while soil carbon diminishes. Repeated forest harvests lead to a significant long-term decline of C soil storage as a consequence of removal of biomass from the site.

This study demonstrates that inside a forest CO_2 fluxes are determined not just by plant respiration-photosynthesis cycle, but even soil and water have an important role. 10% of Norunda heterotrophic behaviour is explained by forest draining and harvesting, and another part has to be quantified from direct CO_2 emissions by streams and lakes. Other hypotheses will be investigated in future studies.

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1. Introduction

Humanity emits more than 8 Gton of carbon into the atmosphere every year, 6.5 Gton from fossil fuels combustion, the rest comes from deforestation (IPCC 2001, [1]). Nevertheless only 3.2 billions tons, that is to say less than half the total, remains in the atmosphere. Where is the carbon stored? Forests, grasslands, peatlands and water of the oceans must be acting as carbon sinks, by removing it from the atmosphere, slowing down carbon store and delaying its effects on climate. Nobody can anticipate if these elements will preserve their role as carbon sinks, or they will turn into sources owing to the predicted global warming. Scientists are carrying out many studies about that.

For example, according to Henry's Law, an increase in ocean temperatures should reduce water capability of absorbing CO_2. Moreover, higher temperature will enhance productivity in terrestrial ecosystems, but it will also result in faster decomposition rates; i.e. an excess of decomposition might lead wetlands to become carbon sources (Moore 2002).

Even forests, although they have been always considered as net carbon sinks, can act as sources of carbon. This is the case of Norunda, the boreal forest analysed in this paper, which has been studied for ten years now. A 100m mast installed in the forest (CTS, Central Tower Site) is equipped for continuous measurements of a variety of fluxes and meteorological data.

As said before, CTS measurements revealed that Norunda has been a source of CO_2 since the research groups started flux measurement in 1994 (fig. 1.1), except for a couple of years in which an uptake took place. The top figure shows a clear pattern, which is almost the same for the majority of forests: in winter the flux of carbon is towards the atmosphere (positive according to the chosen reference system), while it is negative, so towards the forest soil, during the warm semester. This means a carbon dismissal to the atmosphere throughout the winter and an uptake during the summer, due to plants photosynthetic ability. Actually figure 1.1 shows also a release of CO_2 to the atmosphere even during summer; this happens usually in days with low incident radiation, then cloudy or rainy days, when photosynthesis is inhibited by lack of light.

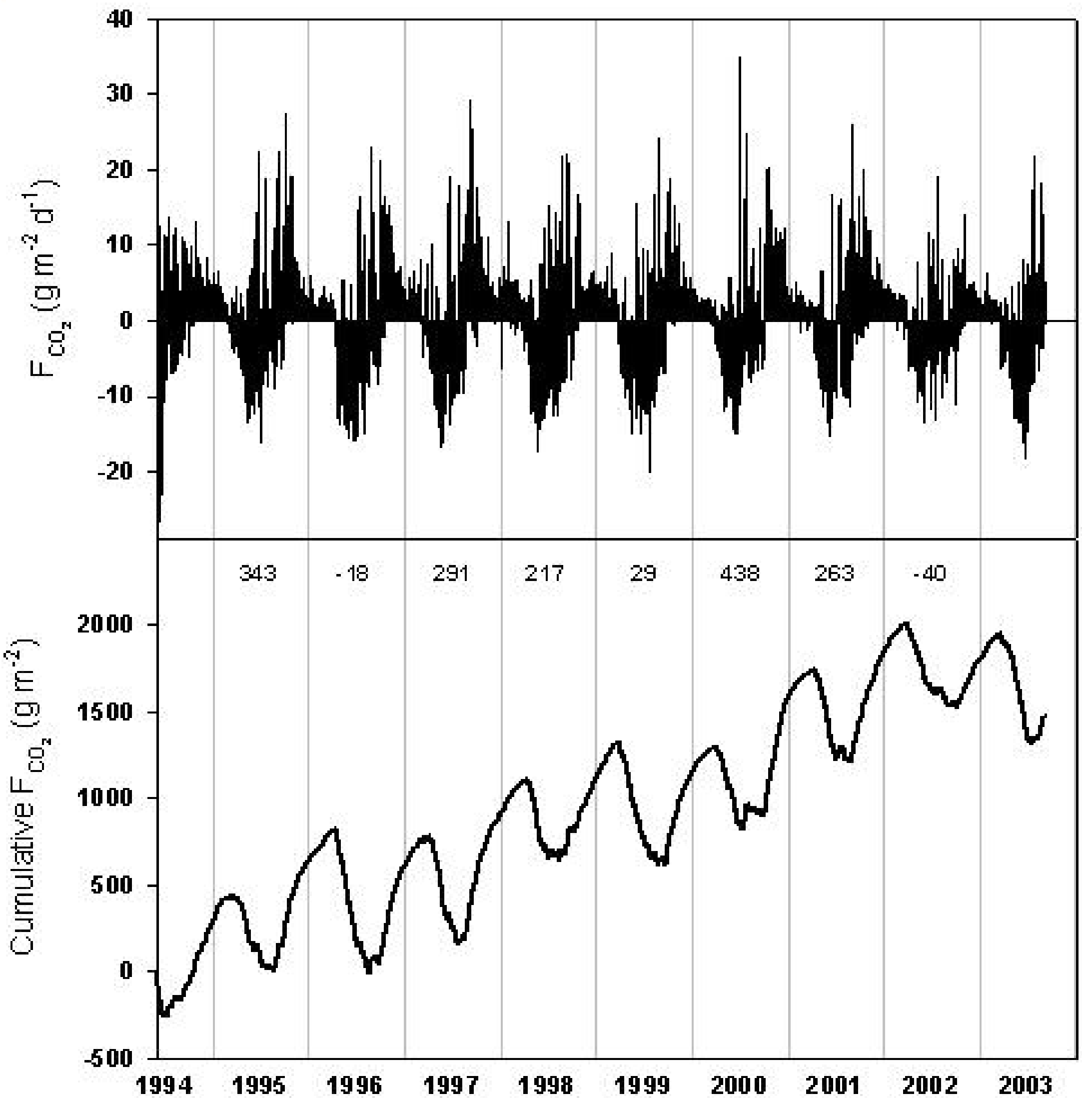

Fig. 1.1. Net daily and cumulative flux of CO_2 in Norunda during the period 1994-2002. Positive flux of carbon towards the atmosphere takes place during winter and autumn, negative flux occurres during the summer. In Norunda the annual balance is positive; there is a net flux of CO_2 towards the atmosphere, meanly 190 g CO_2 m^{-2} y^{-1}

What distinguish Norunda from the majority of boreal forests is that the annual balance is positive, therefore carbon accumulated every year by the ecosystem is less than the one released to the atmosphere. This is what the bottom figure shows; except for 1996 and 2002 forest has always been a carbon source, and ten years after surveys started Norunda has been releasing almost 2 kg CO_2 per square meter.

1.1 Aim of the study

Why does the forest behave like a source of carbon dioxide, and not like a sink? Probably this is due to numerous reasons, and project aim consists in the analysis of two hypotheses in order to assess how much they influence the total carbon balance of the forest.

1. The first hypothesis concerns site morphology and hydrology. The area of measurements is supposed to be slightly depressed, then the tower site could be an inflow area collecting then the whole surface and ground water from the surroundings. As a consequence an extra input of carbon in form of dissolved organic carbon (DOC) should be transported into the area by water streams, influencing the release of CO_2 towards the atmosphere.

2. The second hypothesis regards soil contribution to carbon flux owing to forest exploitation. Norunda, as most Swedish forests, is managed and its territory utilized for wood production, with big impact on the ecosystems.
   In particular the drainage started one hundred years ago has been analysed, together with its implication on decomposition rate of the soil. Draining a terrain means render a larger quantity of oxygen available for decomposers, and acceleration in decomposition leads to a major respiration and then a bigger flux of CO_2 towards the atmosphere. More over the forest is cut every one hundred years, and the effect of clear-cutting has been considered too, as this has a big impact on the quantity of carbon collected in the soil from above and belowground.

2. Background

The interaction between terrestrial ecosystems and climate system is a central question in global climate change research. For instance, the exchange of greenhouse gases between terrestrial surface and atmosphere is strongly modified by the climate itself through different positive and negative feedback mechanisms. Carbon dioxide (CO_2) emissions resulting from respiration in soil and vegetation are the principal sources from which this gas enters the atmosphere, being 10–15 times greater than emissions of CO_2 from fossil fuels (Raich and Schlesinger, 1992).

Nordic areas, in particular forests, wetlands and lakes, play a key role in exchanges of carbon dioxide and methane both at regional and large-scale; hence it is very important to keep them monitored, since they have been also identified to be among the most susceptible to climatic change.

Field data indicate that most temperate and boreal forests are significant sinks for CO_2 (Goulden *et al.*, 1996), with soil representing the main deposit of carbon in European forests (Valentini *et al.*, 2000), but this feature can change. Global circulation models (GCMs) have shown that there is a potential for significant acceleration of global warming due to feedbacks in the carbon cycle. According to Cox et al. (2000), forest ecosystems that are now net sinks for CO_2 might become net sources after about 2050, if projected temperature rises become a reality. This happens because plant maintenance and soil respiration rates both increase with temperature, although an increase in concentration of atmospheric CO_2 alone tends to increase the rate of photosynthesis and thus terrestrial carbon storage. As a consequence, climate warming (the indirect effect of a CO_2 increase) tends to reduce terrestrial carbon storage.

However, another recent study has suggested that the temperature sensitivity of soil respiration may be independent of the mean annual temperature of the soil across a wide variety of ecosystems and average temperatures (Giardina & Ryan, 2000). It has also been suggested that the predicted raise in temperature and precipitation at high latitudes could increase mineralization in forest soils, and thus, increase productivity which in turn would lead to more carbon uptake and increasing sink strength (Medlyn *et al*. 2000).

In view of these uncertainties, characterizing the temperature response for forest soils is particularly important, because these soils contain more than 70% of the world's pool of C in the soil (Post *et al*., 1982; Xu & Qi, 2001).

Our understanding of how these key types of ecosystems function with respect to carbon balance and its interaction with the climate system is too limited to provide answers to this type of questions. Development in micrometeorological methods has now made possible to perform long-term measurements of the fluxes of carbon dioxide and methane at ecosystem level. The high time resolution data provided by eddy correlation measurements are valuable for analysis of how the systems function relating to climatic variables and other external factors.

2.1 Carbon cycle

Almost all of the 10^{23} g of carbon the Earth contains is buried in sedimentary rocks, in form of carbonate or organic compounds, and just a little part is near the Earth's surface. The largest near-surface pool, which has a huge capacity to buffer changes in the atmosphere, is the dissolved inorganic carbon in the ocean. The largest pool of carbon on land is contained in soils (Post *et al.*, 1982., Xu & Qi, 2001).

The major fluxes of the global carbon cycle are those that link atmospheric carbon dioxide to land vegetation and soil and to the sea (fig. 2.1). The carbon cycle is a continue balance between photosynthesis and dissolution into the ocean on one hand, and respiration and exsolution from the ocean on the other, to which fossil fuels combustion and deforestation have to be added.

Oscillations in the atmospheric content of CO_2 are the result of the seasonal uptake of CO_2 by photosynthesis in each hemisphere and seasonal differences in the use of fossil fuels and in the exchange of CO_2 with the oceans. The release of CO_2 by fossil fuels rose from 6.1 GtonC/yr in 1990 to 6.5 GtonC/yr in 1999 and the average value of emissions in the 1990s was 6.3 ± 0.4 GtonC/yr. The annual flux of carbon from land-use change for the period from 1990 to 1995 has been estimated to be 1.7 ± 0.8 GtonC/yr (Houghton, 2000).

However, accurate estimations about release of CO_2 from terrestrial vegetation are complicated to make. In fact huge parts of forests are destroyed every year to obtain available lands for the agriculture, especially in the tropics, while in other areas (for instance Europe and United States) agriculture is abandoned and natural vegetation is allowed to grow again. Global estimates of changes in the carbon held in vegetation and soils are improved and it will get much better with the application of remote sensing by satellites.

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Forests acting as a carbon source: analysis of two possible causes for Norunda forest site.

