Carbon Pool Dynamics in the Lower Fraser Basin from 1827 to 1990

C. A. BOYLE
Civil and Resource Engineering
University of Auckland
Private Bag 92019
Auckland, New Zealand

L. LAVKULICH*
Resource Management and Environmental Studies
436E 2206 East Mall
University of British Columbia
Vancouver, British Columbia V6T 1Z3, Canada

ABSTRACT / To understand the total impact of humans on the carbon cycle, the modeling and quantifying of the transfer of carbon from terrestrial pools to the atmosphere is becoming more critical. Using previously published data, this research sought to assess the change in carbon pools caused by humans in the Lower Fraser Basin (LFB) in British Columbia, Canada, since 1827 and define the long-term, regional contribution of carbon to the atmosphere. The results indicate that there has been a transfer of 270 Mt of carbon from biomass pools in the LFB to other pools, primarily the atmosphere. The major losses of biomass carbon have been from logged forests (42%), wetlands (14%), and soils (43%). Approximately 48% of the forest biomass, almost 20% of the carbon of the LFB, lies within old-growth forest, which covers only 19% of the study area. Landfills are now becoming a major sink of carbon, containing 5% of the biomass carbon in the LFB, while biomass carbon in buildings, urban vegetation, mammals, and agriculture is negligible. Approximately 26% of logged forest biomass would still be in a terrestrial biomass pool, leaving 238 Mt of carbon that has been released to the atmosphere. On an area basis, this is 29 times the average global emissions of carbon, providing an indication of the past contributions of developed countries such as Canada to global warming and possible contributions from further clearing of rainforest in both tropical and temperate regions.

The carbon budget examines the movement of carbon among reservoirs or pools in the atmosphere, oceans, vegetation, animals, soils, and in large deposits such as peat, oil, or coal. Anthropogenic activities have made this budget much more complex and changed the carbon balance significantly through the burning of fossil fuels, the destruction of large areas of forest, and agricultural effects upon soil carbon. Since the middle of the 19th century, the concentration of CO_2 in the atmosphere has increased by 26% to 356 ppm (IPCC 1994). The initiation of this increase appears to have coincided with the initiation of industrialization causing increased burning of fuels and widespread changes in land use. This increase in CO_2 has raised alarms within the scientific community since global temperature increases would have severe implications on many aspects of our current living patterns. Recently, the International Panel on Climate Change (IPCC) has determined that the observed climate change is human induced (IPCC 1994).

Consequently, factors involved in the world's carbon budget and in changes in that budget are being researched to provide a clearer view of the current balance. Within this global endeavor, regional impacts are also being examined since these discrete changes cumulatively result in widespread changes (Turner and others 1993).

Presently carbon is stored in six major pools throughout the world, but there have been significant changes in the percent of carbon in those pools, most notably in the atmosphere and in biota (Table 1). Changes in vegetative cover over this period have contributed heavily to both the increase in atmospheric and the decrease in biotic carbon, since vegetation acts to remove carbon dioxide from the atmosphere. The cutting of the world's temperate and boreal forests primarily started in the 1860s, with wood supplying the lumber, pulp and paper, and fuel-wood industries and the cleared land being used for agricultural purposes (Houghton and Skole 1990).

In examining the ecosystem of the Lower Fraser Basin, part of a three-year interdisciplinary research project at the University of British Columbia, changes in biomass and carbon pools are important as they serve to indicate the impact of human change on the Basin and provide us with some concept of the potential effects of future changes. Land use in the Lower Fraser Basin

KEY WORDS: Carbon pools; Global warming; Carbon release to atmosphere; Greenhouse effect

---

*Author to whom correspondence should be addressed.

Environmental Management Vol. 21, No. 3, pp. 443–455

Table 1. Estimated size of global carbon pools and changes since 1800[a]

Reservoir	Carbon pg	Carbon %	Change since 1800 (%)
Ocean			
Intermediate and deep	35,000	72	<1
Surface	900	2	<1
Fossil fuel	10,000	21	−2
Atmosphere	755	2	27
Soil	1,200	2	−2
Biota	550	1	−21

[a] Adapted from Moore and Braswell (1994) and Houghton and Skole (1990).

(LFB) was described in Boyle and others (1995) for the period prior to 1827 when Europeans first arrived, for 1930, and for 1990 (Table 2). This paper also described the changes in net primary productivity and soil organic carbon. However, changes in biomass and carbon pools in the LFB were not discussed.

The objectives of this paper are to examine the terrestrial carbon pools in the LFB for three periods: pre-1827, 1930, and 1990, including carbon storage in forests, agricultural land, urban land and in mammal biomass, and to assess the changes that have occurred in those pools. These changes will then be related to the regional contribution of stored carbon to carbon in the atmosphere. On a global basis, this will serve to further the understanding of the past contributions of developed countries such as Canada to global warming and possible contributions from further clearing of rainforest in both tropical and temperate regions.

The Study Area

The study area has been defined and described by Boyle and others (1995a) and covers a region of approximately 828,000 ha along the LFB, from Vancouver to Hope, British Columbia (Figure 1). The focus of the interdisciplinary research project was on the impact of human activity on the environment and changes in ecosystem processes in the LFB. The boundary of the area was selected to encompass the basin and the major towns and communities that comprise the Lower Mainland, excluding lands north of Lions Bay, Stave Lake, and Pitt Lake, since there are few communities in these mountainous regions.

Terrestrial Carbon Pools in the Lower Fraser Basin

Forests

Forests in the Lower Fraser Basin are primarily comprised of Douglas fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterphylla*), and western red cedar would have been a significant component prior to European settlement (Boyle and others 1995a). Some measures of biomass have been made for Douglas fir forests in British Columbia on Vancouver Island (Prescott and Weetman 1994) and in Washington and Oregon (Franklin and Waring 1979), but no biomass measures have been done in the study area. Moreover, the biomass of forest ecosystems changes as the trees age (Long 1982). Once the canopy closes (approximately 40 years), the biomass in the understory declines and the foliar and root biomass appear to reach an equilibrium. Tree bole continues to increase until 150 years, when it begins to level off (Long 1982). Once mortality begins to increase in the stand, the bole biomass may decline.

Wetlands

Biomass in wetlands includes the living biomass as well as peat buildups in bogs and fens. A number of bogs and fens existed in the study area in 1827 (North and Teversham 1984) but were mined, diked, and converted to agricultural production by the beginning of this century. Boyle and others (1996) identify only the total area of wetlands prior to European settlement but, using information from North and others (1979), North and Teversham (1984), Kelley and Spilsbury (1939) and from wetlands remaining in 1990 (Ward and others 1992), the number of bogs and fens and their areas were estimated. Living biomass of bogs has been measured at an average of 40 t/ha, with a range of 24–68 t/ha in southern Manitoba (Reader and Steward 1972). The higher biomass occurred in bogs with either conifers or *Salix* spp. on site but, considering the longer growing season and warmer climate of the LFB, an average of 40 t/ha was used for bogs. The peat buildup beneath the bogs contains a significant mass of biomass that also has to be considered, especially for before 1827 and 1930, before much of the peat was mined.

