1 Introduction

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1.1 Greenhouse Gases and Reservoirs

The major greenhouse gases (GHGs) are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC 2001). These gases are emitted from both natural aquatic (lakes, rivers, estuaries, wetlands) and terrestrial ecosystems (forest, soils) as well as from anthropogenic sources (e.g. Cole et al. 1994; Hope et al. 1994; Borges and Frankignoulle 2002; Rosa et al. 2002; Therrien 2003; Tremblay et al. 2003; Blais et al. 2003).

Retention of heat by these gases, through absorption of the infrared light reflected or produced by the Earth, is called the "greenhouse effect". This is a natural phenomenon that keeps worldwide average temperatures around 18^{O}C, which would otherwise be close to -15^{O}C. This mechanism allows for life on Earth. In recent times, GHG concentrations in the atmosphere have increased significantly due to anthropogenic emissions from fossil fuel burning, deforestation, the creation of artificial wetlands, cattle, etc. It is clear that only part of this excess GHGs has been taken up by natural sinks, resulting in increased concentrations and, likely, and enhanced greenhouse effect.

According to both the European Environment Agency and the United States Environmental Protection Agency, CO_2 emissions account for the largest share of GHGs equivalent of 80–85% of the emissions. Fossil fuel combustion for transportation and electricity generation are the main sources of CO_2 contributing to more than 50% of the emissions (Fig. 1.1). Generation of electricity with thermal power plants represents 66% of the world's electric generation capacity (Fig. 1.2, EIA). Hydroelectricity and nuclear power represent respectively only 22% and 11.5% of the world electric generation capacity. Although hydropower represents about 22% of the world generation capacity, it represents a much smaller fraction of the GHG emissions worldwide, since it emits 35 to 70 times less GHG per TWh than thermal power plants (IAEA 1996). Nevertheless, for the last few years GHG emissions from freshwater reservoirs and their contribution to the increase of GHG in the atmosphere are actually at the heart of a worldwide debate concerning methods of energy generation (Rosa and Scheaffer 1994, 1995; Fearnside 1996; Gagnon and van de Vate 1997; St. Louis et al. 2000; Duchemin et al. 2002; Tremblay et al. 2003).

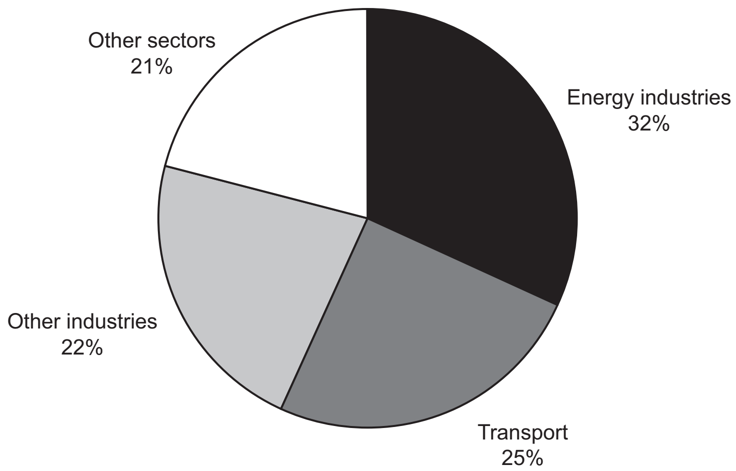

Fig. 1.1. Carbon dioxide emissions per sector of European Union-15, 1999 (Modified from: European Environment Agency, Annual European Community Greenhouse Gas Inventory 1990-1999. Technical Report No. 60, 11 April 2001)