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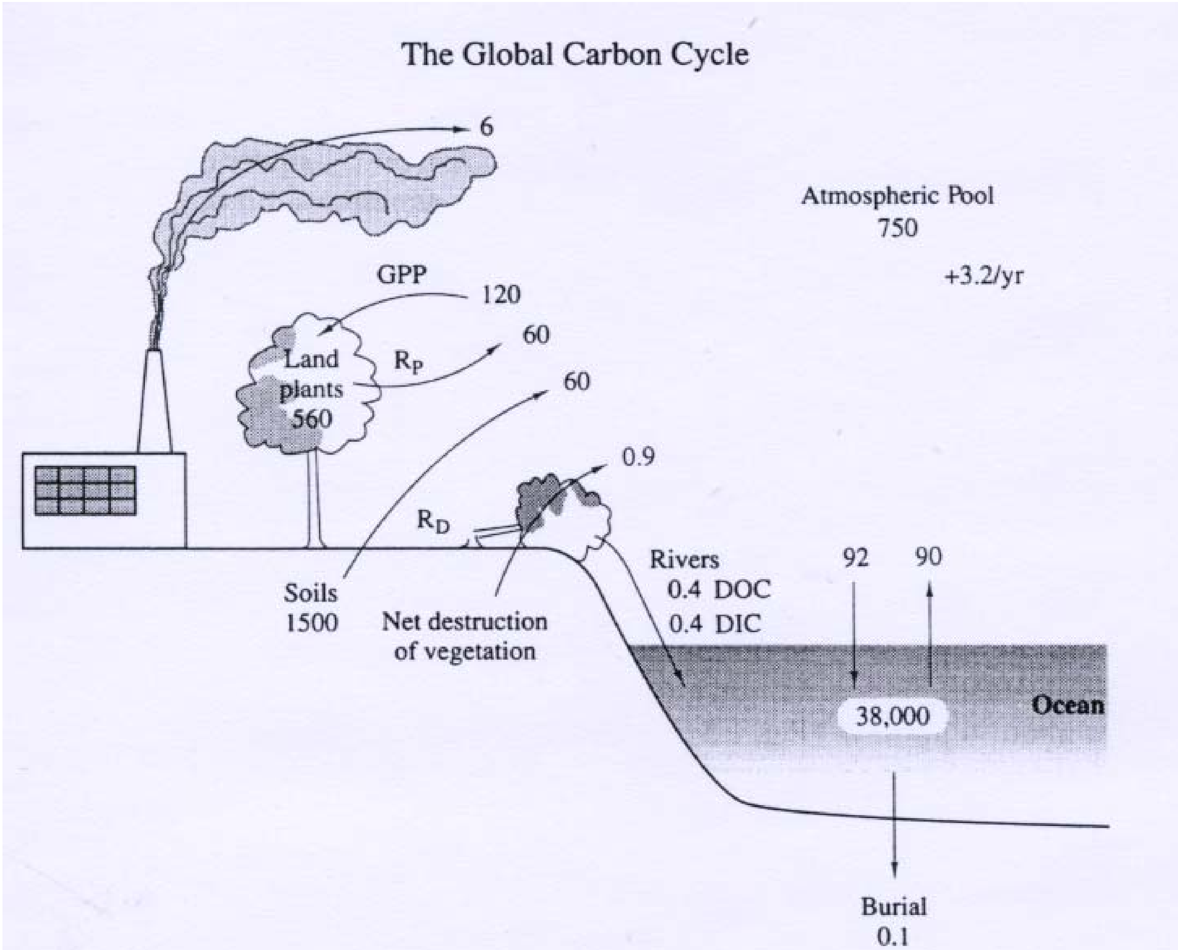


Fig. 2.1. The present-day global carbon cycle. All pools are expressed in units of 10^{15} g (Gton) C and all annual fluxes in units of 10^{15} g C/year, averaged for the 1980s. DOC represents the dissolved organic carbon, DIC the inorganic one; GPP is the gross primary production, R_p the plant respiration. From Schlesinger (1997).

Using models of ocean circulation and CO_2 dissolution in seawater, oceanographers believe that about 33% of the carbon dioxide released from fossil fuels enters the oceans each year. Annual uptake by the oceans is slightly greater than return of CO_2 to the atmosphere and the most recent model estimates of the ocean-atmosphere flux obtained with process-based models are -2.0 ± 0.8 GtonC/yr (IPCC 2001, [2]).

Following Henry's Law - at a given temperature, the amount of gas dissolved in a solute is directly proportional to the pressure of the gas above the substance - excess of carbon dioxide dissolves in seawater where it is buffered by the dissolution of marine carbonates.

2.2 Carbon balance in terrestrial ecosystems

About one third of the annual input of CO_2 to the atmosphere from fossil fuels combustion and deforestation is taken up by terrestrial biosphere (Keeling *et al.*, 1996), and a significant portion of the net uptake of CO_2 occurs at mid-latitudes of the Northern Hemisphere. In particular, north temperate terrestrial ecosystems are implicated as large sinks as a considerable accumulation of C in tree biomass occurs in temperate forests (Tans *et al.*, 1990).

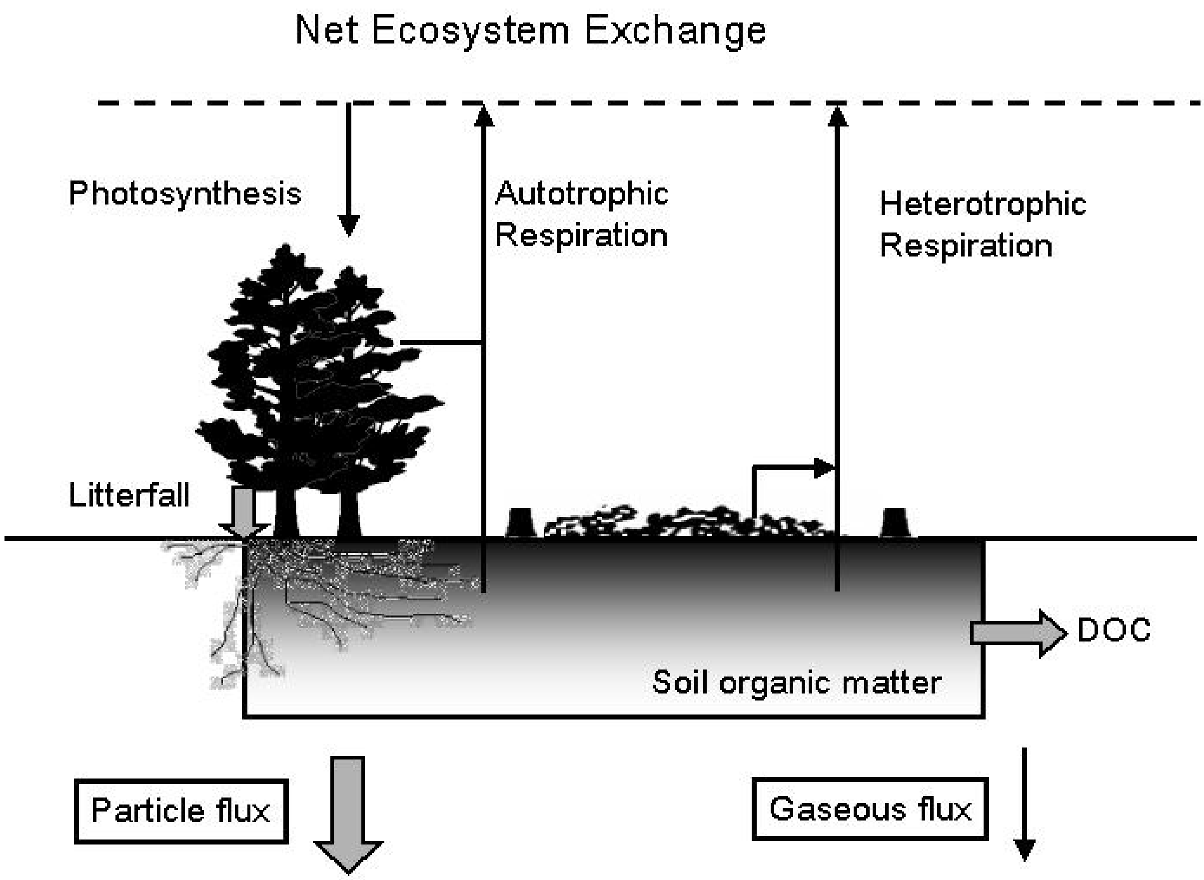


Fig. 2.2. Carbon balance in a terrestrial ecosystem.

The net ecosystem exchange (NEE) of carbon in terrestrial ecosystem is the result of a fragile balance between uptake (photosynthesis) and losses (respiration) (fig. 2.2), and shows a significant diurnal, seasonal, and interannual variability. Under favorable conditions, during daytime the net ecosystem flux is dominated by photosynthesis, while at night, and for deciduous forests also during leafless periods[1], the system loses carbon by respiration.

For 15-20 years scientists have been making use of a technique called eddy covariance to assess the net carbon balance of whole terrestrial ecosystems. The approach evaluates the exchange rate of carbon dioxide (but it is used for water and heat fluxes as well) across the interface between the atmosphere and plant canopy by measuring the covariance between fluctuations in vertical wind velocity and CO_2 mixing ratio.

This method has been first employed to assess CO_2 exchanges in agricultural crops (Baldocchi, 2003), but now it is being utilized to study carbon and water exchange in several different ecosystems, from temperate (Hollinger *et al*., 1994) to boreal forests (Valentini *et al*., 2002), from tropical forests (Kumagai *et al*., 2004) to tropical savannahs.

Like tree biomass, forest soil may act as a sink or a source for the atmospheric CO_2, having a potential impact on the global carbon budget. It can be said that in the short period soil has usually a role as carbon source, but it accumulates enormous quantity of C during millennia, with net increase of soil organic matter.

Finally, even if it represents only a little percent of the total storage, an important role in terrestrial C balance is played by organic carbon dissolved in both streams and in soil water.

2.2.1 Photosynthesis

Photosynthesis is the biogeochemical process transferring carbon from its oxidized form, CO_2, in the atmosphere to reduced organic forms as sucrose, used by plants to maintain and build up tissues. The assimilation can be described by

$$CO_2 + H_2O + \text{sunlight} \rightarrow nCH_2O + O_2 \qquad (2\text{-}1)$$

The assimilation rate is dependent on the internal CO_2 concentration and thus also on how fast CO_2 can enter leaves through the stomata, i.e. the stomatal conductance. There is a trade-off in photosynthesis: when stomata are open, allowing CO_2 to diffuse inward, oxygen and water diffuse outward to the atmosphere. The “loss” of water by stomata is called transpiration, and it is the major mechanism by which soil moisture is transferred back to the atmosphere.

The rate of photosynthesis is highly dependent on irradiance, humidity and temperature, but this dependence follows a non-linear pattern. Then an accurate estimate of photosynthetic production has ever been problematic, but nowadays its

[1] Actually photosynthesis is low even in coniferous forests during the winter, and a net loss of CO_2 is the result.

measurement is possible thanks to sensors able to determine those parameters instantaneously.

2.2.2 Respiration

The stored energy in sugar is released in presence of oxygen, and this reaction releases the CO_2 and H_2O originally fixed by sun's energy. Respiration is the result of mitochondrial activity in plant cells:

$$nCH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (2\text{-}2)$$

Besides leaf tissues respiration, a large contribute to the process is given by stems and roots. Plant respiration generally increases with higher temperatures; this is showed by high taxes of that in tropical forests and it could be cause of a positive feedback in case of the announced global warming (Ryan *et al.*, 1994, 1995).

As well as this process, known as autotrophic respiration, heterotrophic respiration takes place in the soil as a result of microbes' decomposition; components involved in it are the same as the ones for the autotrophic respiration. By measuring carbon flow between the soil and the atmosphere, it is possible to make an estimation of the bulk of organic matter decomposed and released as carbon dioxide through microorganisms' respiration.

2.2.3 Net primary production

Net primary production (NPP) is defined as the difference between gross primary production (GPP), that is the quantified result of carbon assimilation processes, and plant autotrophic respiration:

$$NPP = GPP - R_P \qquad (2\text{-}3)$$

A measure of NPP is given by the annual accumulation of organic matter per unit of land, expressed in g m^{-2} yr^{-1}, but this parameter can also be expressed in units of energy, by measurements of the caloric content of plant tissues, because it typically increases a function of intercepted radiation (Runyon *et al.*, 1994). Plant tissue typically contains about 45-50% carbon, so division by two is a convenient way to convert units of organic matter to organic carbon (Reichle *et al.*, 1973).

Both aboveground, that is to say biomass increment (tree and shrub stems) and detritus production (litter fall and dead mass), and belowground, or roots and fungal components, are involved in the total NPP.

Differences in net primary production are due to vegetation types, age and region. Primary productivity is greatest in the tropics and declines with increasing latitude to low values in boreal forest and tundra; it actually follows a precipitation gradient too, from higher rates in forests to lower in grasslands, showing values close to zero in most deserts (table 2.1).

Ecosystem	**Area ($10^{12}m^2$)**	**C in plants (10^{15} g)**	**Mean NPP (g C/m^2/yr)**	**Total NPP (10^{15} g C/yr)**
Tropical rainforest	10.4	15	800	8.3
Tropical dry forest	7.7	6.5	620	4.8
Temperate forest	9.2	8.0	650	6.0
Boreal forest	15.0	9.5	430	6.4
Tropical savannah	24.6	2.0	450	11
Temperate steppe	15.1	3.0	320	4.9
Desert	18.2	0.3	80	1.4
Tundra	11.0	0.8	130	1.4
Wetland	2.9	2.7	1300	3.8
Cultivated land	15.9	1.4	760	12
Rock and ice	15.2	0.0	0	0.0
GLOBAL TOTAL	145.2			60.1

Table 2.1. Primary production for the world (from Houghton and Skole 1990).