Agriculture

Prior to 1827, there was some burning of land near the coast to improve vegetation for berry growth, but there appears to have been no other agricultural activity (North and others 1979). However, by 1930, a significant agricultural land base had been established (Boyle and others 1996). The agricultural area defined by Boyle and others (1996) for the LFB included pasture, cropland, rural residences and other buildings, and small woodlots. Of the area not under cultivation, approximately one third has been used for buildings, roads, or other impervious construction where plants would not be able to grow (McCallum 1995). Other land not under cultivation would support a mixture of

Table 2. Land cover for pre-1827, in 1930, and in 1990

	Pre-1827		1930		1990	
Land cover	Area (ha)	Percent	Area (ha)	Percent	Area (ha)	Percent
Coniferous	590,800	71	412,000	50	445,800	54
Deciduous/mixed	8,200	1	71,800	8	4,000	<1
Fen	56,000	7	5,500	1	2,400	<1
Swamp/bog/marsh	27,100	3	10,800	1	9,700	1
Crops	0	0	81,100	9	132,100	16
Urban	0	0	25,000	3	86,300	10
Cleared	0	0	79,200	10	8,600	1
Rock/alpine	37,800	5	37,800	5	37,800	5
Lake/river	50,800	6	47,500	6	46,600	6
Ocean	57,500	7	57,500	7	54,900	7

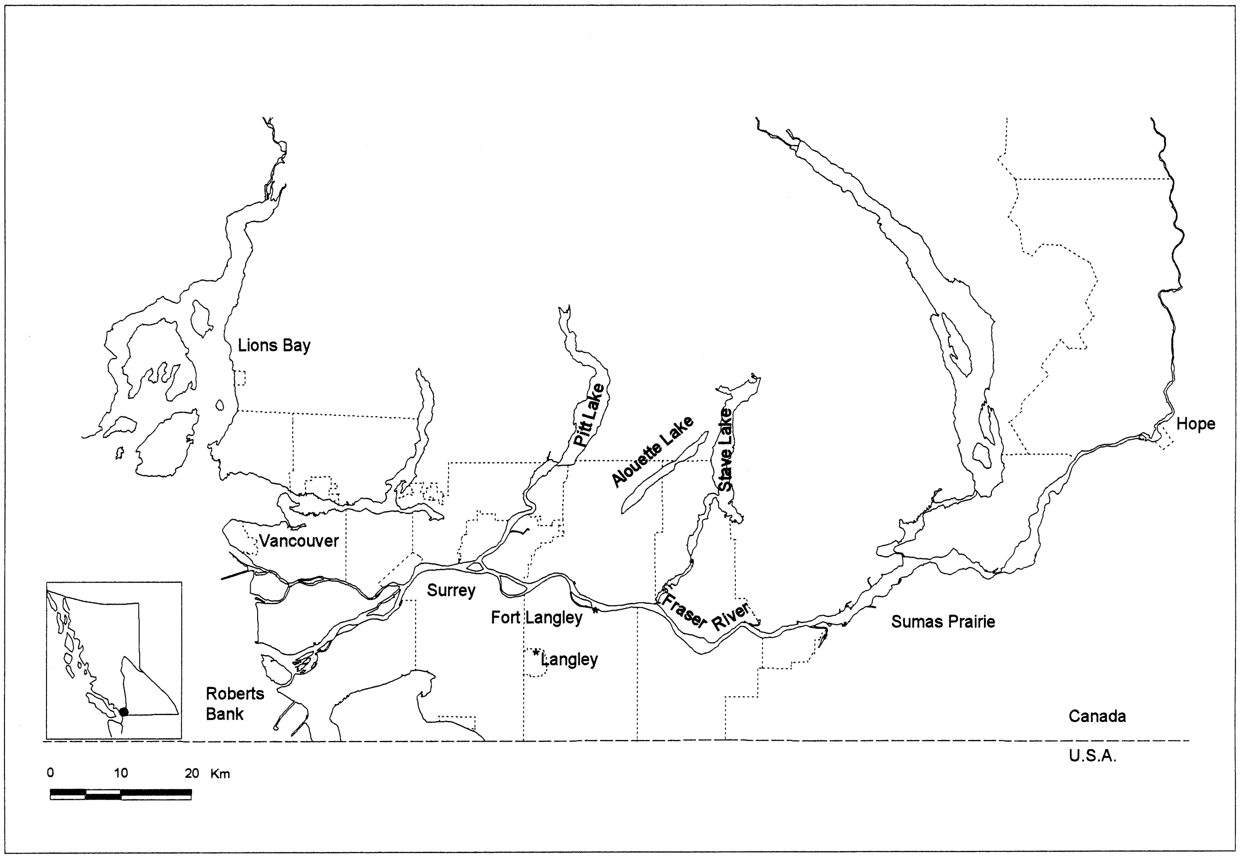

Figure 1. Map of the study area.

lawns, gardens, woodlots, bush, and riparian habitat. Crops grown in the study area include grains, vegetable crops, berries (including cranberries), and fruit trees and include both perennial and annual vegetation as well as the annually harvested crop.

Biomass in Urban Vegetation and Buildings

A significant portion of biomass in an urban or suburban area lies in the trees, shrubs, and lawns lining streets and in urban parks and playgrounds. The amount of biomass in buildings includes wood (lumber, plywood, particle board, fibreboard, etc.) as well as plastic (baseboard, vinyl flooring, piping), carpet, furniture, and books. In the early part of this century, most rural buildings would have been constructed of wood, while both wood and stone were used in urban centers. Residences are still constructed of wood, concrete, bricks, and stucco while apartment buildings, especially high ones, contain less wood to reduce potential fire hazard. Residential and office buildings from the early part of the century still remain, although most have been replaced with more modern buildings. Some items such as iron or copper piping have been replaced with plastic.

Industrial buildings would have been constructed of brick and concrete where possible in 1930, but they would contain less biomass today due to fire and safety concerns. Moreover, they would not contain the amount of biomass in furniture that is found in residences or office space.

Landfills

Although landfills from pre-European settlement periods have been found, such landfills were not compacted nor did they accumulate a significant amount of biomass. Much of the organic waste material would have decomposed rapidly, especially since there would have been little produced per capita. However, the higher volume of waste produced today means that much of it is buried before it can decompose and, once buried, it decomposes slowly, becoming stable after approximately 30 years (Bamryd 1983). Solid municipal waste today contains 80%–85% biomass (Environment Canada 1991).

Mammals

The increase in human population in the LFB means that human biomass must be considered as a portion of the total biomass, together with domesticated animals. The biomass of wild mammals has also likely changed, due to changes in diversity and populations (Boyle and others 1995a).

Human and animal waste were not included, as preliminary calculations indicated that they would be insignificant and they are not usually a long-term carbon pool.