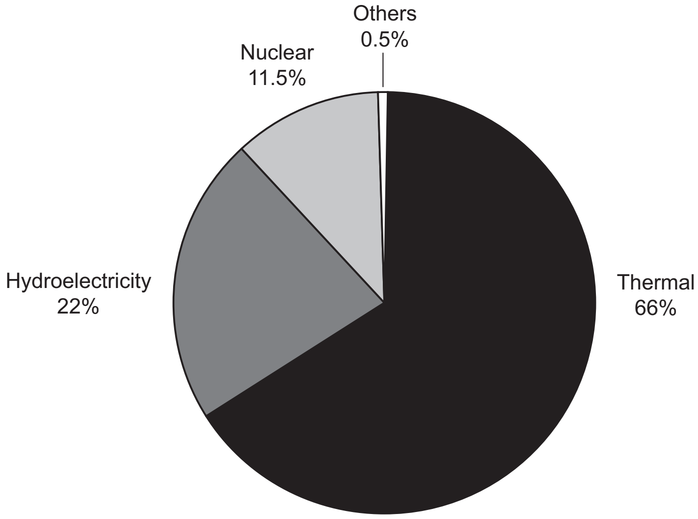

Fig. 1.2. Technology used to generate electricity in the world (modified from EIA, site www.eia.doe.gov)

It must be pointed out, however, that 71% of the worldwide single-use dams are used for irrigation or water related purposes and only 20% of the reported dams are built to generate electricity (Fig. 1.3, ICOLD 1998). Moreover, multi-purpose dams account for nearly 30% of the total number of large dams reported. Worldwide, most of the single-purpose dams (approx. 48%) are for irrigation and therefore contribute greatly to food production. Multi-purpose dams are increasingly important for regional economic development. Irrigation is the first use of multi-purpose dams followed by flood control, hydropower, domestic and industrial water supply, recreation, fish farming and navigation.

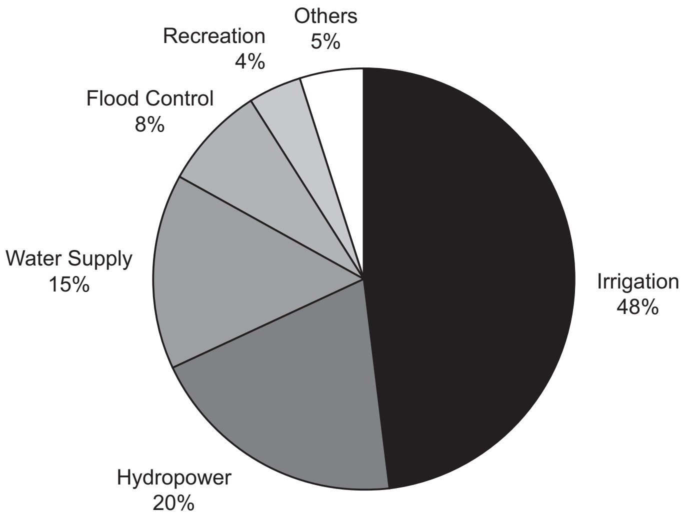

Fig. 1.3. Distribution of single uses of reservoirs in the world (taken from: ICOLD's World register 1998)

This monograph represents the first comprehensive synthesis on GHG fluxes from natural and modified aquatic ecosystems. Other issues related to multiple use of land, biophysical characterization, social and climatic charge impacts of reservoirs are beyond the scope of this monograph. This monograph regroups research results from many countries around the world, representing years of collaboration and activities between research institutes, universities and power facilities. This monograph covers the processes of GHG production as well as carbon dynamics in aquatic and terrestrial ecosystems. It must be pointed out, however, that the information from both terrestrial or aquatic ecosystems comes from three major regions of the world: Europe, Canada-USA and Brazil (Fig. 1.4 and 1.5).