2.2.4 Role of the soil

The amount of C in soil organic matter has been estimated to be twice as much as that in the atmosphere (Schlesinger, 1977, Watson *et al.*, 1990). Moreover soils of the boreal region contain significant carbon reservoirs (about 15% of the total terrestrial C is stored in upland forest soils, according to Schlesinger (1977), and Post *et al.* (1982), that have accumulated over several thousands of years. Short growing season, cold temperature and high moisture contents limit decomposition of organic matter, resulting in thick accumulations of carbon-rich material on the forest floor (Harden *et al.*, 1992). Therefore changes in C storage of boreal soils may significantly alter the global soil C balance and, consequently, affect the concentration of atmospheric CO_2.

In a natural ecosystem the totality of NPP is moved to the soil as dead organic matter, unless disturbances such as fires or herbivores remove vegetation from a site.

In a forest ecosystem the flow of carbon from aboveground sources to belowground pools follows several pathways. Carbon is translocated from aboveground biomass to the root systems during root production and maintenance, and it is added to the mineral soil and forest floor through litterfall and leaching of dissolved organic matter from the canopy. Carbon release from belowground is more complex. Root respiration and decay, and decomposition represent the three largest pathways for carbon release from the soil. In absence of traumatic disturbances, i.e. fires that remove most carbon from the forest soil, the inverse process results essentially from the decomposition of organic matter by microfauna, bacteria and fungi. By using organic matter for their metabolism, microorganisms transform organic matter to CO_2 and H_2O, which are returned to the atmosphere.

Most soil C is decomposed within a few years, but there is also a small fraction resistant to the decomposition even for thousands of years (Eijsackers and Zehnder, 1990). Therefore the slowly decomposing old compounds constitute the majority of soil C while the youngest compounds represent only a little percent of it, and this age structure is pointed out in the mean age of soil C.

As C flow to and out of the soil are not balanced, soil itself can act as a source or a sink for C. If more C is removed than is added to the forest floor, the soil will be a source and the amount of C in it will tend to decrease; vice versa if more C is added than is removed, the soil will be a sink and C will be accumulated in it.

When there is an imbalance this can be due to the young age of soils: for example, the formation of the organic layer within Scandinavian forest soil started about 10000 years ago, following the retreat of the continental ice sheet (Pennanen *et al.*, 2001). More over soils are frequently disturbed by natural events – i.e. fires – or by human action - for example drainages or harvests - that do not enable the complete maturity of the soil.

2.2.5 Organic carbon dissolved in the water

A small percent of the global carbon is stored in lakes, rivers and in soil water as dissolved organic (DOC) or inorganic (DIC) carbon. DOC represents the amount of carbon available for the microbial metabolism, therefore it is a parameter used to calculate microorganisms decomposition as the process of assimilation and conversion to CO_2. Dissolved organic carbon enters streams and lakes through several pathways including overland flow, flushing of soil water, autochthonous inputs from algal exudates, and especially direct leaching from litter (Meyer, Wallace and Eggert, 1998).

Lakes have traditionally been regarded as net autotrophic systems, in which mobilization of solar energy by phytoplankton and algae forms the base of secondary production by bacteria and higher trophic levels. In such systems, CO_2 fixation exceeds whole lake respiration. However, data from lakes of worldwide distribution has indicated that many lakes are actually net sources of CO_2 and that bacterial respiration exceeds primary production (Cole *et al.*, 1994).

Many studies were carried out in order to understand the role of lakes for carbon flux, and one of the result was that boreal lakes are usually supersaturated in CO_2, which results in a net flux of carbon to the atmosphere. That happens because boreal lakes usually have a high content of DOC, which imply a high partial pressure of CO_2 (Sobek *et al.*, 2003). Net heterotrophy has been attributed to bacterial degradation of organic carbon imported from the catchment (Tranvik, 1988, Del Giorgio *et al.*, 1997), thus the degree of heterotrophy, and thereby the partial pressure of CO_2 in lake water, is coupled with the external supply of DOC.

Organic carbon dissolved in streams can be seen as a way of translocation of carbon instead. Although riverine fluxes are a minor component of the global carbon cycle (fig. 2.1), the transfer of organic carbon between catchments and ecosystems in general represents an important flux, especially in highly disturbed watersheds; i.e. areas subjected to clear-cut pour big quantity of organic carbon into streams.

2.3 Carbon related researches at Norunda

Norunda Forest is involved in two European Union projects and two Nordic projects for the comprehension of the interactions between land surface and atmosphere.

NOPEX (NOrthern hemisphere climate-Processes land-surface EXperiment). NOPEX was born as an organization of a large-scale climate process and land surface experiments in the boreal forest zone. Its specific aim is to investigate fluxes of energy, water and carbon between the soil, the vegetation and the atmosphere as well as between the lakes and the atmosphere on local to regional scales. NOPEX region is situated in the Baltic Sea drainage basin. The project long-term data acquisition started at two sites in 1994.

CTS: Central Tower Site, 30 km north of Uppsala, a mast 102 meters high equipped for continuous measurements of a variety of fluxes (i.e. carbon dioxide for soil and air, sensible and latent heat, tree transpiration, soil evaporation, canopy heat storage) and meteorological data (air and soil temperature, radiation, humidity, wind, precipitation). This is actually the project site.

MMO: Marsta Meteorological Observatory, 10 km north of Uppsala, is equipped for similar but less extensive set of measurements (not active anymore).

CTS site is backbone in the Continuous Climate Monitoring (CCM) program within NOPEX.

EUROFLUX. The project is based on 30 study sites where continuous long-term carbon, energy and water exchanges are investigated together with ecological processes controlling the ecosystem biospheric exchanges. The study sites represent various terrestrial ecosystems of the European continent, surrounding various species, community structure, management practices and distribution concerning to the change of European climate conditions. The methodology for ecosystem exchanges of carbon and energy is based on the eddy covariance theory. Sites are distributed along a North - South transect, going from about 41° to 65° North Latitude and from about 20° West to 25° East longitude. The selected sites fall into four main climate classes: Mediterranean, Temperate - Atlantic, Temperate - Continental and Boreal.

CHIOTTO (Continous HIgh-precisiOn Tall Tower Observation of greenhouse gases). The project objective is to build an improved infrastructure for the continuous monitoring of the concentrations of greenhouse gases on the European continent above the surface layer using tall towers. The project is based on and extends existing research projects (AEROCARB, T-COS and TACOS). This will be an important step towards a fully operational continuous observing system in the framework of the Kyoto Protocol for the sources and sinks of the most important greenhouse gases (CO_2, CH_4, N_2O, CO, SF_6) over Europe. Quality controlled atmospheric concentration, CO_2 flux and additional meteorological data are archived in a data center accessible to the scientific community through the World Wide Web.

NECC (Nordic centre for studies of Ecosystem Carbon exchange and its interaction with Climate system). The Center consists of 14 research groups from institutes in Denmark, Iceland, Sweden and Finland. The general aim of NECC is to obtain a better understanding of the factors regulating the carbon balance of typical sub-arctic and boreal ecosystems, by analyzing the processes across different age-classes, soil types and species for representative terrestrial and limnic ecosystems in relation to climatic and other external and internal factors. The study started in 2002 and will carry on until 2007. The results will be of high importance to increase the precision in the estimates of carbon exchange both for the Nordic region as well as for the northern hemisphere.

3. Methods

Figure 1.1 points out the role of Norunda forest as a source of carbon in the last ten years. One of the hypotheses put forward to discuss the problem is that the area examined is supposed to be an inflow area. Practically the area is supposed to acquire an extra input of organic carbon thanks to the water flow. Study of topographic maps of the zone, and determination of drainage basin have been done before the fieldwork.

During the fieldwork samples for DOC analysis were collected all around the catchment basin, drawing water from streams, little lakes and swamps, in order to know the amount of organic carbon present in the water, and discharge of the principal streams around the tower was measured. Evaluating the area of the catchment basin, a rough estimation of organic carbon leaving it through water streams has been done.

The second hypothesis concerns the impact of forest management on soil carbon storage. A simulation model, based on the one achieved by Jari Liski in 1997, has been used to analyse which influence a one-off disturb (drainage) and a long period cyclic disturb (clear-cut) have on forest soil and its role of sink or source of carbon.

3.1 Site description

Norunda is located about 30 km north-northwest of Uppsala, Sweden. Climate records show that the climate is different from other boreal forests, especially concerning to the fairly warm annual average temperature, 5.5°C (1961-1990). Mean precipitation is 527 mm per year while the average annual rate of evaporation is 454 mm (Lundin *et al.*, 1999).

The river flow regime of the region is characterized by spring snowmelt and autumn rain high flows and winter and summer low flows (Gottschalk *et al.*, 1979). The flow regime is, however, unstable and the seasonal pattern can differ from this average pattern during individual years (Krasovskaia, 1995).

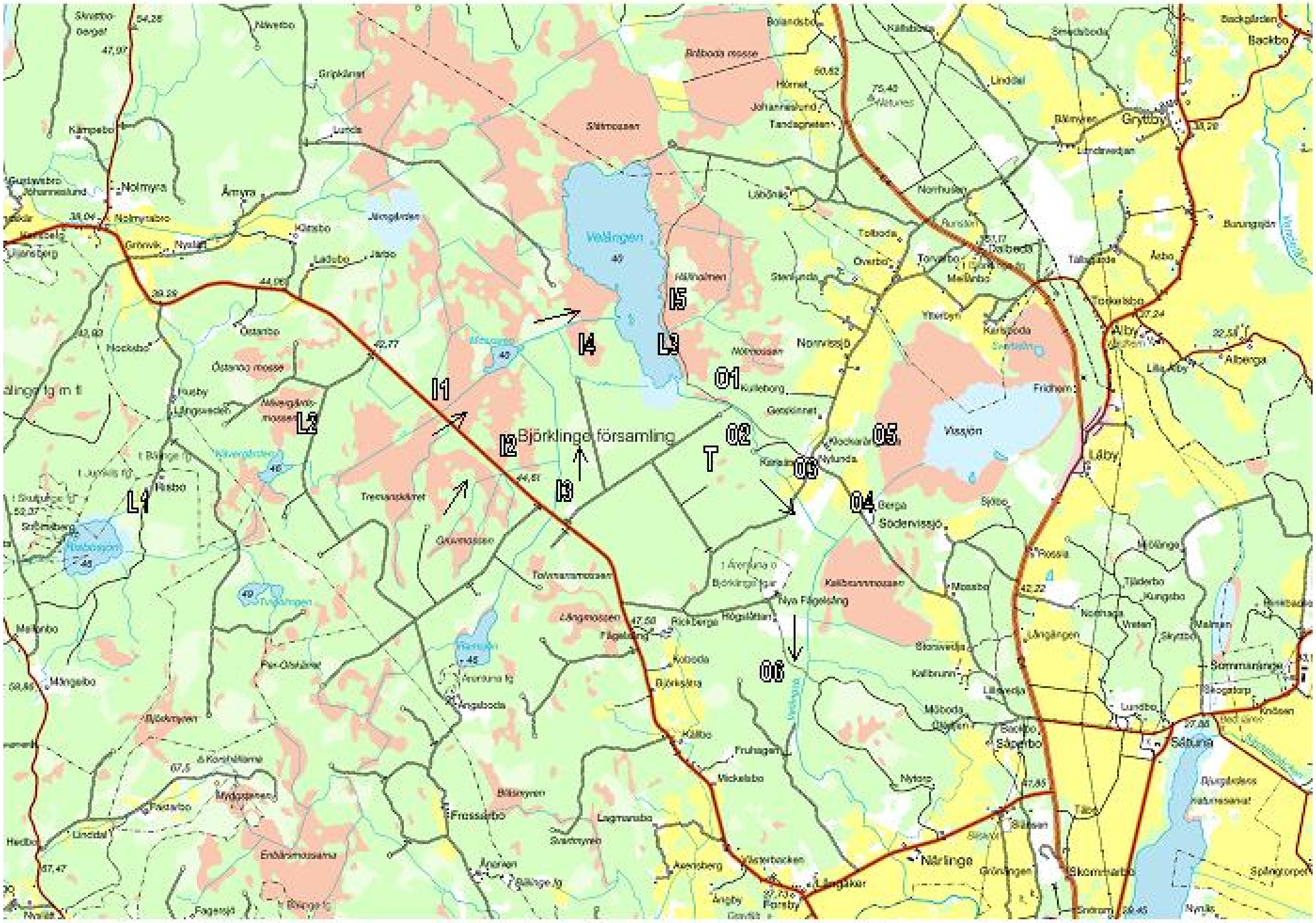


Fig. 3.1. Norunda land use map and sampling spots: L1-L3: lakes. I1-I5: inflow samples. O1-O6: outflow samples. T: tower. Green areas indicate presence of forest; white ones represent clear-cuts, orange points out wetlands and yellow crops. Arrows indicate principal flow directions.