Methods

Forest Biomass

To determine the biomass in the forests of the LFB, data from Kimmins and others (1985) and Franklin and Waring (1979) were used to determine average biomass in stands 40 years or less, 41–120 years, and over 120 years old (Table 3). Root biomass was not usually given so it was calculated as 20% of the above story biomass (Grier and Logan 1977) and decay was estimated at 0.03 t/yr (Spies and others 1988). Boyle and others (1995a) estimated the age structure and area of the forests for each specified time period and, using this data, the total biomass of the forests was calculated for the period prior to 1827, for 1930, and 1990.

Table 3. Biomass averages for different forest ages

	Biomass (t/ha)	
Age (yr)	Average	Range
0–40	160	80–310[a]
41–120	440	200–795[b]
>120	900	382–1486[c]

[a] Webber (1977), Binkley (1982, 1983), and Binkley and others (1984).

[b] Bigger and Cole (1983) as cited by Kimmins and others (1985) and Franklin and Waring (1979).

[c] Franklin and Waring (1979) and Grier and Logan (1977).

Wetland Biomass

Data from Ward and others (1992) provided sufficient information to determine the area of undisturbed and disturbed bogs and fens in the study area in 1990, while Kelley and Spilsbury (1939) provided data on the area of bogs and fens for 1930. Data from North and Teversham (1984) was used to identify bog and fen areas in the mid-1800s on the digitized map produced by Boyle and others (1995a), and this was used to estimate areas for pre-1827. Estimates of living biomass in swamps, bogs, fens, and marshes in the area was extrapolated from Banner and others (1988) and Zoltai and Pollett (1983), using biomass from other wetland areas in Canada and in the northwestern United States. An average of 5 m was used for the thickness of the peat layers in bogs and fens in the study area (Kelley and Spilsbury 1939, Banner and others 1988) and a density of 0.1 g/cm^3 (Clymo 1983). This information, together with data from Boyle and others (1996) on wetland areas, was then used to calculate the total biomass in wetlands in the study area.

Agricultural Areas

There was little or no agricultural activity in the LFB prior to the arrival of European settlers in 1827. However, by 1930, much of the land had been cleared for agriculture and clearing continued at a rapid pace. The amount of land that was actually under agricultural production in the LFB for 1991 was 90,000 ha (Statistics Canada 1991a). This included crop, pasture, and fallow land. Another 42,000 ha included as rural/agricultural land by Boyle and others (1996) was comprised of impervious land (roads, houses, etc.), lawns, parks, golf courses, and small woodlots. Approximately one third of this land would be impervious (Ponce 1989), while the rest was assumed to have an average biomass similar to grassland. The biomass in agricultural buildings was included under urban land, since Statistics Canada

Table 4. Estimated biomass per hectare for different agricultural crops[a]

Crop	Biomass (t/ha) 1930	1990
Greenhouse	4.1	5.4
Fruit trees	144	160
Berries	11.3	12.5
Cranberries	N/A	35
Vegetables	22	5.4
Grains	4.2	5.6
Others	4.2	5.5

[a]Calculated from Loomis (1981) and Statistics Canada (1991c, 1993).

(1991b) provides details on the number of buildings and their different types in the LFB, but not the detailed location. According to Statistics Canada (1991a), 1100 ha in the LFB are under cranberry cultivation, which would have the same biomass as a swamp and was assumed to be 21 t/ha.

Cropland in the LFB includes grain, corn, berry and fruit crops and would include harvest, standing, and below ground biomass. Loomis (1981) provides average factors to determine the biomass from the economic yield and, using Statistics Canada (1991c, 1993) data on crop yields for British Columbia, the amount of biomass per hectare for different agricultural crops was estimated (Table 4). It was assumed that fruit trees would have a biomass similar to that of young trees, 160 t/ha. Yields of cranberries were much higher than other berries, providing a biomass estimate of 35 t/ha.

For 1930, according to the Dominion Bureau of Statistics (1931), a total of 39,352 ha of land was under cultivation in the LFB. Crop yields of grain were approximately 75% of the 1990 yields (Dominion Bureau of Statistics 1931), and this reflects advances in pesticide control and fertilizer and improvement in strains that produce larger plants and yields. A similar increase would have occurred in vegetables, although the data were insufficient to determine the actual vegetable crop increases. Although there would have been some increase in berry and fruit production, it is unlikely that fruit trees, in particular, have increased by 25% in biomass. It was assumed that there was a 10% increase in biomass for fruit and berry crops. No cranberries were reported as part of the crop for that year.

Biomass in Buildings

In order to determine the biomass stored in the urban areas of the LFB, the amount of biomass found in a building had to be determined. Data on the materials in building construction in 1969 (Central Mortgage and Housing Corporation 1978) provided the amount of lumber, plywood, and other wood used per square meter of floor space for different types of buildings in BC. Discussions with moving companies yielded an average of 15 kg/m^2 of biomass in furniture, books, and appliances. Data from Sheltair Scientific Ltd. (1991) indicated that a standard three-bedroom house with 350 m^2 floor space and 5.2 tonnes of biomass in furnishings would have approximately 107 kg of biomass per square meter, close to the 1969 estimate (Table 5). Using data on the number and type of dwellings in the study area from the Dominion Bureau of Statistics (1931) and Statistics Canada (1991b), the amount of biomass in residences could be estimated.

Table 5. Estimated biomass per square meter for different building structures[a]

Type of residence	Avg. floor space, m^2 (for BC)	Biomass (kg/m^2)
Single detached	108	110
Attached duplex	104	95
Row	103	85
<5 floor apartment	73	80
>5 floor apartment	57	30

[a]Central Mortgage and Housing Corporation (1978).

Data on the spatial area of industrial, retail, and office space and number of employees in those occupations was available for the Greater Vancouver Regional District (GVRD) for 1991 (Greater Vancouver Regional District 1994) but such data were not available for the other three regional districts. An estimation of the space-to-employee ratio was calculated for retail, office, and industrial space using the GVRD data. This was then used to estimate the retail, office, and industrial area for the entire study area using Statistics Canada (1991b) data detailing the number of people in various occupations for the four districts. Once this area was calculated, the biomass per square meter could then be determined.

For 1990, the biomass in commercial establishments was considered to be similar to that in large apartment buildings, so a rate of 30 t/m^2 was used for those buildings. Industrial buildings would have a similar amount of wood in the construction, but the furnishings would be much less, so a rate of 15 t/m^2 was used for industrial space. The amount of biomass in buildings in 1931 may have been higher than that used today and the average square area may have increased, but no data were available to determine if such changes had occurred.

For 1930, industrial and business establishments were likely built with more biomass per meter than used today. For commercial establishments, the amount of

Table 6. Building biomass per animal for wooden structures

Animal	Building biomass (t/animal)
Cattle	1.7
Horses	1.2
Sheep	0.15
Pigs	0.2
Chickens	0.03

biomass was calculated using the ratio determined for apartments less than five floors high, 85 t/m^2. Industrial establishments, with little biomass in furniture, used a ratio of 70 t/m^2. The census data did not specify the occupations of individuals in the census divisions for 1931 but did for 1941 (Dominion Bureau of Statistics 1941). An assumption was made that the ratio of provincial employment to division employment had remained relatively constant for those 10 years, so those ratios from 1941 were used to estimate occupational data for 1931. The data were then used to calculate the approximate area of office, retail, and industrial space and the biomass in commercial and industrial buildings.

