Forest Science & Technology to Reduce Atmospheric Greenhouse Gases – An Overview, with Emphasis on Carbon in Canada's Forests

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Abstract

The forest as a CO_2 sink comprises, in addition to mature and immature trees, C accumulated in understorey plants, animals, forest soils, peat bogs and wetlands. Estimates of how much carbon (C) is entering and leaving a forest ecosystem cannot be obtained merely by estimating gaseous CO_2 fluxes. The C cycle also involves direct transfer of CO_2 to soil in rain and snow, non-photosynthetic or "dark" fixation of CO_2 by myriad soil and aquatic micro-organisms, roots, fungi and animals, and loss of C in forms other than CO_2 via air, groundwater flow and runoff.

The complexity of the carbon cycle challenges us to develop reliably accurate means of inventorying C accumulation in trees. In productive forests the C of wood (C_{wood}) can be determined by estimating tree merchantable volume and, by density conversion, mass of dry wood. Percentage C in dry wood varies by species and type of wood, but otherwise C_{wood} can be readily calculated. The C present in foliage, branches, bark and roots can, as a first approximation, be assumed to be equivalent to that in the merchantable boles.

National Forestry Database statistics and our elemental analysis data on total carbon in wood were used to determine how much C is present in and being removed annually from Canadian forests. In 1998 Canada extracted 45 million tonnes of C_{wood} from 0.5% of its more than 244 million hectares (ha) of productive forest area. That annual harvest contained less than 0.001% of the 6400 gigatonnes of C_{wood} existing in boles of merchantable trees. However, harvesting over the last three centuries has reduced C content in productive forests to well below 50% of their pre-1700 sink capacity. To refill the sink, it is proposed that a ceiling of 50 million tonnes C_{wood} be set as the annual allowable cut.

Mean temperature increases of as much as 8 °C have been forecast for Canada over the next 100 years. The impact of those increases on tree growth and survival will depend not so much on changes in the annual mean but on what individual trees actually experience during the growing season in relation to the extremes they are able to tolerate. From a physiological perspective, maintaining shelterwoods with canopies approaching full closure is the only option for modulating extremes, thus for keeping forests growing healthily.

Recycling and refabricating wood and paper represent major societal and industrial opportunities to offset greenhouse gas emissions. Canadians can contribute to the C sink level of the nation by ensuring that paper and wood products have longer in-service lifetimes.

"There is a crying need for a definite policy for the provinces and for Canada as a whole. Not for simply a paper one, but a comprehensive plan which will insure not only the proper conservation of our natural resources but also the production of the greatest amount of the best wood." E. Wilson, 1935 issue of *The Forestry Chronicle.*

Introduction

The tall closed-canopy forest stands greeting European settlers in eastern North America from 1600 – 1800 were more a nuisance than a blessing, especially for those who had to cut the trees and clear the land in order to grow crops. Nevertheless, overseas interest in the massive multi-centurion eastern white pine provided 'hard money' for hard labour. The resulting trade encouraged settlements to spring up throughout Acadia and Lower Canada, followed by Upper Canada (Lower 1938, 1973). More than two centuries of timber harvesting, shipbuilding and exporting had passed by the time of Canada's 1867 confederation, but the attitude in the late 1800's was that there was an "unending supply of white pine ... enough for the next 700 years" (NFB Canada, 1965). By then the squared timber industry had grown very large. In the year 1870, the prime minister, Sir John A. MacDonald, noted: "The procession of [white pine] rafts [on the Ottawa River] beneath my window has not ceased in the last three months" (NFB Canada, 1965)." The logs were floated to Quebec City, squared and loaded into the holds of ships – as many as 3000 large ships in a single summer – bound for Britain (Hughson and Bond, 1965; Lower, 1973). One knot the size of a quarter over a 60-foot squared length was the limit of tolerance if one was to be paid the highest value (NFB Canada, 1965). Today, we would be hard pressed to find one such tree anywhere.