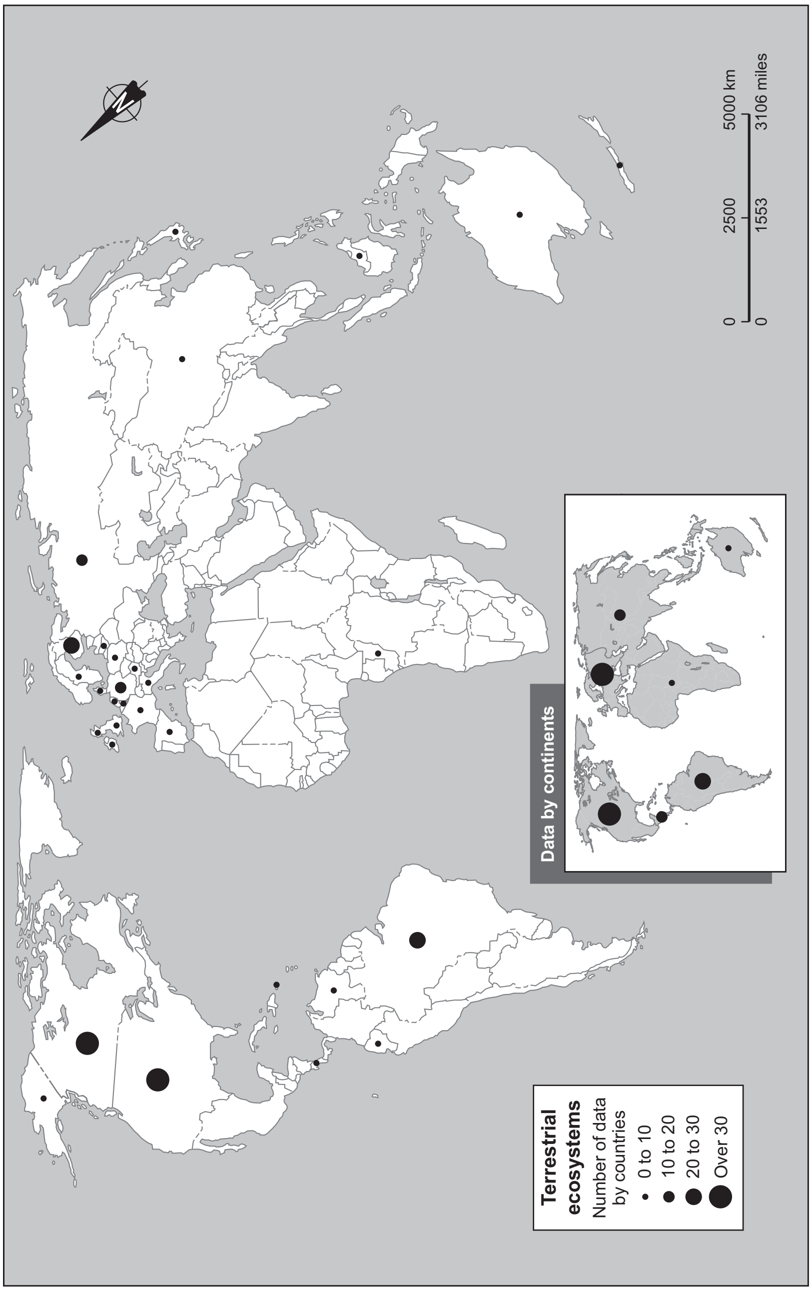

Fig. 1.4. Qualitative world distribution of studies data on greenhouse gas flux or carbon mass balances and processes in terrestrial environments