The biomass in barns and other such buildings was estimated using data from the British Columbia Lands Department (1931). The amount of biomass in standard barns per animal was calculated and averaged for different animals (Table 6). Using data on animal species and quantities in the LFB from 1931, the biomass in barns could be estimated. In the LFB today, many old, wooden barns are being replaced with environmentally controlled, aluminum-sided buildings that would have little biomass. From traveling throughout the region, a rough estimate was made that 60% of the barns had been replaced with aluminum-sided buildings and, using the biomass estimates from the 1930 buildings, the biomass of the remaining 40% was calculated.

No data were available on the biomass of vegetation in urban areas in the LFB. Consequently, an estimate of 60.5 t/ha was used, as estimated by Rowntree and Nowak (1991) for US cities.

Biomass in Landfills

The total biomass placed in landfills since 1940 was estimated using data from B. H. Levelton and Associates (1992), assuming that 60% of the waste landfilled was biomass (Environment Canada 1991) (assuming plant and food material to contain 40% dry biomass). B. H. Levelton and Associates (1992) also estimated waste production at 0.88 kg/person/day for 1941 and, assuming 60% to be biomass, a rate of 0.7 kg/person/day was used to calculate the municipal solid waste production for the period from 1827 to 1940. Bamryd (1983) estimated that 50% or more of the biomass in solid wastes accumulated in landfills. Assuming that a 50% loss takes place over 30 years, the amount of biomass in municipal landfills was then calculated for 1930 and 1990. An estimate of 0.5 kg biomass waste/person/day was used to calculate the waste production prior to 1827 and an assumption was made that it would decompose within 10 years.

The amount of biomass in industrial landfills is primarily due to wood and pulp wastes (Environment Canada 1992). According to Jenkins (1931) most of the wood waste produced prior to 1930 was either utilized or burned. B. H. Levelton and Associates (1992) calculated the amount of wood waste landfilled since 1960 for British Columbia Environment Canada (1992) notes that 1,000,000 m^3 (413,000 tonnes) of wood wastes were being landfilled in the LFB in 1977 and at that time 35 wood waste disposal sites contained 4.4 million m^3 of woodwaste. These data were used to determine the percentage of the provincial wood waste that was landfilled in the LFB for 1977, and this was used to calculate the total wood waste that has been landfilled in the LFB.

A further 500,000 t/year of material from the construction industry was landfilled in 1990 (Environment Canada 1992), and an estimate of 40% biomass (Environment Canada 1991) is assumed for this waste. This was correlated to changes in population (6.5 t/person/yr), so that estimates of the volume of construction waste could be calculated over the past 170 years.

Biomass in Mammals

Boyle and others (1995a) provided some estimates of wildlife in the LFB prior to 1827 and for 1990. Using average weights of wildlife species (Cowan and Guiguet 1973), the biomass they contributed to the LFB was calculated. Waterfowl and salmonids were not included since they were seasonal, not year-round, residents, although both contained a significant amount of biomass. Average weights of farm animals (Table 7) were used with data from the Dominion Bureau of Statistics (1931) and Statistics Canada (1991a) and an average of 72% water for mammals (Withers 1992) to determine the biomass of farm animals today. The weight of Canadian men, women, and children was averaged using data from Demirjian (1980), giving an average weight of 63.5 kg/person and an estimation of 72% water in humans was used (Lentner 1981). The biomass in human populations prior to 1827, in 1930, and in 1990 was calculated using population data from the Dominion Bureau of Statistics (1931) and Statistics Canada (1991b).

Table 7. Estimated weight of humans and livestock[a]

Mammal	Estimated average weight (kg)	Estimated average dry biomass (kg)
Human	63.5	18
Bull	842.5	236
Beef cow	550	154
Dairy cow	640	179
Steer	410	115
Heifer	365	102
Calf	135	38
Horses/ponies	455	127
Pigs	170	48
Goats	65	18
Sheep/lambs	47.5	13
Rabbits	2	0.6
Chickens/hens	1.8	0.5
Mink	1.2	0.3

[a] From Brisbane (1995), Withers (1992), and Lentner (1981).

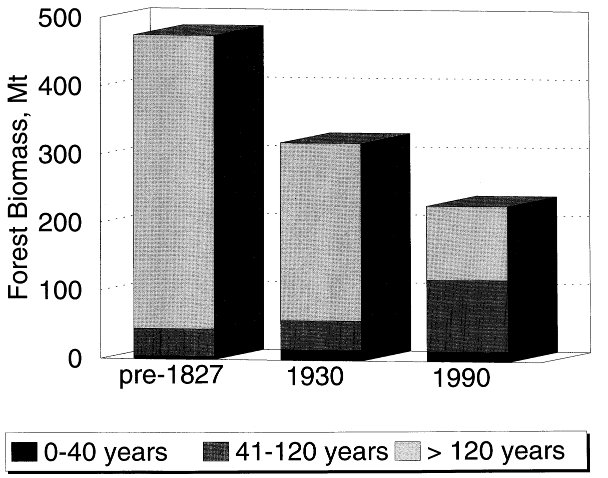

Figure 2. Biomass in forests in the LFB prior to 1827 and for 1930 and 1990.

Table 8. Fate of forest biomass following harvesting assuming 53% biomass harvesting[a]

Fate	Initial use (%)	After 1 year (%)	After 60 years (%)	After 100 years (%)
Construction	12	12	6	0.05
Packaging	8	5	0.05	0
Paper	13	6	0.05	0
Burned/decayed	67	68	75	92
Landfill	0	9	28	8

[a] Calculated using data from Kurz and others (1992). Totals may not add to 100% due to rounding.

Results and Discussion

Biomass in Forests

The biomass contained in forests has dropped by more than half over the past 170 years and contains about 230 Mt of biomass today, a loss of 247 Mt of biomass from the forest (Figure 2). Prior to 1827, over 90% of the biomass had been contained in trees older than 120 years, but today only about 48% is in old trees. According to Boyle and others (1995a) these older trees, containing almost 50% of the biomass of the forest in the LFB, occupied only 19% of the forested area in the LFB.

The loss of carbon from this pool also indicates that the higher carbon uptake of younger trees does not compensate for the mass of carbon lost through logging the old-growth timber. As a result, although the vegetation continually takes up carbon as a sink, overall the logging of the forest is resulting in a major release of carbon.

Of the aboveground biomass in logged trees, 66% is removed as harvested timber and the rest remains to decay as unusable cull (Kurz and others 1992). Assuming that root biomass is equivalent to 20% of the aboveground biomass (Grier and Logan 1977), only 53% of the total plant biomass is harvested. According to Kurz and others (1992), 24% of the harvested timber is used for building construction, 14% for packaging, 24% for paper, and 38% is burned just after harvest. After 100 years, using Kurz and other's (1992) estimates, only about 0.05% of the logged forest biomass remains in long-term storage (buildings, furniture, etc.), 8% in landfills, 1% (roots) in the ground, and the rest has either been burned or has decayed (Table 8). Once mobilized, less than 10% of forest biomass enters another stable, terrestrial carbon pool. Most of it is converted to carbon dioxide.