Granite, sedimentary gneiss and leptite dominate the bedrock in the topographically flat pre-Cambrian plain that characterizes the region (Lundin *et al.*, 1999). Important is the presence of stones of all sizes. Soil is podzolized and classified as dystic regosols, meanly deep more than 100 cm. It is typically of glacial origin, rich in clayey, sandy and gravelly tills, with glacial and postglacial clay present allover the site.

Small lakes are frequent and marshy areas widespread especially towards the north. In particular CTS site (60°05’N, 17°29’E, alt. 45 m) is a swampy area rich in glaciofluvial deposits along the eastern watershed and in clay in the southern part; as expected till of glacial origin is the predominant soil.

The forest is essentially composed of Norway Spruce (*Picea abies* (L.)) and Scots Pine (*Pinus sylvestris* (L.)); the former grows in preference where soil is wetter and deeper, and undergrowth is rich in soft moss, while the latter is more common in dry and rocky terrains. Small areas where water table is just under the ground are rather frequent, and water is often collected in little swamps where birch (*Betulla alba* (L.)) is the most common tree specie. As expected forest is higher where the water table is deeper, and furthermore tree trunks are thicker, which might be an indication that drainage increases forest productivity. Where any drainage has never taken place the presence of treed bogs is really important; canes, waterweeds and thin-stemmed birches, characterize these zones.

The stand age around the tower is about 100 years, and the maximum height is over 30 m for some spread pine, although usually canopy is not higher than 25 meters; the latter is normally closed with occasional openings, with a stem density of 8-900/ha. The range for the leaf area index between 3 and 6 (personal communication, Lagergren, 2004) where pine dominated stands are generally thinner while spruce dominated stands are denser.

3.2 Role of DOC

3.2.1 Sampling and analyses

Results coming from topographic maps led to the individualization of the catchment basin (figure 3.2), in order to define the sampling spots. Measurement locations have been chosen so that the sampling touched lake Velången inlets and outlets, which encircle the tower. Samples have been taken in two different periods: the first session in May 10^{th}-13^{th}, the second one in June the 22^{nd}. Water samples have been taken just under the surface.

Surface water from small ditches was sampled into sterile polypropylene 50 ml containers, and stored cool in a fridge. Then they have been analysed at Lund University Limnology Department. Samples for DOC were filtered to get rid of microorganisms and acidified to remove inorganic carbon, and then measured on Shimadzu TOC-5000 total carbon analyser.

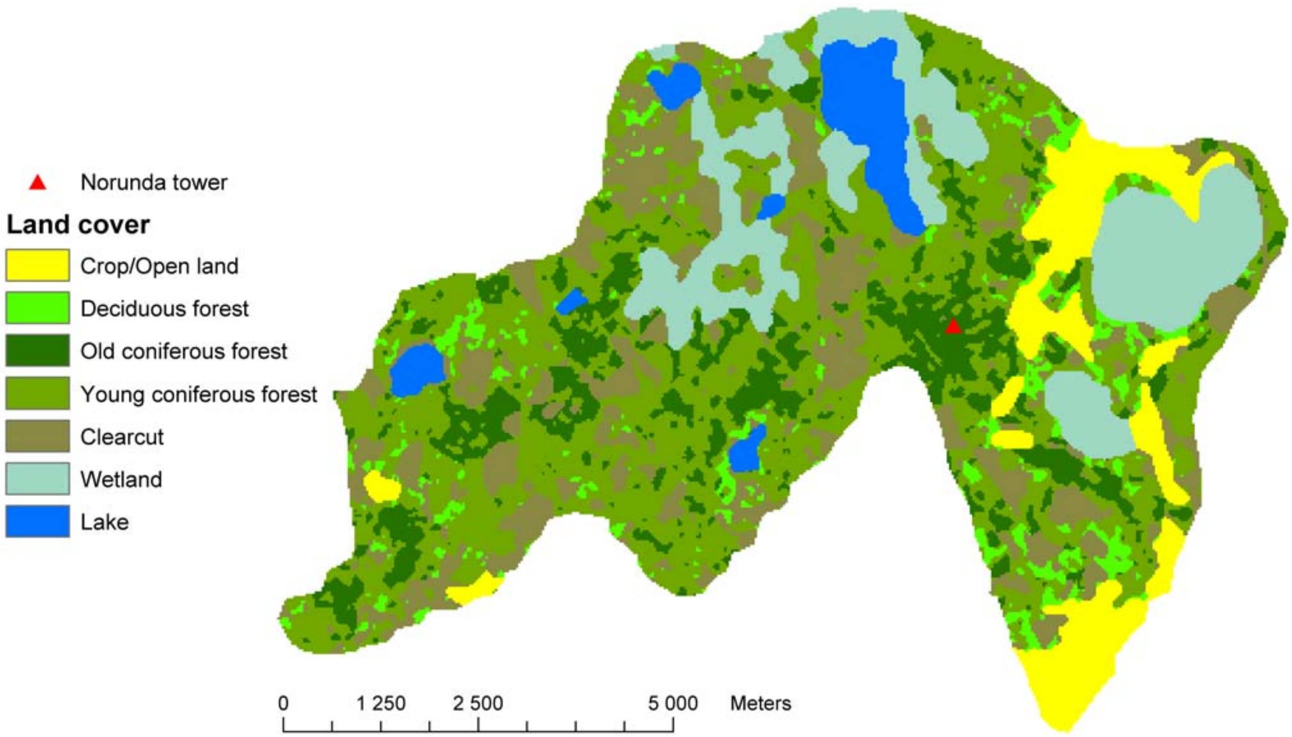


Fig 3.2. Norunda catchment basin: land use

3.2.2 Water flows

In order to estimate flow direction and the quantity of water transported by streams in the area around the tower, some of the spots have been selected to calculate the stream discharge. Discharge for a stream is the volume of water flowing through a cross-section every second. It was determined for both points that suppose to belong to the inflow basin and to the outflow in order to obtain an idea of the balance. Discharge was measured at easily reachable spots, i.e. where the water came out from bridges and tubes, because the evaluation of cross-section area was simpler and inaccuracies were reduced. Measurements have been carried out in two different periods, May 10th-13th and June the 22nd.

The flow velocity as measured by a current meter[2]. The propeller is fixed to the stick and aimed against the flow direction, and resistance put on makes the propeller turn. Propeller has to be placed at about 40% of the stream depth; to be more accurate values were taken at different positions along the width, repeating the procedure two or three times.

[2] Type Ott (Kempter, Germany) No. 39728 type 10002, method of calibration: BARGO, rod of 22 mm diameter, with a propeller diameter 125 mm, pitch 0.25 m, No. 1-40970

Fig. 3.3. Current meter.

If n denotes the number of revolution of the propeller the following relation expresses the water velocity v

If $n < 0.76$ $v = (0.2392n + 0.016)$ m/s (3-1)
If $n > 0.76$ $v = (0.2552n + 0.004)$ m/s (3-2)

The preliminary was to take four measurements for the inflow (fig. 3.1), but the calculation of discharge was possible only for two of them, because the flow was too slow for spots I2 and I4 and the propeller did not turn. Then inflow values are available just for spots I1 and I3, while four spots were found for the calculation of the outflow (O1, O2, O3, O6). The second session of data is even more incomplete, because water flow was even slower, and measurement of location O1 was not possible. So only three outflow discharges have been calculated in June.

Once obtained flow velocity and cross section area, calculation of discharge was obtained by multiplying the cross section area (in m^2) and the speed (in m/s)

$$Q = A_c \cdot v \quad (3\text{-}3)$$

3.3 Drainage and harvest impact

Several studies were carried out to understand the impact of forest management on soil organic carbon content. Norunda has been drained about 100 years ago, according to what forest owners said, and about 35 years ago a great increase in forest productivity has been observed by dendrochronology data (fig 3.2). The latter was probably caused by fertilization, and it has not been taken into consideration for the study.

Drainage has a role in changing soil characteristics, as microorganisms' respiration, therefore decomposition rate, is supposed to enhance as a result of the larger oxygen availability. As a consequence soil organic carbon storage should decrease after the drainage.

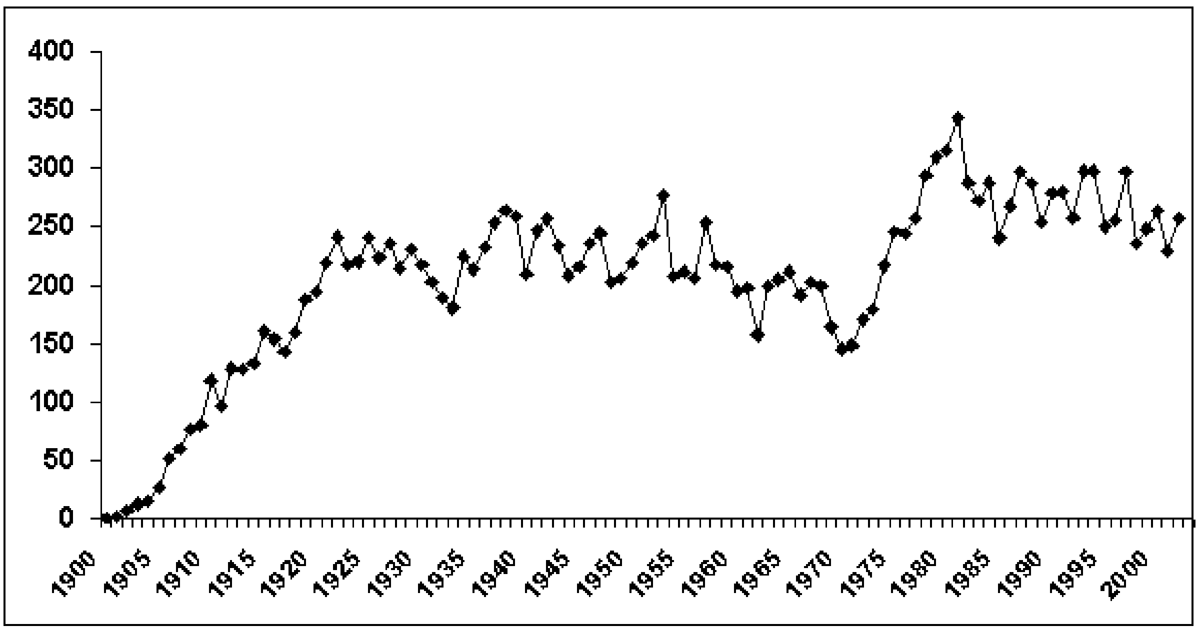


Fig 3.4. Total biomass growth (kg C m^{-2} $year^{-1}$) in Norunda forest. To be noticed the sudden increase in productivity between 1970 and 1980, probably due to forest fertilization (Lagergren 2004).

Moreover Norunda, as most forests in Sweden, is subject to clear-cuts at one hundred year intervals; since stand age is in some cases over 100 years (personal communication Lankreijer, 2004), the forest should be cut down following standard forestry practises. Clear-cutting has a big impact on soil carbon content, since suddenly most of the forest biomass is removed. Hence an initial peak in soil C, due to needles and branches left on the terrain, and dead roots starting degradation after trees cut, is expected after harvesting. Then a rapid decrease, owing to the few organic matter reaching the soil, is predictable immediately later.

In order to understand changes occurred in the soil owing to harvestings and drainages realized, the simulation model achieved by Jari Liski (Liski *et al.* 1997), revised for the study aim, has been utilized.

3.3.1 Simulation model

The model is based on the assumption that fresh litter decomposes rapidly at first but gradually the decomposition rate decreases.

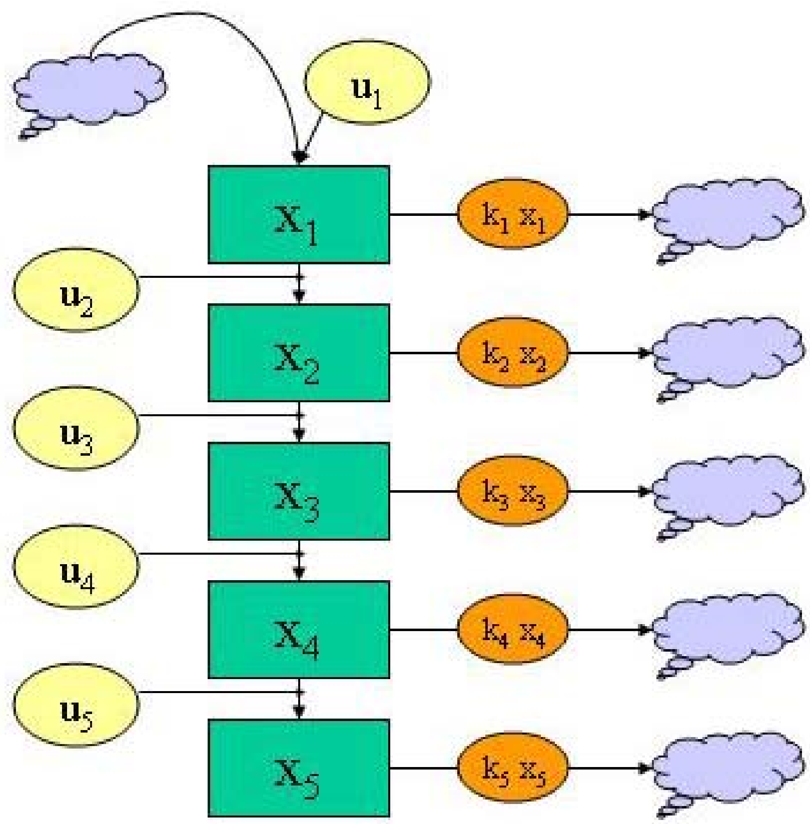


Fig. 3.5. Flow chart of the model. The rectangles represent the soil C compartments, the cloud C outside the soil. Arrows show C flows and ellipses the regulation of this flow. x_i denotes the weight of organic C in the compartment, u_i the flow of C into it, while k_i are the decomposition rates.