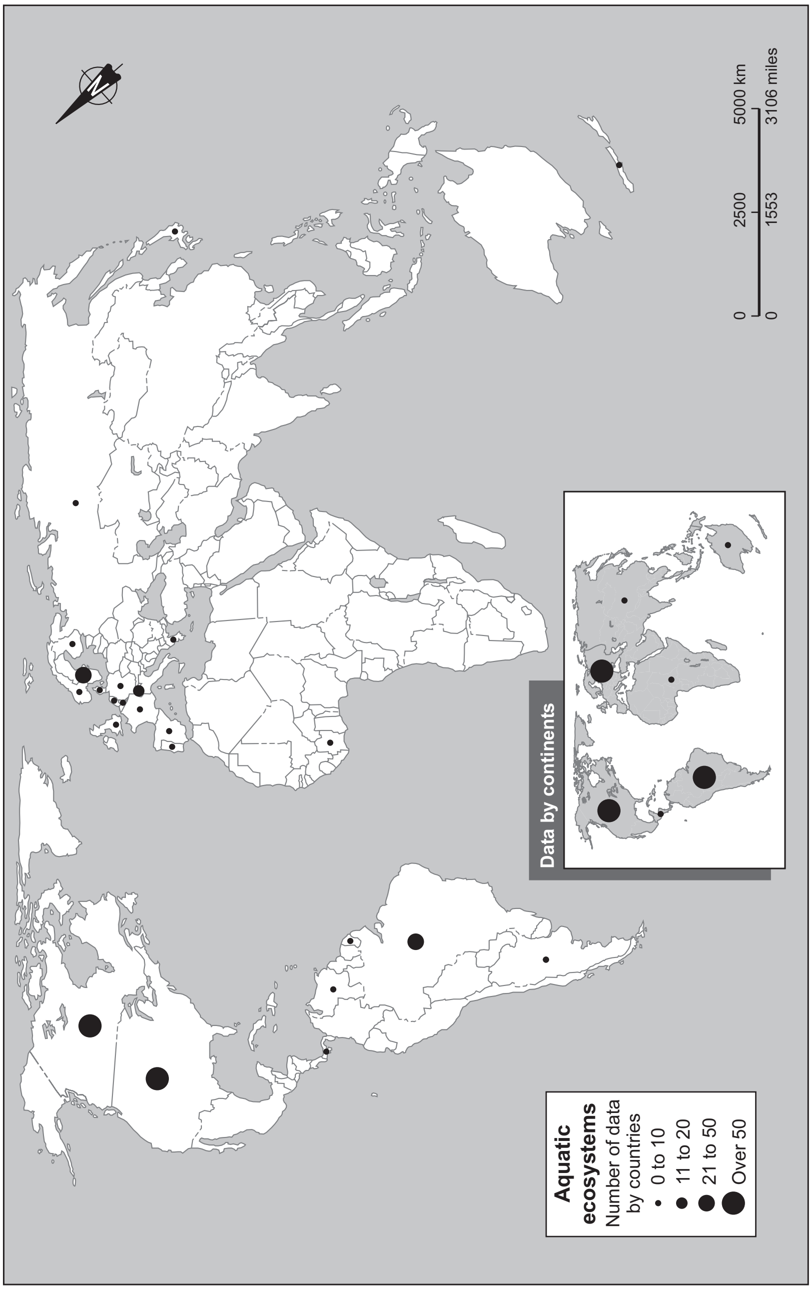

Fig. 1.5. Qualitative world distribution of studies data on greenhouse gas flux measurements and processes in aquatic environments

These regions contain only 28% of the world reported dams (Table 1.1). There is very little information, however, from Asia, which contains 68% of the reported dams.

Table 1.1. Top 20 countries by number of large dams (modified from WCD 2000)

Country	ICOLD, World register of dams 1998	Other sources	Percentage of total
Asia			
China	1855	22000	
India	4011	4291	
Japan	1077	2675	
South Korea	765	765	
Australia	486	486	
Total Asia	8194	30217	63
Europe			
Spain	1187	1196	
Turkey	625	625	
France	569	569	
Italy	524	524	
United Kingdom	517	517	
Norway	335	335	
Germany	311	311	
Albania	306	306	
Romania	246	246	
Total Europe	4620	4629	10
America			
United States	6375	6375	
Canada	793	793	
Brazil	594	594	
Mexico	537	537	
Total America	8299	8299	18
Africa and others			
South Africa	539	539	
Zimbabwe	213	213	
Others	3 558	3558	
Total Africa and others	4310	4310	9
Total	25423	47655	100

1.2 Reservoir Dynamics

The flooding of forest, soils, rivers and lakes generated by the creation of reservoir modifies, for a period of time the biochemical parameters, which influence the GHG dynamics of that new environment. The ecology of reservoirs has been relatively well documented in the literature. However, most studies have focused on short-time scale observation getting a snapshot of reservoir mechanisms. To better understand GHG dynamics in reservoirs, it is better to use a long term approach, since these environments are dynamic in terms of the carbon cycle mostly in the first few years after impoundment. For this purpose, we will use data generated by the La Grande hydroelectric complex follow-up environment program, the world's largest and longest environmental follow up program to our knowledge.