Consequently, although some of the biomass lost since 1827 may still be in terrestrial pools outside the study area, most of it will be lost after 100 years. Even after one year, only 21% is in use with 9% in landfills. Applying this model to the LFB data, approximately 39% of the logged forest biomass was still in use, in landfills, or in the ground in 1930; in 1990, that biomass had decreased to 26%. Therefore, 182 Mt of biomass from logged forests has been lost through decay or burning since 1827 or, assuming the biomass contains 50% carbon (Kauppi and others 1992), 364 Mt of carbon dioxide have been emitted to the atmosphere since 1827 from logged forests.

Biomass in Wetlands

According to Banner and others (1988), a layer of approximately 5 m of peat occurred beneath the bogs of the LFB. Using a peat density of 0.1 g/cm^3 (Clymo

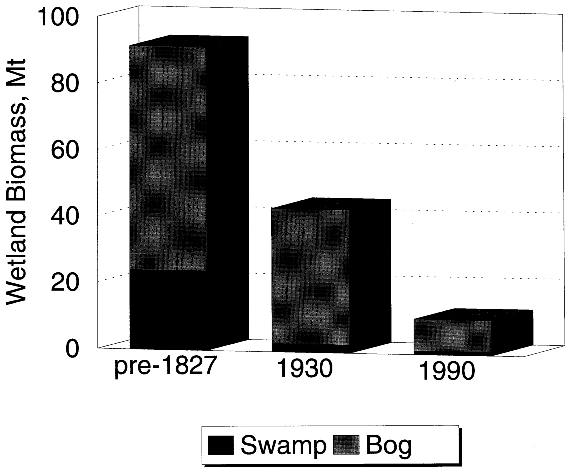

Figure 3. Biomass in wetland vegetation in the LFB prior to 1827, in 1930, and in 1990.

1983), approximately 67 Mt of peat was located in bogs in the LFB prior to European settlement (Figure 3).

Using data on *Carex* spp. swamps, which are the common types of swamps and fens found in the LFB (Banner and others 1989), an average of 21 t biomass/ha was calculated, with a range of 19–23 t/ha (Bernard and MacDonald 1974, Bernard 1974, Mörnsjö 1969). These swamps were found in the northern United States or in southern Sweden and swamps in the LFB may be slightly higher in biomass. However, using these data, an estimated total of 91.4 Mt of biomass were found in wetlands prior to 1827; this dropped to 43.2 Mt in 1930 and down to 10.6 Mt of biomass in 1990, a total loss of over 80 Mt of biomass (Figure 3). Most of this biomass was stored in dead vegetation in peat bogs and, if burned, would have released 148 Mt of carbon dioxide to the atmosphere.

Biomass in Agricultural Vegetation

By 1990, the biomass in agricultural vegetation had increased by 4% to 209,000 tonnes since 1930 (Figure 4) but it still only comprised 0.07% of the carbon in the study area. For 1930, approximately 84% of the agricultural biomass was harvested or removed annually, while this had increased to 91% by 1990.

Biomass in Buildings and Urban Areas

The two major biomass sinks in buildings and urban areas lie in vegetation and residential buildings (Figure 5). The biomass per capita in buildings in 1990 is approximately 2% of the biomass lost from forests in the LFB since 1827 and has increased from 2.8 t/person in 1930 to 3.9 t/person in 1990, primarily due to the increase in residences per capita (0.15 single dwellings/person in 1930 to 0.19 single dwellings/person in 1990). This is somewhat higher than the average of 2.1 t/capita cited by Bamryd (1983) for industrialized countries, possibly due to the amount of wooden farm buildings and the amount of wood in construction used in British Columbia. Overall, the amount of biomass in buildings and urban vegetation has increased by 9 Mt, (400%), the equivalent of 17 Mt of carbon dioxide. Including urban vegetation, the per capita biomass in urban areas was 5.7 t/person in 1930 and 6.8 t/person in 1990.

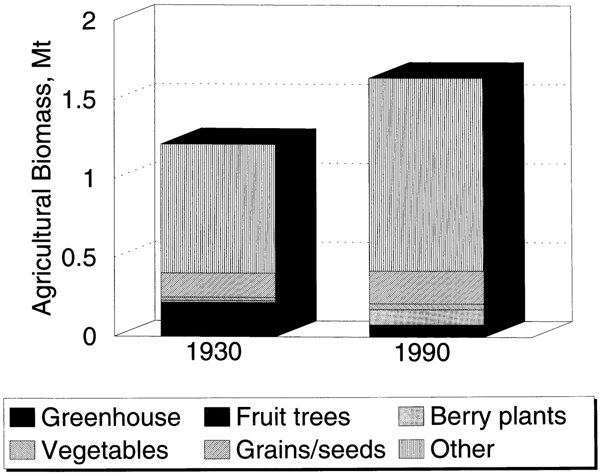

Figure 4. Biomass in agricultural vegetation in the LFB prior to 1827, in 1930, and in 1990.

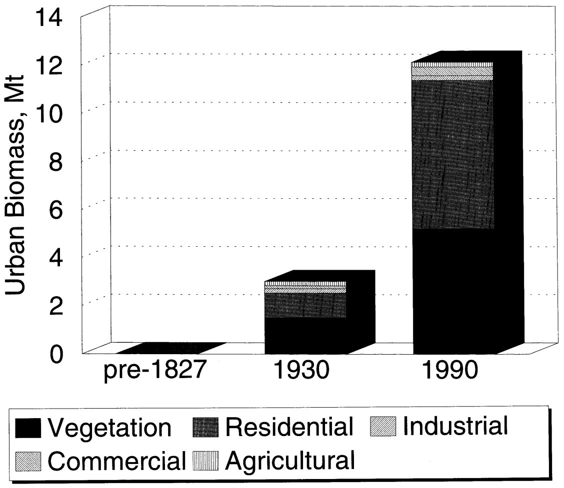

Figure 5. Biomass in buildings and urban vegetation in the LFB prior to 1827, in 1930, and in 1990.

The human population of the LFB, prior to European arrival, has been estimated at 4000 (Boyle and others 1995a). It is likely that their buildings would have used less biomass per person than buildings today, but to provide an estimate, 3.9 t/person will be used. From

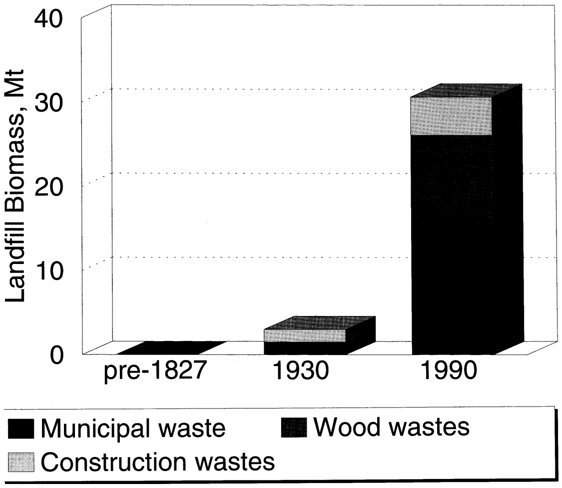

Figure 6. Biomass of material in landfills in the LFB.