That happens because initially the most easily decomposable energy-rich compounds, such as sugar and proteins, decay, but afterwards less degradable substances, such as lignin compounds, have to be decomposed and new recalcitrant residues, for instance complicated humus polymers, are formed.

The model consists of five compartments (x_1,...x_5) that contain organic soil carbon of different age (fig 3.3). Fresh litter enters the first compartment and the residue has not been decomposed during its residence time is transferred to the following compartment, which has a lower decomposition rate. The others compartments work like the first one, except for the fifth one where the organic matter remains until it is completely decomposed.

3.3.2 Parameterisation of the model

Decomposition rates in the compartments

Except for the first compartment, where the decomposition rate is strongly dependent on the temperature, the study utilizes the decomposition rates used by Liski (Liski *et al.* 1997), who adjusted them for coniferous forest sites in Southern Finland to compare model-calculated results with the data from a chronosequence and in the literature. The choice can be considered correct as precipitation and temperature are not so different, both Finnish forest and Norunda are composed principally by Spruce and Pines, and they both grow on a podzolized soil. Decomposition rates were taken from Liski report, and they are shown in table 3.1.

Compartment	Value ($years^{-1}$)
k_1	0.324
k_2	0.070
k_3	0.016
k_4	0.002
k_5	0.001

Table 3.1. Decomposition rates in the model compartments.

The specific decomposition rate in the first compartment is a function of annual mean temperature, which may change in time. For the second compartment decomposition rates of coniferous litter were not available, and the decomposition rate needed to be estimated on the basis of decomposition rates reported for different organic material. Liski chose an intermediate value between the decomposition rate for the *Calluna* stems between the years 5-10 (Heal *et al.* 1978), the one for rye-grass between the years 5-10 (Jenkinson 1977) and the one for the decomposition in the mor type between the years 5-15. The decomposition rate of the third compartment is based on a decomposition rate of balsam fir (*Abies balsamea* (L.)) boles during the first 80 years of decomposition (Lambert *et al.* 1980). The original rate, 0.011 $year^{-1}$, was measured in a subalpine forest where the annual mean temperature is 0°C and the period without concrete frost in the organic horizon is only six months. To account for the warmer climate in his study area, Liski multiplied this rate by 1.45, which is the effect of about 3°C higher mean annual temperature on the decomposition rate of Scots Pine needles.

Actually Norunda site has an average temperature of 5.5°C, but the same value for the decomposition rate can be used according to Nadelhoffer *et al.* (1991), who found that respiration rates between 3°C and 9°C were similar and never differed significantly. Moreover Schmidt *et al.* (1999) showed that no significant effect on the CO_2 efflux occurs in soils incubated at 5°C, 10°C and 15°C for a forest situated in the north of Sweden.

Experimental data for decomposition rates were not available for soil organic matter older than 100 years which is found in the last two compartments of the model. For this reason these rates were approximated on the basis of the chronosequence data. As decomposition is the slowest in the fourth and the fifth compartments of the model, these compartments stabilize the latest and, consequently, determine at which age the total soil C storage reaches equilibrium. To reach equilibrium at the soil age of about 2000 years, i.e. 1000 years after C has started accumulate in the 5th compartment, their decomposition rates for these compartments need to be of the order 0.001 year^{-1}. Therefore, 0.002 was taken as the decomposition rate for the 4th compartment and 0.001 for the fifth one.

Residence time in the compartments

The decrease in decomposition rate is rapid in the early phases of decomposition, but gradually this rate of decrease in the decomposition rate slows down in the age of organic matter (Berg *et al.* 1982). To describe this kind of decrease in the decomposition rate and still be able to have a constant decomposition rate in each model compartment (except for the first one, depending on the air temperature), the residence times of the compartments were chosen to increase with increasing age of C. Consequently, residence times of 15, 80 and 900 years were chosen for the compartments x_2, x_3, x_4 respectively, while for the first one residence time depends on decomposition rate, and therefore on the air temperature.

Input rate of C to the soil

The input rate to the soil represents the sum of the amount of litter coming from aboveground and the belowground production, that is to say roots. This input rate was assumed to be constant during the whole simulation in a first moment, and then changed to test the model sensitivity.

So an average of the measurements carried out in twelve years (1991-2002) has been taken as input annual rate of C to the soil. The average aboveground litter fall production for Norunda is 0.168 kg C m^{-2} year^{-1} (Lindroth *et al.* 2002), and the input rises with forest growing old. Even if it is just an average on a few years the value is reasonable, also according to Lonsdale (1988), who estimated annual total litter fall production using the following equation, developed from 181 forest sites around the world:

$$Y = 10^{(1.02 - 0.000059a - 0.012l)} \qquad r^2 = 0.63$$

where Y represents the annual aboveground litter fall in Mg ha^{-1} yr^{-1}, a is the altitude in meters and l the latitude in decimal degrees. In view of Norunda elevation and latitude Y come out to be 0.198 kg C m^{-2} year^{-1}. Moreover Nakane (1994) found an aboveground litter fall of 0.180 kg C m^{-2} every year in a Scots pine ecosystem (Jädraås, central Sweden).

For the belowground litter fall the value measured by LUSTRA (Lindroth *et al.* 2002) has been taken, namely 0.143 kg C m^{-2} year^{-1}.

So the total annual input of carbon in Norunda soil is 0.311 kg C m^{-2} year^{-1}, and that is the value chosen as input for our simulation model. This value is absolutely in agreement with the one used by Liski (1997), who opted for 0.30 kg m^{-2} year^{-1} in a pine forest in Finland.

3.3.3 Testing of the model

The model has been tested by Liski and Westman (1995) by calculating the equilibrium soil C storage for four forest sites of varying productivity, and comparing the obtained values to measured mean storages in 10000 year old soils for the same forest types. Since the studied sites were dominated by either Scots pine or Norway spruce, producing homogenous coniferous litter, the same decomposition rates and residence times were used for the different forest types. Only the input rate of C varied according to the forest type, assuming that in absence of fires or harvests all C bound in vegetation ends up in soil. The model predicted the measured soil C reasonably well, especially for the site where the production rate was most accurately (the other production rates were obtained by multiplying that site's by a correction coefficient) where the model-calculated storage value was only 1% larger than the measured storage.

Norunda soil carbon storage obtained with the model has been compared to a study conducted by Callesen *et al.* (2003) who measured soil organic C pools in 234 well-drained Nordic forest floors. According to the model, considering Norunda a well-drained site, the total bulk of carbon in its soil is 7.15 kg/m^2 (results not published) at the equilibrium, that come within the range of value obtained by Callesen for a southern boreal forest (6.2-7.2 kg/m^2).

4. Results

4.1 Discharge and DOC

As clearly shown in figure 3.1 superficial waters in the little drainage basin around the mast follow a northward-northeastward course west of the tower, while it flows southward in the eastern part. Lake Velången collects all the water coming from west of the tower, while its only large effluent (the one will become Björkligeån river) gathers water from every watercourses southeastern of the mast. Water goes through an area close to the tower, but it is actually Lake Velången that acquires all the DOC coming from watercourses in the drainage basin. Then it is clear there is no collection of DOC in the source area of the tower.

Table 4.1 shows streams velocity and discharge measured in Norunda in May and June 2004. In May stream discharge was superior to the one measured in the second session, because of the higher water level, influencing the cross section area, and the greater velocity. Discharges are strongly influenced by snow melting, just occurred in the first session, which pours big amounts of water into streams. This contribute enhances water volume and speed. Anyway for both periods most streams had a very slow flow, impossible to be measured, and the smallest ones were almost still. This happened because the area is extremely flat and many watercourses have a remarkable flow only after the snow melts.

Table 4.2 shows DOC content of the drainage basin streams and lakes.

Here differences between the two sessions of measurements are not as remarkable as they were for the discharge; it is possible to notice a slight decline in the average inflow DOC content and a low recovery in the outflow one. Inflow water has a higher amount of carbon than the outflow; this means that water flowing into lake Velången is richer in organic carbon than the one leaving the catchment basin.

Starting from these data, an estimate of total amount of organic carbon transported throughout Norunda catchment basin by water DOC has been done (table 4.3). Location O6 has been selected, since it is situated at the outlet. The drainage basin area has been drawn freehand on an ArcView layer (fig. 3.2), and calculated as 63.3 km^2, and the total water carbon content estimated for the period 13th of May – 22nd of June.

Location	Velocity (m/s)		Cross section (m^2)		Discharge (m^3/s)	
	May	June	May	June	May	June
I3	0.33±0.03	0.19±0.02	0.09±0.03	0.048±0.013	0.031±0.013	0.009±0.003
I1	0.13±0.03	0.11±0.03	0.55±0.04	0.40±0.04	0.07±0.02	0.042±0.014
O1	0.13±0.02	/	1.56±0.08	1.46±0.08	0.20±0.04	/
O2	0.34±0.03	0.20±0.05	0.68±0.07	0.37±0.03	0.23±0.04	0.07±0.02
O3	0.13±0.03	0.06±0.01	2.18±0.08	1.52±0.10	0.28±0.06	0.09±0.02
O6	0.18±0.02	0.09±0.03	1.20±0.08	0.71±0.11	0.22±0.04	0.06±0.03

Table 4.1 Norunda catchment basin discharge.

Supposing a linear relation between discharges in the two measurements the discharge in m^3 per 40 days has been calculated.

Location	DOC content (mg L^{-1})	
	May	June
STREAMS		
I1	37±1	34±1
I2	55±1	59±1
I3	35±1	37±1
I4	53±1	51±1
I5	67±1	57±1
O1	30±1	29±1
O2	27±1	29±1
O3	29±1	28±1
O4	29±1	31±1
O5	19±1	27±1
O6	31±1	29±1
Streams average	**37±4**	**38±4**
LAKES		
L1	30±1	29±1
L2	30±1	30±1
L3 (Velången)	35±1	32±1
Lakes average	**31±3**	**30±2**
TOTAL AVERAGE	**36±3**	**36±3**

Table 4.2. DOC content in streams and lakes around the mast.

Then the two values of DOC obtained by the organic carbon analyser have been averaged; this can be considered a good approximation, as slightly changes in DOC content occurred in that period for all the spots. By multiplying the cumulative discharge and the average DOC, the total estimate of organic carbon flowing through the drainage basin in the whole period, and consequently the grams of carbon transported along the catchment every day, were obtained. This value has been divided by the area of the catchment, obtaining the total amount of organic carbon leaving the site: about 6 mg per m^2 every day.

Area (km^2)	**Tot discharge (m^3/50 d)**	**Mean DOC (mg L^{-1})**	**Tot discharge of DOC in O6 (g C d^{-1})**	**DOC discharge (g C d^{-1} m^{-2})**
~63.3	~496000	30±1	~374000	~0.006

Table 4.3. Estimate of carbon discharge by DOC analyses in Norunda catchment basin

4.2 Application of the model

Changes in decomposition rates have been made in the model to simulate the effect of the drainage carried out 100 years ago, and the annual input of carbon coming from the litter has been modified in order to simulate the harvests taking place in the last 200 years. The input values selected are 5.5°C for the air mean annual temperature and 0.31 kg C m^{-2} $year^{-1}$ for the annual above and belowground litter fall.

Decomposition rate and litter fall were kept constant for the first 7000 years, time necessary to the soil carbon storage to reach a equilibrium (12.43 kg/m^2). Fig. 4.1 shows the amount of organic carbon in the soil of a boreal forest that has the same annual average temperature and total biomass production rate as Norunda.

As said before Liski's rates for decomposition have been used, except for the first compartment where the rate is temperature dependent. The only change was multiplying all the initial decomposition rates by 0.62, in accordance with a study conducted by Davidson *et al.* (1998), finding that average relation between soil respiration in a miry and in a drained site.

The difference is due to the larger amount of oxygen available after the water table lowering, which allows a better decomposition and CO_2 production. Hence the forest was assumed to be a marshy site before the drainage, and this is plausible since water table is almost at the ground level in zones where drainage did not take place. Moreover the lower efflux from a swamp site is probably influenced not only by wetness and its effect on diffusion of O_2, but also presumably by lower C inputs on the soil. Trees are sparse, moss is common, and rates of net primary productivity are apparently lower in a marshy than in a drained site.