The biophysical characteristics of La Grande hydroelectric complex (Fig. 1.6) have been studied for more than 20 years, as part of Hydro-Québec's environmental follow-up program. This follow-up program tracked changes occurring in water quality, plankton, benthos and fish in different modified environments of the La Grande hydroelectric complex. As demonstrated in the monograph, these long term follow-up studies have been extremely useful for developing our understanding of the carbon dynamics in boreal reservoirs.

1.2.1 Water Quality

The evolution of major water quality parameters measured in the photic zone of three reservoirs of the La Grande complex, during the ice-free period, is shown in Fig. 1.7. The changes observed in this zone were generally limited and remained within the range of values favourable to strong biological productivity. The slight variations observed from one reservoir to another may be explained by their specific characteristics: flooded land area, density and type of flooded vegetation, length of filling period, configuration, average depth and water residence time. Changes in water quality are explained mainly by the following three phenomena:

- Submersion of vegetation and forest soils, which causes mineral salts and soil nutrients to dissolve in water—a process that is accelerated by wave action on forest soils. This phenomenon, which occurs at the start of impoundment, partly explains the rapid increase in total phosphorus concentration and decrease in pH.

Fig. 1.6. Location of La Grande River hydroelectric complex

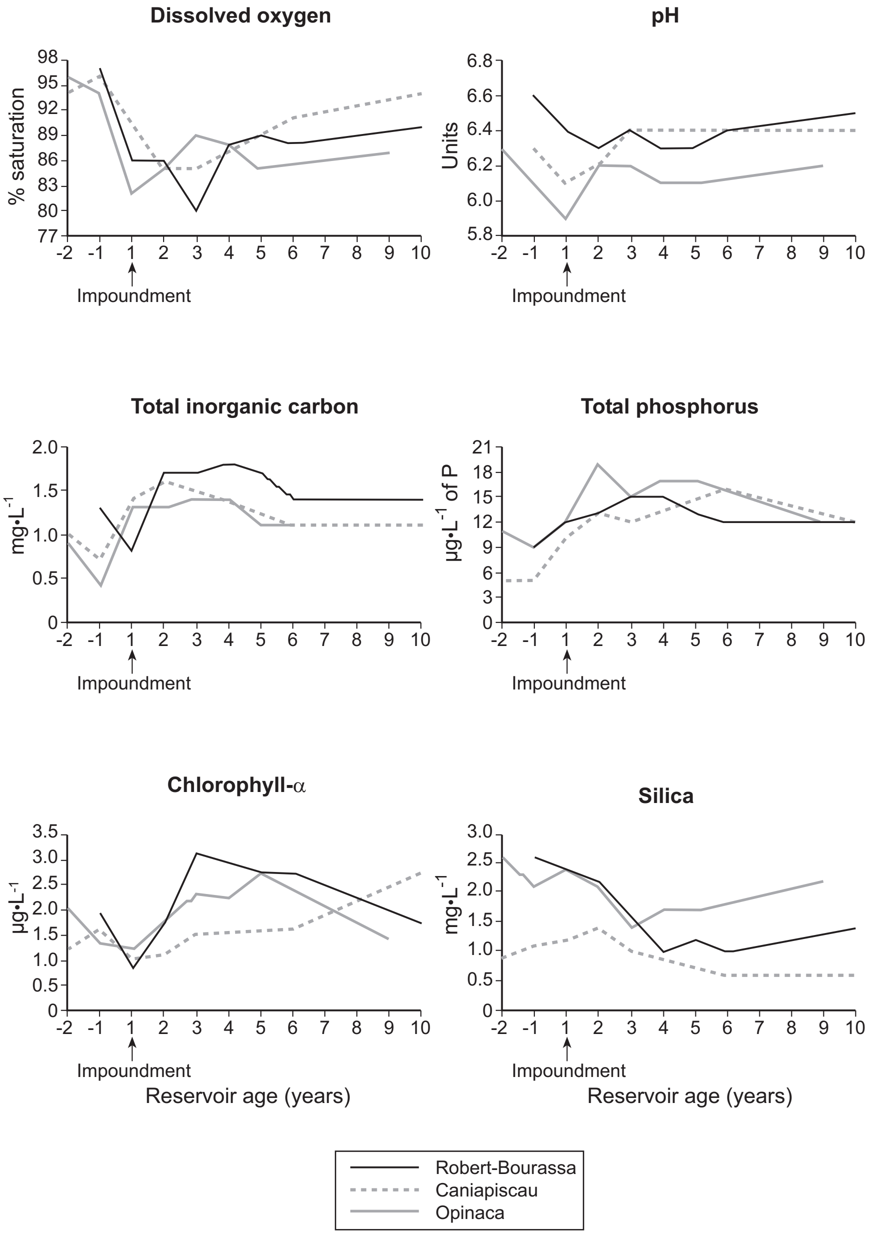

Fig. 1.7. Changes in main parameters linked with decomposition of submerged organic matter in the photic zone (ice-free period, La Grande Complex reservoirs)

- Mixing of waters of various qualities coming from rivers and lakes in the flooded zone.
- Decomposition of vegetation and humus in flooded soils by a series of micro-organisms, such as bacteria. In decomposing this organic matter, the micro-organisms consume dissolved oxygen and release CO_2, resulting in a decrease in pH. This phenomenon is accompanied by a release of minerals and nutrients such as phosphorus.