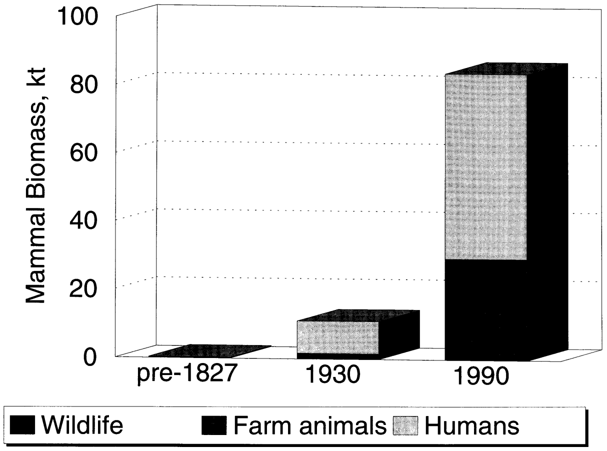

Figure 7. Biomass contained in year-round resident mammals of the LFB prior to 1827, in 1930, and in 1990.

this estimate, the biomass that may have been in their buildings would have approximated 15,600 tonnes, 0.5% of the biomass in buildings and vegetation in 1930 and 0.1% of the biomass in buildings and vegetation in 1990 (Figure 5).

Biomass in Landfills

Biomass in landfills has increased significantly, especially the contribution from municipal solid waste. Landfills are becoming a major storage of biomass in the LFB, with a total of 31 Mt of biomass in landfills in 1990, and now contain 5% of the carbon in the study area (Figure 6). If combusted, that biomass would release 112 Mt of carbon dioxide. If the carbon input into landfills continues, landfills may become a significant carbon sink in the future. They are already the third largest source of methane, a powerful greenhouse gas, for the world (Peer and others 1993) and, as landfills increase in number and size, will become even more of a concern.

Biomass in Mammals

The populations of both humans and farm animals have risen significantly since 1930, a biomass increase of 53,000 tonnes (Figure 7). Wildlife biomass has also increased, by 160%, although diversity has decreased (Boyle and others 1995a). The overall increase in biomass since 1827 has been 54,000 tonnes, the equivalent of 97,000 tonnes of carbon dioxide.

Changes in Carbon Pools Since 1827

Assuming an average of 50% carbon content in biomass, the amount of biomass carbon in pools in the LFB can be calculated. Soil data from Boyle and others (1995a) were incorporated with the above data. The results indicate that there has been a dramatic decrease in biomass carbon in the LFB, a total loss of 270 Mt or 48% (Figure 8). The most significant losses have been from forests (42%), soils (43%), and wetlands (14%), and the increases due to increased urbanization and agriculture have been insignificant. Approximately 80% of the carbon was lost prior to 1930—the rate of loss has slowed since then.

The only significant pool that is increasing is landfills, which now contain 5% of the biomass carbon in the LFB. Landfills are becoming major accumulators of carbon and may become the major sinks of carbon in the future as biogenic pools are depleted. Carbon pools in human population, agricultural production, and building construction are insignificant compared with the pools in forest, wetlands, and soil.

Assuming that 26% of the logged forest biomass was still in a terrestrial biogenic pool in 1990, a total of 238 Mt of carbon had been released into the environment from the LFB since 1827 (Figure 9). It is difficult to relate this release to the LFB population, due to the complexities generated by area imports and exports, life-span, immigration, life-style, culture, and policies. However, to provide some indication of this release to global releases of biogenic carbon over this time period, some global comparisons have been included.

According to Houghton and Skole (1990), the net release of carbon from terrestrial ecosystems worldwide has been on the order of 135 Gt of carbon for 1800–1980, while from 1980 to 1989 the average annual terrestrial release has been 1.6 Gt (IPCC 1994) for a approximate total of 150 Gt of carbon for 1800–1990. This is an average global release from terrestrial ecosystems of 1000 t/km^2. The release from the LFB is much higher on an area basis, 238 Mt over 8300 km^2 or 28,600

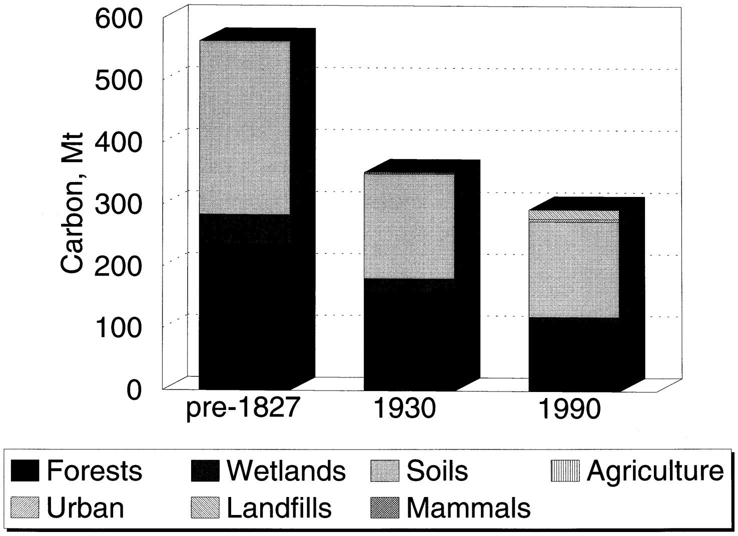

Figure 8. Biomass carbon in the LFB prior to 1827, in 1930, and in 1990.

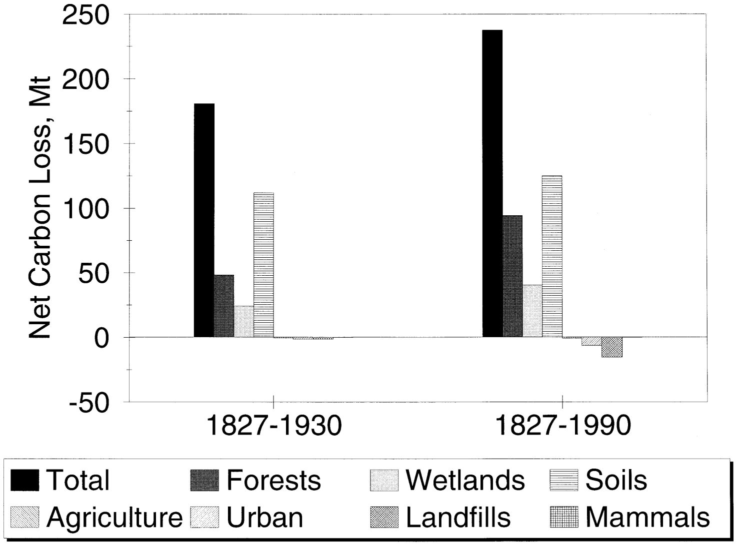

Figure 9. Estimated net loss of carbon to the atmosphere for different pools in the LFB for 1827–1930 and 1827–1990.

t/km^2, almost 29 times the average global terrestrial release. The amount from the LFB constitutes 0.16% of the global terrestrial release, from an area that is 0.006% of the world's land area.