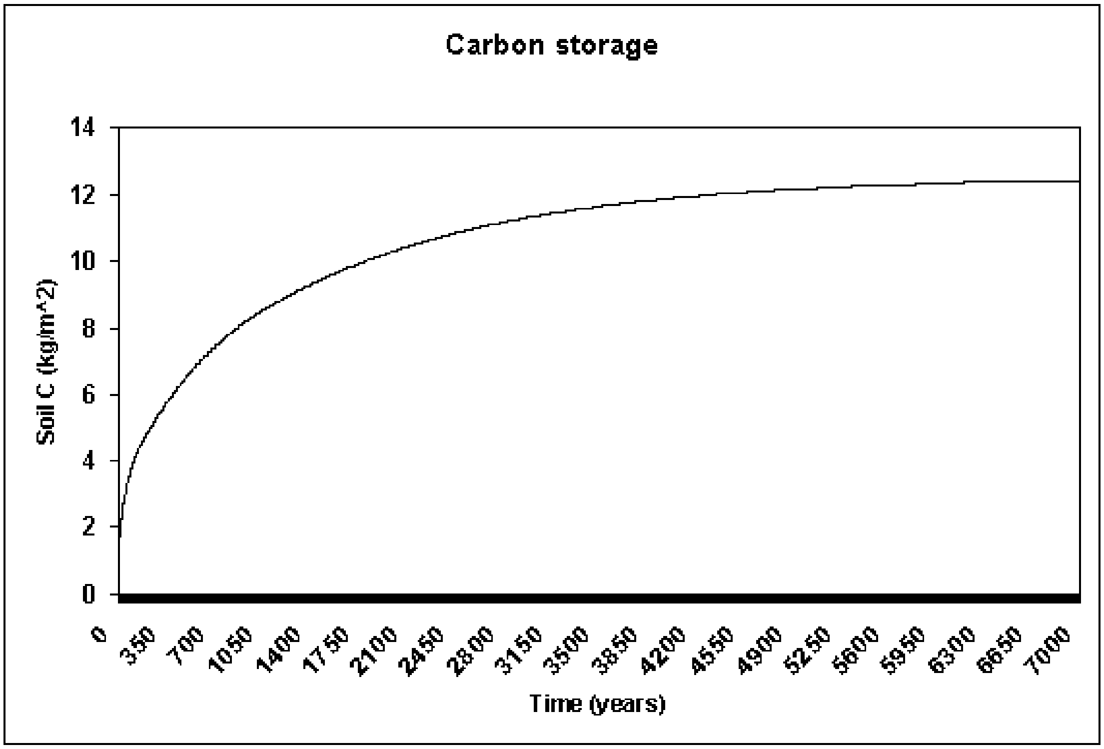
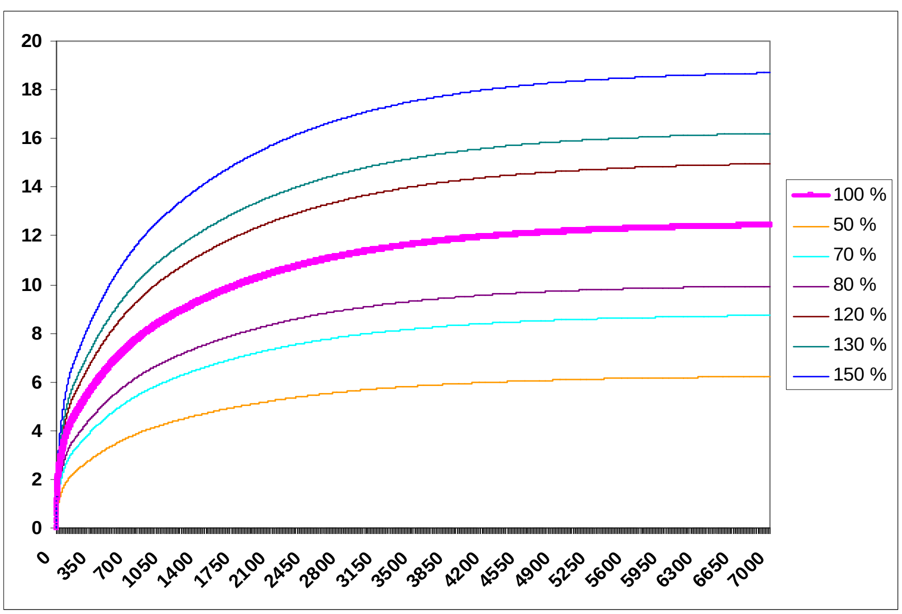


Fig 4.1. Soil carbon conditions in Norunda before forest was managed.



% litterfall	% storage
100	100
50	50
70	70
80	80
120	120
130	130
150	150

Fig 4.2. Amount of carbon in soils of different ages as simulated using different litter fall rates.

This hypothesis has been taken into consideration in the sensitivity test of the model, in which the latter has been run inputting different litter fall rates (fig.4.2). It is easy to note that a linear relation exists between litterfall and soil carbon content.

4.2.1 Effect of drainage on soil carbon storage

One drainage, taking place about 100 years ago, was simulated and changes in decomposition rate were made to take it into account. As expected soil carbon storage decrease immediately after the drainage, owing to highest decomposition rate turning carbon into CO_2, which is released to the atmosphere. The soil carbon concentration takes long time to reach a second equilibrium, at least 3000 years, after which the amount of C has reduced by 5.13 kg/m^2, or 41.3% (fig. 4.3). It is interesting to notice that the equilibrium value achieved after 10000 years is the same the soil would have reached if it had been well drained from the beginning.

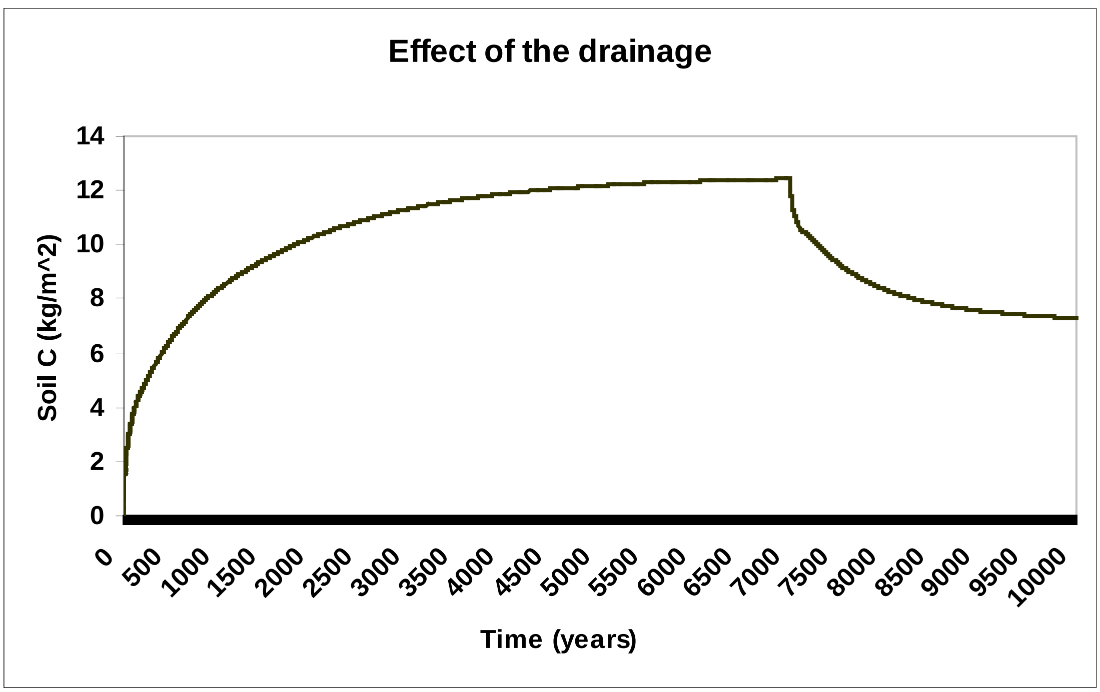


Fig 4.3. Carbon storage change after draining a boreal forest soil

One hundred years after the drainage, namely the present time according to our initial assumption, soil C is estimated to be lower by 1.85 kg/m^2, that is 14.9% and it is still rapidly decreasing (fig. 4.4). This means that soil releases CO_2 to the atmosphere by decomposition in order to reach the equilibrium. Loss of carbon is extremely rapid in the first twenty years, after which the soil release to the atmosphere more than 1 kg

C m^{-2}, then decrease stabilizes and the curve assumes a linear shape due to the fact loss of carbon is about 10 grams per year.

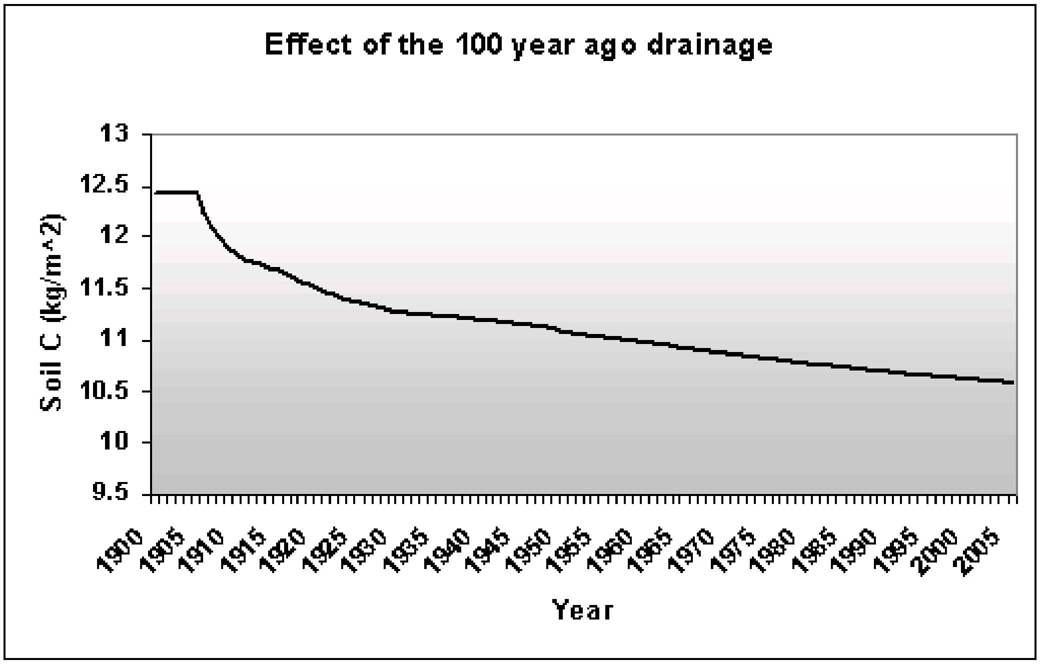


Fig 4.4. Decreasing in soil organic carbon after the drainage

4.2.2 Effect of harvests

Forest harvesting changes the input rate of C to the soil compared to an unmanaged site. At the time of the harvest, a large amount of dead organic matter, constituted by roots, needles and most branches, is left at the site as harvest residues. Anyway plant productivity reduces drastically since only few trees are not cut for seed spreading. Plant production starts recovering the years following, however less organic matter reaches the soil than at an unmanaged site. Forest harvesting also changes the soil temperature and moisture regime such that the decomposition rate of soil organic matter may be accelerated, at least in the organic layer (Gorham *et al.*,1979) Because this increase in decomposition is poorly known for boreal forest it has not taken into consideration in this study.

Clear cuttings occurring every 100 years have been simulated (fig. 4.6), so every 100 year period was called "cycle"; two harvests have been supposed to have taken place before the present time (fig. 4.7). As done for the drainage simulation the model was first run to equilibrium with the input rate of C to the soil of an unmanaged site (0.31 kg m^{-2} year^{-1}).

Forest owners estimated that about 75% of branches and needles mass is removed, then 25% of their biomass stock is supposed to be added to the soil as organic carbon. The whole amount of roots are supposed to remain in the terrain and start decomposing immediately after the cut. Stems have not been taken into consideration since they are supposed to be completely removed after the clear-cutting.

According to Lindroth *et al.* (2002) the total bulk of C in Norunda needles and leaves is 0.65 kg m^{-2}, while it is 1.95 kg m^{-2} for branches. Hence 25% of the sum, 0.65 kg m^{-2}, has to be added to the total roots' mass, namely 2.5 kg (Lagergren, personal communication, 2004), at the time of harvest. Just after clear-cutting, litter fall ceases, but beginning from the year later forest soil restarts receiving litter from the aboveground, and roots begin to produce organic matter again; then a partial, even if minimal, carbon re-establishment starts the year immediately following the clear-cutting.