Greater variations in oxygen, major ions and nutrients were measured in bottom layers of the reservoirs where drops in redox potential permitted better exchanges between flooded substrates and overlying waters. However, these restricted areas had very little effect on the overall water quality of these large and deep reservoirs. Follow-up of reservoirs in the La Grande hydroelectric complex clearly indicates that maximum water quality changes are reached within 2 or 3 years after impoundment and reservoirs regain physical and chemical characteristics similar to those found in natural waters within 10 to 15 years (Schetagne 1994).

The short duration of changes is largely due to the fact that only a small portion of flooded organic matter (forest soils, tree branches, trunks and vegetation) is readily and rapidly decomposable in the cold water of boreal reservoirs. Trees branches, trunks and roots, as well as the underlying soil humus, have been found still intact in 60-year-old reservoirs (Van Coillie et al. 1983).

The duration of water quality parameter changes could be longer in some tropical reservoirs. This is likely due to warmer water temperatures that favour the decomposition of flooded organic matter or fresh material coming from run-off under anoxic conditions. These conditions favour methane production. However, one must keep in mind that not all tropical reservoirs have anoxic conditions and therefore, are emitting methane (Tremblay and Lambert 2003). There are very few data from tropical regions (e.g. Galy-Lacaux 1996) and to our knowledge only Petit Saut reservoir in tropical French Guiana (flooded in early 1994) has a follow-up program (Galy-Lacaux et al. 1997; Gosse et al. 1998; Galy-Lacaux et al. 1999).

1.2.2 Plankton

Phytoplankton biomass (through measure of chlorophyll-*a*) monitored in La Grande Complex increased for a number of years after impoundment inducing a depletion of silica as diatoms which are an important phytoplankton group in this region (Fig. 1.7 and 1.8). Increased water residence time and nutrient enrichment contributed to temporary increases in zooplankton and benthos biomass in most of the modified bodies of water. Both phytoplankton and zooplankton reached a maximum biomass within 3 to 5 years after impoundment, then declined and stabilized after about 10 to 15 years to levels comparable to natural values (Schetagne 1994; Chartrand et al. 1994).