In other words, human impact on terrestrial ecosystems in the Lower Fraser Basin has resulted in a much higher proportion of carbon being released from this area than the global average and has contributed significantly to the atmospheric carbon content. Moreover, this amount does not take into account the fossil fuels that are imported into the LFB and consumed for energy purposes—it looks only at the existing resources in the basin. If drains on resources external to the LFB were included, the carbon release would be much higher. This is not meant to assign blame or responsibility for climate change, as much more data are required to determine individual responsibility (Smith 1994) or even properly formulate questions regarding responsibility (Dove 1994). However, it does indicate that land-use management should take the loss of carbon pools as a serious issue and provides one perspective from which to examine local versus global sustainability.

The primary source of the released carbon was old-growth forest, which contains a higher biomass per hectare than tropical rain forest (Ryan 1994). This forest was a major pool of carbon, and the release of this contained carbon is not being reversed by current forest management practices since trees are cut at a younger age. Moreover, the loss of carbon from soils after deforestation is also not being reversed and the other large carbon accumulator, wetlands, requires up to 10,000 years to accumulate significant amounts of carbon. Landfills appear to be our major growing sink of carbon.

In a historical context, the LFB was colonized and heavily populated over a relatively short period of 150 years. The loss of carbon is similar to preindustrial releases that may have occurred in areas that are now heavily populated in Europe, Asia, and the Middle East, although over a longer timeframe (Smith 1994). It is similar to the deforestation that is currently underway in Canada, the US and many tropical rainforests. Old-growth forests, their organic carbon-rich soils, and peat-rich wetlands are significant pools of carbon, and continued cutting of these forests and draining of wetlands, both in developed and developing countries, will only continue the release of carbon to the atmosphere.

Conclusions

The major changes in biomass and carbon pools in the Lower Fraser Basin have been decreases in forest, soil, and wetland biomass due to cutting of forests, removal of peat, loss of wetlands, and agricultural practices. Over 80% of these losses occurred prior to 1930, as suggested by Houghton and Skole (1990). Increases in biomass have occurred in agricultural vegetation, urban buildings and vegetation, landfills, and mammals but these do not offset the decreases. Approximately 48% of the forest biomass, almost 20% of the carbon of the LFB, lies within the old-growth forest, which covers 19% of the study area, and these old-growth forests are still being logged.

Overall, there has been a decrease of 270 Mt of carbon in biomass pools in the LFB from an area of 8300 km^2 and a population of less than 2 million people. An estimated 238 Mt of biomass carbon, the equivalent of 870 Mt of carbon dioxide, has been released from carbon pools to the atmosphere since 1827. On an area basis, this is 29 times the global contribution of carbon to the atmosphere per square kilometer since 1800. This serves to further the understanding of past contributions by developed countries such as Canada to climate change and possible future contributions from further clearing of rain forest in both tropical and temperate regions. It also serves to remind countries such as Canada and the United States that they, too, have forests that can act as huge carbon pools. These developed countries should place some emphasis and funding towards maintaining their remaining old-growth forests rather than only focusing on pressuring developing countries to stop logging tropical rain forest.

Acknowledgments

This research has been funded by the Tri-Council of Canada, under the Green Plan.

Literature Cited

Bamryd, T. 1983. Human impact on the biogeochemical cycling of carbon between terrestrial ecosystems and the atmosphere. *Environmental Biogeochemistry Ecological Bulletin* 35:301–313.

Banner, A., R. J. Hebda, E. T. Oswald, J. Pojar, and R. Trowbridge. 1988. Wetlands of Pacific Canada. Pages 307–346 *in* National Wetlands Working Group (ed.), Wetlands of Canada. Environment Canada, Ottawa, Ontario, 445 pp.

Bernard, J. M. 1974. Seasonal changes in standing crop and primary production in a sedge wetland and an adjacent dry old-field in central Minnesota. *Ecology* 55:350–359.

Bernard, J. M., and J. G. MacDonald. 1974. Primary production and life-history of *Carex lacustris*. *Canadian Journal of Botany* 52:117–123.

B. H. Levelton and Associates. 1992. An inventory and analysis of control measures for methane for British Columbia. Ministry of Environment, Victoria, British Columbia, 139 pp.

Binkley, D. 1982. Nitrogen fixation and net primary production in a young Sitka alder stand. *Canadian Journal of Botany* 60:281–284.

Binkley, D. 1983. Ecosystem production in Douglas-fir plantations: Interaction of red alder and site fertility. *Forest Ecology Management* 5:215–227.

Binkley, D., J. D. Lousier, and K. Cromack, Jr. 1984. Ecosystem effects of Sitka alder in a Douglas-fir plantation. *Forest Science* 30:26–35.

Boyle, C. A., L. Lavkulich, H. Shreier and E. Kiss. 1996. Changes in vegetative cover and subsequent effects on Lower Fraser Basin ecosystems from 1827 to 1990. *Environmental Management* (in press).

Boyle, C. A., F. Ganders, U. Pott and A. Vizcarra. 1995. Human activity and the Lower Fraser Valley ecosystem. Pages 18–38 *in* The Lower Fraser Basin in transition. Proceedings of a symposium and workshop, 4 May 1995. Resource Management and Environmental Studies, University of British Columbia, Vancouver, Canada, 122 pp.

Brisbane, P. 1995. Management of agricultural wastes in the Lower Fraser Valley (draft). BC Ministry of Environment, Lands and Parks. Vancouver, British Columbia.

British Columbia Lands Department. 1931. Farm building series. British Columbia Lands Department, Victoria, British Columbia.

Central Mortgage and Housing Corporation. 1978. Materials used in residential construction. Central Mortgage and Housing Corporation, Ottawa, Ontario, 559 pp.

Clymo, R. S. 1983. Peat. Pages 159–225 *in* J. P. Gore (ed.), Mires: Swamp, bog, fen and moor. Ecosystems of the world 4a. Elsevier Scientific, New York, 440 pp.

Cowan, I. M., and C. J. Guiguet. 1973. The mammals of BC. BC Provincial Museum, Victoria, British Columbia.

Demirjian, A. 1980. Anthropometry report: Height, weight and body dimensions: A report from Nutrition Canada. Nutrition Canada, Health Services and Promotion Branch, Ottawa, Ontario, 133 pp.

Dominion Bureau of Statistics. 1931. Census of Canada, 1931. Government of Canada, Ottawa, Ontario.

Dominion Bureau of Statistics. 1941. Census of Canada, 1941. Government of Canada, Ottawa, Ontario.