Recovery of the litterfall (figure 4.5) during forest regeneration is expressed by a logistic curve provided by Nakane (1994) for a Scots pine (Pinus sylvestris) ecosystem in central Sweden.

$$L = \frac{L*}{1 + a \cdot e^{(-bt)}} \qquad (4\text{-}1)$$

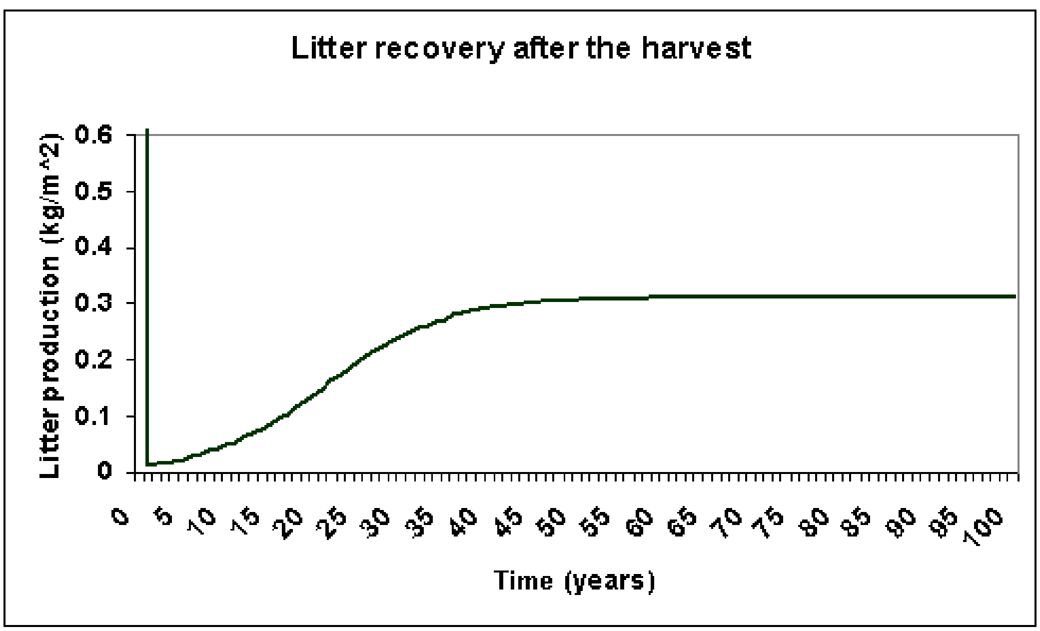


Figure 4.5. Litterfall progression after forest clear-cut. The initial peak is due to the enormous bulk of organic matter pouring into the soil, owing to roots and other plant parts not harvested.

where $L*$ is the amount of litter fall, in kg m^{-2} year^{-1}, before the clear cutting, t is the time after the harvesting, in years, and a,b are two coefficient Nakane found for the pine ecosystem.

$$a = 25 \qquad b = 0.15 yr^{-1} \tag{4-2}$$

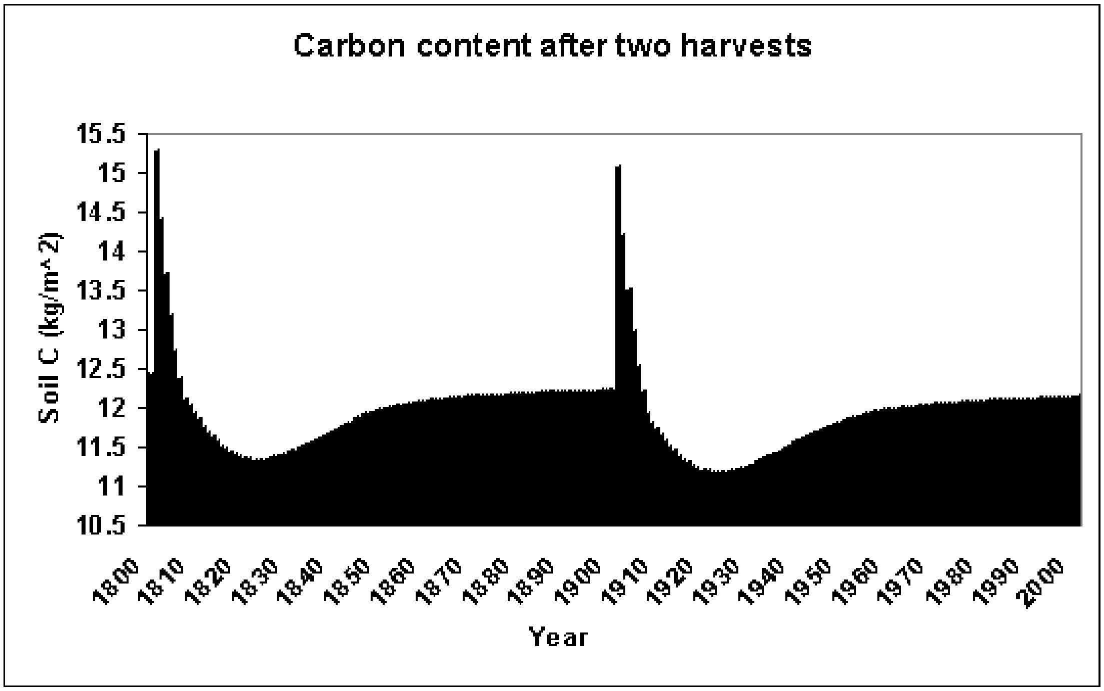


Fig. 4.6. Trend in soil organic C after two harvests.

Soil carbon storage at the time of the harvest increases due to harvest residues left at the site, but it is also rapidly decomposed, then after few years the bulk of carbon in the soil is less than it was before cutting (figure 4.6). Soil carbon diminishes in the soil until about 25 years after harvesting, when it reaches a minimum, then it starts enhancing again, pretty rapidly until year 55-60, and next more slowly till it almost reaches a new balance at the time of new harvesting. The carbon present in the soil at the subsequent equilibrium is lower than at the previous one by about 2.3%.

After the second harvest soil follows the same trend as after the first one, but minimum is less pronounced and recovery more rapid, and at the time of the following harvest soil C storage is further reduced by 1.1%. If the site is repeatedly harvested at an interval of 100 years (fig. 4.7) a new equilibrium is reached in about 5000 years, when the amount of soil carbon is 10% smaller than before starting harvesting the site. Even if the loss of carbon is not as high as in the drainage simulation, carbon dioxide release will continue for a very long time before reaching a new equilibrium.

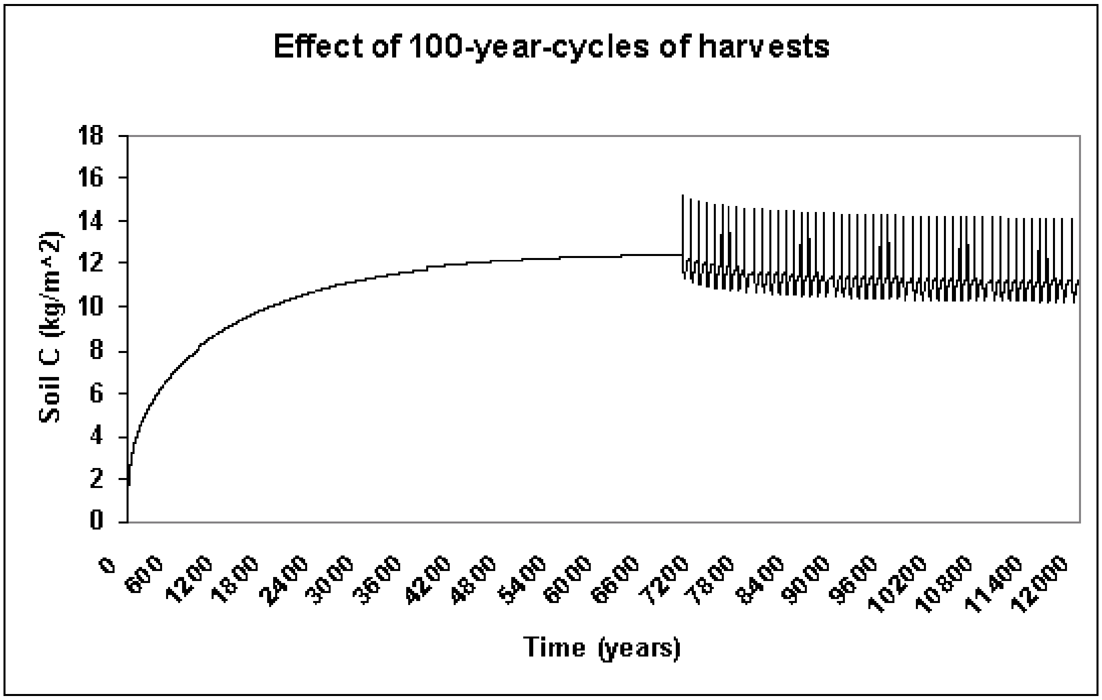


Fig. 4.7. Effect of 100 years clear-cuttings cycles on soil organic carbon.

4.2.3 Combined effect of drainage and harvests

The model has been finally run considering two harvests occurred in the last 200 hundred years and the 100-year-old drainage (figure 4.8).

Naturally at the end of the first cycle carbon amount in the soil is the same as it was in the simulation of the harvest, since the drainage has not occurred yet. The second cycle shows completely different trend from the very beginning, since the simulation provides for a drainage occurring simultaneously the second harvest. The amount of carbon starts decreasing at a rate much higher then before, owing to the two disturbs combined effect. Then the recovery due to the rapid vegetation growth assumes greater effect than the loss caused by the enhanced decomposition rate, but after a peak reached at about 50-55 years carbon storage starts decreasing again. At the end the model estimates soil carbon content in 10.34 kg m^{-2}.

Assuming no more drainages will be carried out on the forest, and supposing cyclic clear-cuts every 100 years, the soil would reach a new equilibrium only about 5000 years after the first clear-cut, and the amount of carbon stored in the soil would be 48.6% lower than before forest was managed (fig. 4.9).

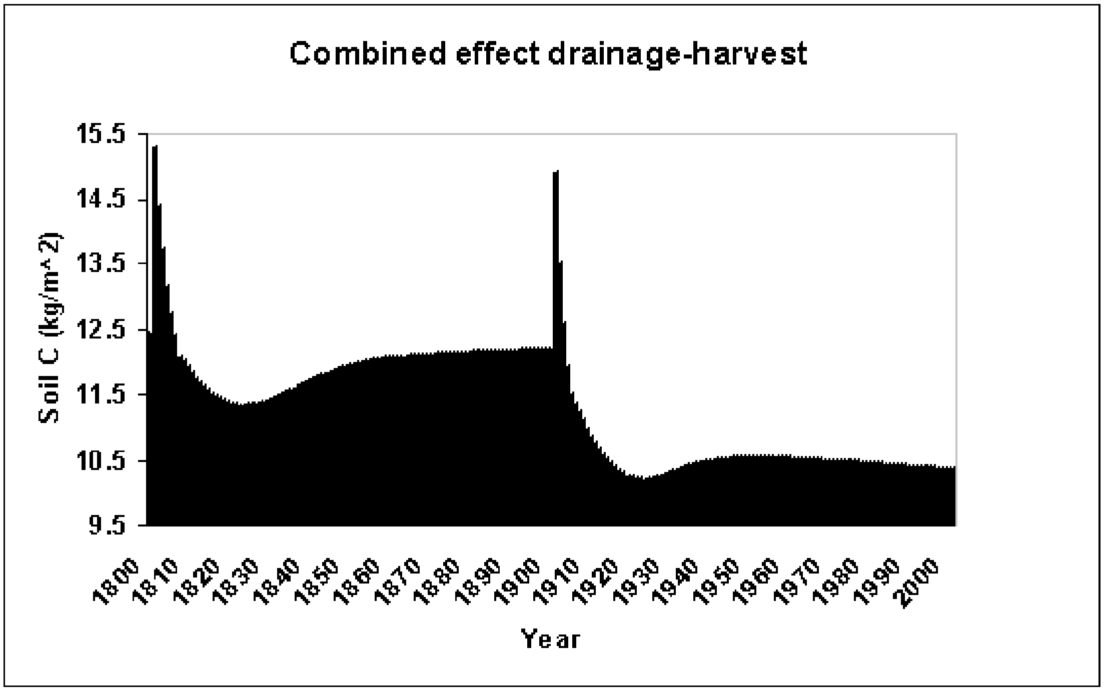


Fig. 4.8. Soil carbon amount in Norunda at the present time, after two clear-cuts and a drainage.