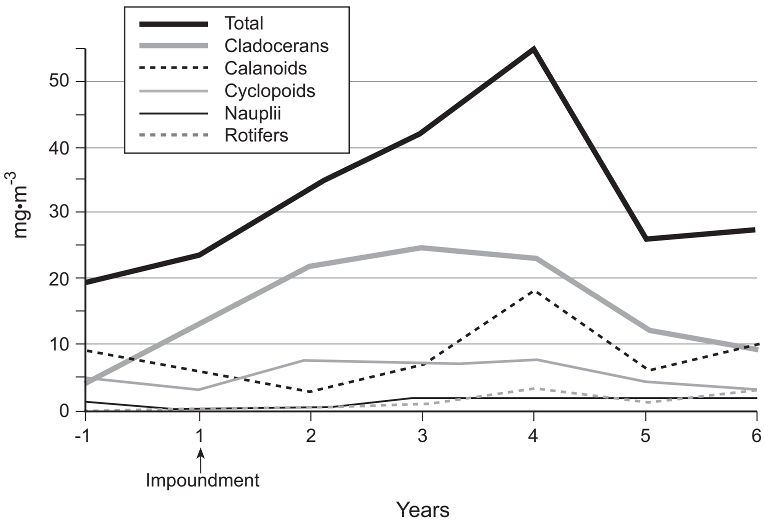

Fig. 1.8. Changes in zooplanktonic biomass: Robert-Bourassa reservoir (in La Grande complex)

1.2.3 Benthos

Benthic organisms of La Grande Complex had to adapt to the major physical transformations related to reservoir creation. After a slight decline in their biodiversity due to the increased scarcity of less mobile species and of species better adapted to fast-running water, the new aquatic environments were rapidly occupied by lake dwelling species. The presence of extensive substrate, supplied by submerged plants, considerably increased the surface available for species in search of food.

In addition, examinations of fish stomach contents and monitoring of fish populations revealed that the diversity and quantity of benthic organisms were sufficient to bring about substantial increases in growth rates and condition factors (plumpness index) of fish species that feed on the benthos, such as lake whitefish, and their predators, such as pike.

1.2.4 Fish

Following the first year after impoundment, we saw a decrease in fish yields due to the dispersal of populations in a larger volume of water. This decline was quickly followed, in subsequent years, by an increase in yields resulting from overall water enrichment and fish growth. After 15 years or so, yields returned to levels comparable to those observed in undisturbed natural environments surrounding La Grande Complex (Fig. 1.9).

Northern pike and lake whitefish are the species that benefited the most from the creation of large reservoirs. Reproduction rates for these species suggest that much of their increase in yield was attributable to better recruitement, associated with a better survival rate in the first years after impoundment (Deslandes et al. 1995). The growth rate of the principal species in Robert-Bourassa reservoir increased markedly after impoundment. Like growth, the condition factor of almost all the species increased after impoundment. After several years, the fish's condition factor gradually returns to those of natural systems.

The data provided by the environmental follow-up program of the La Grande hydroelectric complex have demonstrated that all the parameters measured (water quality, plankton, benthos, fish, etc.) in boreal reservoirs return to values similar to those found in natural lakes within 10 to 20 years depending on the parameter measured. Therefore, after biological upsurge following impoundment, all the parameters measured indicate that a reservoir behaves like a lake. Since greenhouse gas production in aquatic ecosystems is related to whole biological productivity and water quality, fluxes of GHG from boreal reservoirs should follow the same patterns as these over time. This might not be the case in tropical regions due to the possible presence of anoxic zones.

1.3 Contents and Rationales

In order to fulfill the objectives of determining sources and processes of carbon leading to greenhouse gases emissions from both natural and modified aquatic ecosystems, methodological improvements were required, especially for the determination of spatial variability of fluxes from large water bodies. Large water bodies are quite often remote from laboratory facilities, hence real time *in situ* techniques had to be developed to reduce costs and facilitate logistics. These developments, as well as other methodological aspects, are presented in Chap. 2 and 3.