Dove, M. R. 1994. North–south differences, global warming, and the global system. *Chemosphere* 29(5):1063–1077.

Environment Canada. 1991. The state of Canada's environment. Environment Canada, Ottawa, Ontario.

Environment Canada. 1992. State of the environment for the Lower Fraser River Basin. SOE Report No. 92-1. Environment Canada, Ottawa, Ontario, 79 pp.

Franklin, J. F., and R. H. Waring. 1979. Distinctive features of the northwestern coniferous forest: Development, structure, and function. Pages 59–86 *in* R. H. Waring (ed.), Forests: Fresh perspectives from ecosystem analysis. 40th Annual Biology Colloquium, Oregon State University, Oregon.

Greater Vancouver Regional District. 1994. Greater Vancouver key facts. Strategic Planning Department, Greater Vancouver Regional District, Vancouver, British Columbia.

Grier, C. C., and R. S. Logan. 1977. Old-growth *Pseudotsuga menziesii* communities of a western Oregon watershed: Biomass distribution and production budgets. *Ecological Monographs* 47(4):373–400.

Houghton, R. A., and D. L. Skole. 1990. Carbon. Pages 393–408 *in* B. L. Turner II and others (eds.), The earth as transformed by human action. Cambridge University Press with Clark University, Cambridge, New York, 713 pp.

IPCC. 1994. Climate change 1994: Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. Cambridge University Press, New York.

Jenkins, J. H. 1931. Sawmill waste and its utilization in British Columbia. Forest Service Bulletin, Department of the Interior, Ottawa, Canada, 56 pp.

Kauppi, P. E., K. Mielikäinen, and K. Kuusela. 1992. Biomass and carbon budget of European forests, 1971 to 1990. *Science* 256:70–74.

Kelley, C. C., and R. H. Spilsbury. 1939. Soil survey of the Lower Fraser Valley. British Columbia Department of Agriculture, British Columbia, 67 pp.

Kimmins, J. P., D. Binkley, L. Chatarpaul and J. de Catanzaro. 1985. Biogeochemistry of temperate forest ecosystems: Literature on inventories and dynamics of biomass and nutrients. Information report PI-X-47 E/F. Canadian Forestry Service, Chalk River, Ontario, pp. 227.

Kurz, W. A., M. J. Apps, T. M. Webb, and P. J. McNamee. 1992. The carbon budget of the Canadian forest sector: Phase I. Information report NOR-X-326. Forestry Canada, Northwest Region, Edmonton, Alberta, p. 91.

Lentner, C. (ed.). 1981. Geigy scientific tables, Vol. 1. Units of measurement, body fluids, composition of the body, nutrition. Ciba-Geigy, Basel, Switzerland, 266 pp.

Long, J. N. 1982. Productivity of western coniferous forests. Pages 89–125 *in* R. L. Edmonds (ed.), Analysis of coniferous forest ecosystems in the western United States. Hutchinson Ross Publishing, Harrisburg, Pennsylvania.

Loomis, R. S. 1981. Productivity of agricultural systems. Pages 150–172 *in* O. L. Lange, P. S. Nobel, C. B. Osmond, and H. Ziegler (eds.), Physiological plant ecology IV: Ecosystem processes: Mineral cycling, productivity and man's influence. Springer-Verlag, New York, 644 pp.

McCallum, D. 1995. Trace metal dynamics and land use relationships in an urban watershed. MSc thesis. Department of Civil Engineering University of British Columbia, Canada.

Moore, B., and R. H. Braswell, Jr. 1994. Planetary metabolism: Understanding the carbon cycle. *Ambio* 23(1):4–12.

Mörnsjö, T. 1969. Studies on vegetation and development of a peatland in Scania, south Sweden. *Opera Botanica* 24:187.

North, M. E. A., and J. M. Teversham. 1984. The vegetation of the floodplain of the Fraser, Serpentine and Nicomekl rivers, 1859–1890. *Syesis* 17:47–66.

North, M. E. A., M. W. Dunn, and J. M. Teversham. 1979. Vegetation of the southwestern Fraser lowland, 1858–1880. Lands Directorate, Environment Canada, Vancouver, British Columbia, 1 p.

Peer, R. L., S. A. Thorneloe, and D. L. Epperson. 1993. A comparison of methods for estimating global methane emissions from landfills. *Chemosphere* 26(1–4):387–400.

Ponce, V. M. 1989. Engineering hydrology. Prentice Hall, Englewood Cliffs, New Jersey, 627 pp.

Prescott, C. E., and G. F. Weetman. 1994. Salal cedar hemlock integrated research program: A synthesis. Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, 85 pp.

Reader, R. J., and J. M. Steward. 1972. The relationship between net primary production and accumulation for a peatland in south-eastern Manitoba. *Ecology* 53:71–94.

Rowntree, R. A., and D. J. Nowak. 1991. Quantifying the role of urban forests in removing atmospheric carbon dioxide. *Journal of Arboriculture* 17(10):269–275.

Ryan, J. C. 1994. Greenhouse gases on the rise in the Northwest. *New Indicator, Northwest Environment Watch,* 17 August 1995.

Sheltair Scientific Ltd. 1991. Optimize: A method for estimating the lifecycle energy and environmental impact of a house. Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Smith, K. R. 1994. Pre-industrial missing carbon and current greenhouse responsibilities. *Chemosphere* 29(5):1135–1143.

Spies, T. A., J. F. Franklin, and T. B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington, USA. *Ecology* 69(9):1689–1702.

Statistics Canada. 1991a. Agricultural census for BC. Statistics Canada, Ottawa, Ontario.

Statistics Canada. 1991b. Profile of census divisions and subdivisions in British Columbia Part B. Statistics Canada, Ottawa, Ontario.

Statistics Canada. 1991c. Field crop reporting series, 29 November 1991, Vol. 70, No. 8. Statistics Canada, Ottawa, Ontario.

Statistics Canada. 1993. Fruit and vegetable production. Statistics Canada, Ottawa, Ontario.

Turner, B. L., II, R. H. Moss, and I. L. Skole (eds.). 1993. Relating land use and global land-cover changes: A proposal for an IGBP-HDP Core Project. Global Change Report, IGBP Report No. 24, HDP Report No. 25, Stockholm, Sweden.

Ward, P., K. Moore, and R. Kistritz. 1992. Wetlands of the Fraser lowland, 1989: An inventory. Technical report 146. Canadian Wildlife Service, Environment Canada, Vancouver, Canada, 216 pp.

Webber, B. D. 1977. Biomass and nutrient distribution patterns in a young *Pseudotsuga menziesii* ecosystem. *Canadian Journal of Forest Research* 7:326–334.

Withers, P. C. 1992. Comparative animal physiology. Saunders College Publishing, Philadelphia, 949 pp.

Zoltai, S. C., and F. C. Pollett. 1983. Wetlands in Canada: Their classification, distribution and use. Pages 245–268 *in* A. J. P. Gore (ed.), Mires: Swamp, bog, fen and moor. Ecosystems of the world, 4B. Elsevier Scientific Publishing, New York.