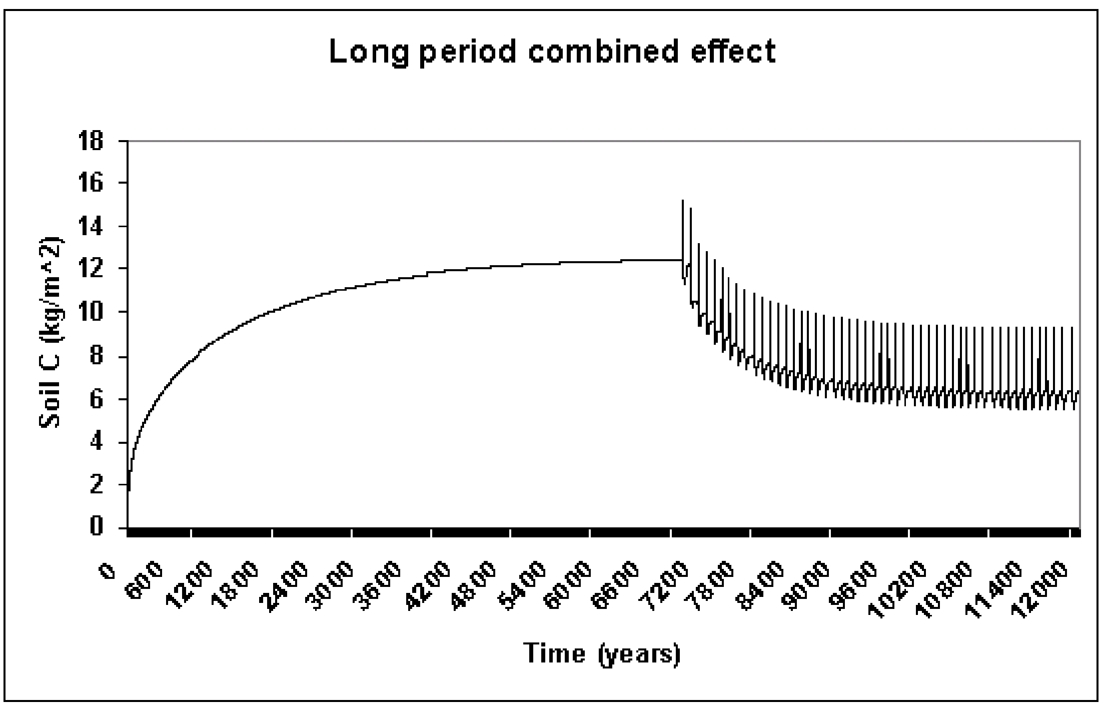


Fig. 4.9. Combined effect of the two disturbances in a long period prospect.

5. Discussion

5.1 DOC role in the net ecosystem exchange

Norunda is not an inflow area. The source area of the tower does not collect water from the catchment (fig. 3.1), which instead pours into Lake Velången. Therefore there is no extra input of carbon in form of DOC coming from neighbouring drainage basins.

However DOC analyses showed high carbon concentrations in Norunda lakes and watercourses, comparing to average Swedish values. Sobek *et al.* (2003), sampling lakes in three different regions, report values of 8, 10 and 12 mg L^{-1}, while Jonsson *et al.* (2002) measured a range 0.4-9.9 mg L^{-1} analysing 51 lakes in northern Sweden. DOC concentrations in three lakes sampled in Norunda catchment are comprised between 29 and 35 mg L^{-1}. Since Praire *et al.* (2002) found that lakes with a DOC concentration > 4-6 mg L^{-1} are net heterotrophic, and Jansson *et al.* (2000) discovered that transition from heterotrophic and autotrophic takes place in this concentration interval, there is evidence that Norunda lakes emit CO_2.

Data from the studied drainage basin have been compared with Algesten *et al.* (2003), who analysed almost 80000 Swedish lakes. Sampling data resulted to be significantly different between the population, which can be considered a representative sample for all Sweden.

This discrepancy is partially due to the limited sampling period: data have been collected only in two occasions, in the first half of May and at the end of June. Probably organic matter carried into water from the soil by snow melting could, in the first session, influence DOC concentration. The second data series experiences the big organic matter transport typical in spring (Laudon *et al.*, 2004). Then it is necessary a long period sampling to get precise results.

Moreover organic carbon concentration can be influenced by human disturbances: forest cutting provokes big soil movements, then terrain and vegetal parts end into water, enhancing its organic carbon level. This hypothesis is verified by DOC analysis in the streams. Some zones, in the nearby of I4 and O1 sites, had been recently cut down, and it is not a chance they have among the highest DOC concentration for the inflow and the outflow respectively.

Usually the highest values were recorded in streams, particularly the little ones, where the scarce water does not allow a good mixing up of the organic matter coming from the catchment. Actually the lowest DOC value were found in the outlets, where discharge is higher, while concentrations up to 50 mg L^{-1} have been measured at location I2, I4, I5, where flow is almost zero (tables 4.1, 4.2).

However, according to the literature and the data, the main accumulation basin of Norunda catchment, Lake Velången, is supposed to be net heterotrophic. Data collected show that Velången inlets have a DOC concentration much higher than the outlets (table 4.2). Clearly Lake Velången accumulates carbon, which is probably released to the atmosphere in form of CO_2. Maybe this discharge does not usually affect measurements from the tower, since the latter is located south of the lake and prevalent winds come from west-southwest (Lankreijer, personal communication, 2004). Anyway, as the whole catchment water is supersaturated in carbon dioxide, the loss of CO_2 has to be quantified.

The evaluation of carbon transport along the basin is subject to large uncertainties due to the few measurements. For DOC concentration, i.e., an average between the two values observed has been calculated, without taking into consideration eventual variations occurred during the period; total discharge in Norunda catchment basin has been evaluated supposing a linear decrease between the first and the second measurement.

Stream discharge is instead susceptible to many deviations caused by rainfall. Anyway a linear interpolation is at the moment the best approximation, as the distribution is supposed to move up and down the line, and there is not turbulent contribution due to snow melting. Big uncertainties are due to the measurement of discharges, owing to human errors and to the small accuracy of the instruments used. Another source of uncertainties is the measurement of catchment area (fig. 3.2), rather accurate thanks to ArcView but not of course absolutely precise, owing to errors in hand-drawing boundaries.

The fate of the exported DOC will determine its potential impact on the environment and on carbon cycle. After entering the stream network, DOC may be or transported either enter long-term storage as riverine/lacustrine/marine sediment, but the most part is respired or otherwise oxidized to CO_2 (Worral *et al.*, 2003). The specific fate of stream DOC depends on both chemical properties of the DOC and physical, hydrological and biogeochemical characteristics of the drainage network. DOC is, at least in part, oxidized by microbes (Jansson *et al.*, 2000; Stepanauskas *et al.*, 2000) and photodegradation (Bertilsson and Tranvik, 2000) leading to increased partial pressure of CO_2 in organic rich headwaters (Sobek *et al.*, 2003). Evaluation of this contribute on Norunda carbon budget has to be done throughout measurements during the whole year.

5.2 Drainage and harvest impact

Norunda, according to the simulation model, is a forest in unstable conditions, thus after being drained and harvested the soil persists in discharging carbon to the atmosphere.

Drainage is a technique utilized to lower the water table, in order to render nutrients and substances that plants need available in the terrain; in this way it is possible to enhance plant productivity. On the other hand lowering the water table lets decomposers have accessible oxygen for respiration, and decomposition process become faster. Consequently, as shown in fig. 4.3, drainage a big quantity of carbon is removed from the soil, with a consequent CO_2 release to the atmosphere.

According to the model, in the 100 years following drainage, Norunda discharges 1.85 kg C m^{-2}, that means almost 7 kg CO_2 per square meter. Drainage influences mostly the oldest soil compartments, and this makes soil in unstable conditions for thousands of years, with soil keeping on releasing CO_2 to the atmosphere.

A big assumption has been done for drainage simulation, which shows an immediate decrease in carbon content. In reality there is a delay in water table lowering, depending on soil porosity, which makes the effect slower.

The effect of harvesting, instead, is rather limited for the forest soil stability condition: after a rapid decrease in storage, and a following recovery, at the end of the cycle soil comes back to a steady condition. This happens because most of the harvesting related C reduction is due to decrease in the amount of young soil organic matter. However, beside this temporary effect, forest regular clear-cuts leads to a significant long-term decline of C soil storage (fig. 4.6). As clearly shown in fig. 4.7 after one cycle the soil recover a balance, which is however smaller than the previous; the decrease is a consequence of the removal of biomass from the site that would have otherwise become soil organic matter. Hence the loss of carbon will continue for thousands of years, until the new balance will be reached, if as predicted Norunda continue to be cut down once a century.

Combining the two disturbances a bigger loss of carbon is predictable in the long period, and it is actually what the model shows. Nevertheless it is remarkable that in the last years, following a very remote harvest, the two disturbs are in phase difference (fig. 4.8), so drainage effect is attenuated by carbon recuperation after the harvest. On the matter of fact clear-cuttings lead the soil C storage to be smaller than the potential storage in absence of disturb, so it to say that harvest mitigating effect on soil carbon loss is just temporary, because the drainage occurred in the recover period after the harvest itself.

According to the model, since the measurements started (1994), forest soil has been releasing an amount of carbon equal to 50 grams (table 5.1), that is to say, 183 g

CO_2 per square meter. This means that the combined effect drainage clear-cut counts for 10% of the total CO_2 release since 1994 (fig 1.1).

Year	Soil C (kg m^{-2})
1994	10.39
1995	10.38
1996	10.38
1997	10.37
1998	10.37
1999	10.37
2000	10.36
2001	10.36
2002	10.35
2003	10.35
2004	10.34

Table 5.1. Soil carbon storage in the last 10 years

The soil contribution to carbon loss in Norunda has to be evaluated not forgetting of assumptions and approximations done before compiling the model, therefore uncertainties are supposed to be large.

First of all the model has been run with a temperature datum which is the mean annual for Norunda during the period 1961-1990. Since the first compartment is temperature dependent, and applications on the model have been done after soil reached equilibrium, that is to say 7000 years, it would have been better to take into consideration changes occurred in Swedish climate in this period.

Anyway (data not shown) a sensitivity test changing mean air temperature has been done, and results are not significantly different than the ones obtained using 5.5°C as reference value. Then, according to the simulation model used, increase in temperature predicted for the next years and centuries should not influence soil retaining carbon capacity.

Moreover changes in soil humidity could hardly influence decomposition rate, but the choice was to keep this parameter constant; concerning to that, a big simplification was to assume that drainage (the process that mostly changes soil humidity conditions) influence all the compartments at the same time and in the same way. Actually the oldest compartments are also supposed to be the deepest ones, so their water content does not change after draining the soil as much as the one in the first or the second compartment; even though it was not possible to estimate this characteristic, so they have not been taken into consideration.

As regards the clear-cut, a big assumption has been done choosing the amount of organic carbon placed at soil's disposal after the clear-cut. It is probably correct consider stems contribution as zero, since all the big trunks are removed to be used for wood production; roots contribution has been totally taken into account, because roots are not supposed to harvested after the cut. Concerning to branches and needles, instead, the choice was to use a rough estimate obtained by information from foresters. Their share has been evaluated to be 25% of the total mass.

5.3 Other hypotheses

This study considers only two of the numerous hypotheses which could explain Norunda behaviour as a source of CO_2. Other ideas have been identified in order to be investigated in future studies.

First of all Norunda is an old grown forest, where plants need more water to feed all the tissues, and rainfall interception is high (about 26% of the total precipitations, personal communication Lankreijer, 2004) because of canopy big dimension. This means that less water is present in the soil and then water table subsides with all the implications on soil respiration and decomposition.

Moreover, the forest fertilization carried out in the sixties and the seventies has not been simulated, even if its contribution could be important on soil carbon content. Fertilization promotes greater decomposition, then higher CO_2 emission to the atmosphere, and larger productivity at the same time, leading to a bigger carbon accumulation by the soil.

Finally, as shown in figure 1.1, flux of CO_2 is negative in 1996 and 2002, and anyway remarkable differences are evident from year to year. This is due to photosynthesis and soil respiration response to interannual climatic variation: temperature, precipitation and irradiation, directly influencing litterfall and PAR, but also snow cover, which does not permit soil freezing, are central factors of carbon flux variability. Since data series is a short-term one, further meteorological information should be collected, to assess their role on Norunda behaviour.

6. Conclusions

The study conducted offers interesting starting-points to assess the role of dissolved organic carbon and the importance of forest management on forests total carbon balance.

The first hypothesis put forward cannot be considered valid, since the source area of the catchment is not an inflow: no extra input of carbon in form of DOC reaches the tower. However lakes and streams analysed were supersaturated with CO_2 compared to the atmosphere, according to the relationship between DOC and lake surface pCO_2. This implies a net flux of carbon dioxide to the atmosphere, which should be quantified by further analyses.

Approximate results obtained in spring show that contribution of DOC transport along the drainage basin is not probably decisive to explain Norunda eterotrophic behaviour. 6 mg of carbon transported every day seem to be a very small increase compared to the tower values, especially in consideration that DOC samples have been taken in spring, when maximum values are usually measured (Laudon, 2004).

Forest exploitation was found to provoke a net release of carbon into the atmosphere, which is in many cases compensated by photosynthesis, but becoming decisive in making a forest source of carbon if combined with other factors. As seen in figures forest cut leads the soil losing carbon for thousands of years before reaching a new equilibrium; drainage makes the soil lose carbon for long time as well. Anyway, even if disturbances are relevant for the ecosystem balance, their impact has found to be not sufficient to explain the entire phenomenon. According to the model, loss of carbon counts for less than 10% of the total carbon release measured in Norunda (table 5.1 and figure 1.1).

Governments have to take into consideration consequences of forest management, and the role of soil and water, so that the increase of forested areas will be a valid compensation to the global CO_2 growth. Waiting for new and convenient technologies to produce emission zero power, afforestation and reforestation can represent the first step to the application of Kyoto protocol, recently come into force (February 2005).

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