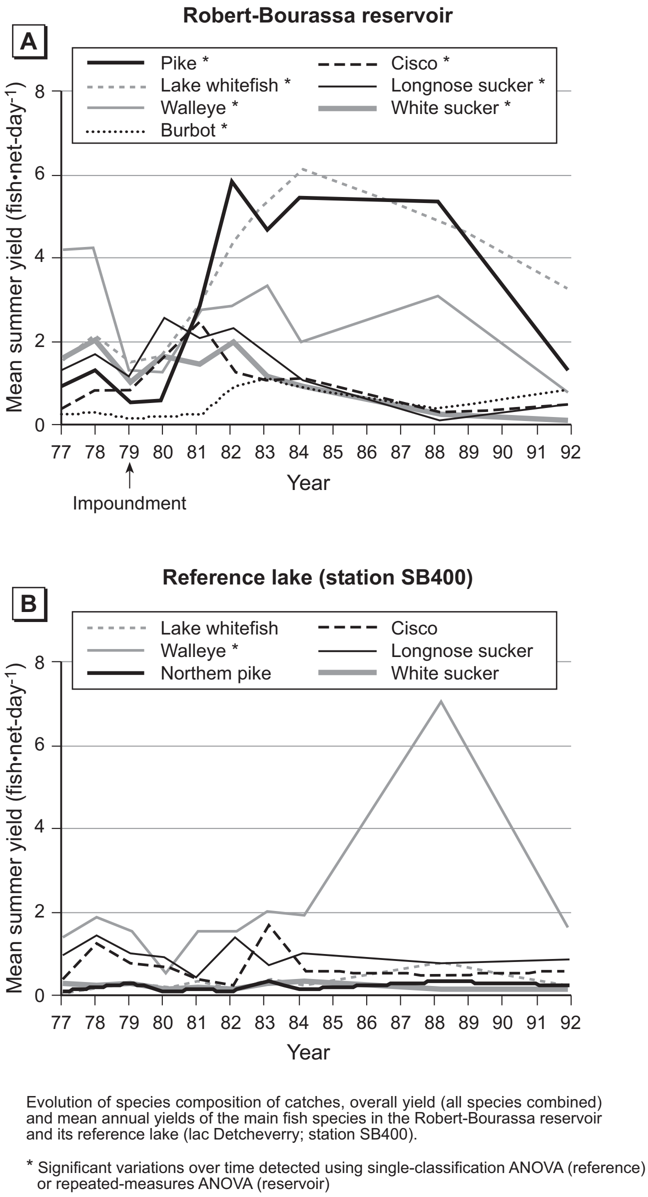

Figure 1.9

Fig. 1.9. Evolution of fish biomass and captures per unit of effort in Robert-Bourassa reservoir (in La Grande Complex) and a natural lake

To compare reservoirs with other methods of energy generation (based on a life cycle approach), it became important to consider different natural reference ecosystems to reveal the amplitude of GHG fluxes from these environments. A priority was given to document natural ecosystems in terms of GHG or carbon fluxes from terrestrial sources (Chap. 4 and 6), from drainage basins (Chap. 16), from lake sediments (Chap. 5), from lake surfaces (Chap. 8 and 9) and from estuaries (Chap. 7).

In reservoirs, emphasis was put on processes related to the role of freshly flooded soils which favour GHG emissions in young reservoirs (< 10 years). Using reservoirs of different ages, we documented the approximate duration of modified fluxes in reservoirs (Chap. 8, 9, 10, 11 and 12). The role of primary producers and food web structure (Chap. 17), planktonic CO_2 respiration/consumption ratios (Chap. 20), and bacterial activity (Chap. 18 and 19) in GHG fluxes from water bodies were investigated. The origin of carbon related to GHG emissions was also investigated using stable isotope tracers (Chap. 14 and 15) as well as its transformation in the water column (Chap. 21 and 22).

Since the potential for hydroelectric development is very important, particularly in Asia and South America, and the cost of impact assessment are increasing over time, there was a need to develop models to predict CO_2 and CH_4 fluxes in reservoirs (Chap. 12 and 25), and to simulate different situations and identify missing information (Chap. 23 and 24). The development of these models is based mainly on data collected in La Grande Complex (boreal ecosystem, 25 years of data) and Petit Saut (tropical ecosystem, 7 years of data) follow-up programs as well as from ELARP-FLUDEX experimental reservoirs and from in vitro experiments (Chap. 8, 10, 12, 15, 22, 24, 25).

Findings of all these studies are presented in 24 separate articles, each forming a distinct chapter. In addition, a final chapter presents a general synthesis and future prospects for research for GHG emissions from reservoirs.

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