Despite the optimism of 30 years earlier, by 1900 quality white pine was in short supply (Hughson and Bond, 1965; Lower 1938, 1973). As the squared timber industry faded, demand arose in west-migrating North America for lumber and railway ties. Newspaper production from groundwood also surged, providing incentive to cut the smaller trees (Hunter, 1943; Lower 1938, 1973; NFB Canada, 1965). Eastern Canada has exported inestimable quantities of C from its forests, but British Columbia has undoubtedly provided more than the rest of Canada combined – in logs not uncommonly aged more than 1000 years. The Woods Hole Research Center estimated that worldwide about 10^{11} tonnes of C were released to the atmosphere from changes in land use between 1850 and 1990 (http://www.whrc.org/science/carbon/carbon.htm).

Since the inception of professional foresters in 1900, there has always been strong debate and polarization about how to manage Canadian forests (Rodgers, 1951; Fensom, 1972). Foresters are still struggling to reach consensus on even a definition for 'forestry.' Confronted with global warming and climate change, *forestry* if it is to survive as a profession must be *the art and science of sustaining healthy forest ecosystems in perpetuity.* Such a definition by no means implies that trees should never be harvested from the forest, but it gives first priority to the maintenance of healthy ecosystems. The aim can no longer be simply to protect trees from insects and fire until the "renewable resource" reaches harvestable size, rather it must be to ensure that both trees and environment remain indefinitely health-sustaining. By sustaining forest ecosystem health, forestry will concomitantly be managing for an optimum balance between wood productivity and C sink capacity, and for many added benefits.

The Carbon Cycle in Forest Ecosystems

Forest ecosystem health and the carbon budget cannot be managed for in the absence of solid grounding in ecophysiology (Larcher, 1983). For example, IIASA (Nilsson et al., 2000) recently attempted a full carbon accounting (FCA) of the forests in Russia for the year 1990 on the basis that:

> *"Sooner or later, verifiable carbon accounts will become a necessary precondition for mutual recognition and implementation of legally binding commitments, such as those established by the Kyoto Protocol of the UNFCCC. They will be even more important when it comes to carbon trading. ... we concluded that the only scientifically justifiable way to deal with carbon accounting is to produce a full carbon account that encompasses and integrates all carbon-related components, and is applied continuously in time. We assume that the components can be described by adopting the concept of pools and fluxes to capture their function."*

The error associated with the estimate was large, and in the end Nilsson et al. (2000) wrote:

> "...the uncertainties surrounding the carbon accounts must be significantly reduced. ... it is essential to develop new methods for assessing the uncertainties in the carbon account."

An indication of the size of the forest sink in Canada is provided at the end of this paper, but it seems more important at this stage of the Kyoto Protocol to learn how to think about C acquisition and flow into and out of forest ecosystems, and to be confident that the concepts have a solid scientific foundation. Once the C storage and flow concepts are solidly in place and agreed on internationally, they should enable acceptable guidelines to be developed not only for carbon accounting and crediting processes but also for innovative forest management. It obviously is also important to recognize and prioritize research needs.

The flow of C as it occurs into and out of forest ecosystems in the absence of human intervention is shown thematically in **Figure 1**. The cycle is more complex than we may wish. There are a great many "uncertainties", and excepting photosynthesis and respiration very little fundamental research has been done on the numerous input and output mechanisms. On the other hand, there is no shortage of field data on C fluxes. However, the total flux balance approach can only be as informative as the known and integrated components and processes, and there can be no doubt that many of the sinks and sources still remain to be clearly identified, much less functionally explained or incorporated into an acceptable model.

It is important to recognize that the 'carbon dioxide cycle' is part of a larger 'carbon cycle' operating over oceans, freshwater bodies, agricultural lands, and urban areas as well as forest ecosystems (Figure 1). There has been a tendency to simplify forest flux analyses to CO_2, evidently on the assumption that photosynthesis and respiration account for everything. How much C is acquired by forest ecosystems other than through photosynthesis is unknown, but as explained below there is no doubt that alternative mechanisms for assimilating C are in operation. Large quantities of C are also lost from trees in forms other than CO_2; thus, technically they cannot be referred to as respiratory losses. Isoprene, other terpenes and a long list of other kinds of volatile organic carbon are released to the atmosphere, particularly during the hot summer months (Lerdeau 1998). Trees exude and when it rains have leached from their surfaces many kinds of water-soluble organic compounds which contribute to both above and below ground pools of dissolved organic matter (DOM).

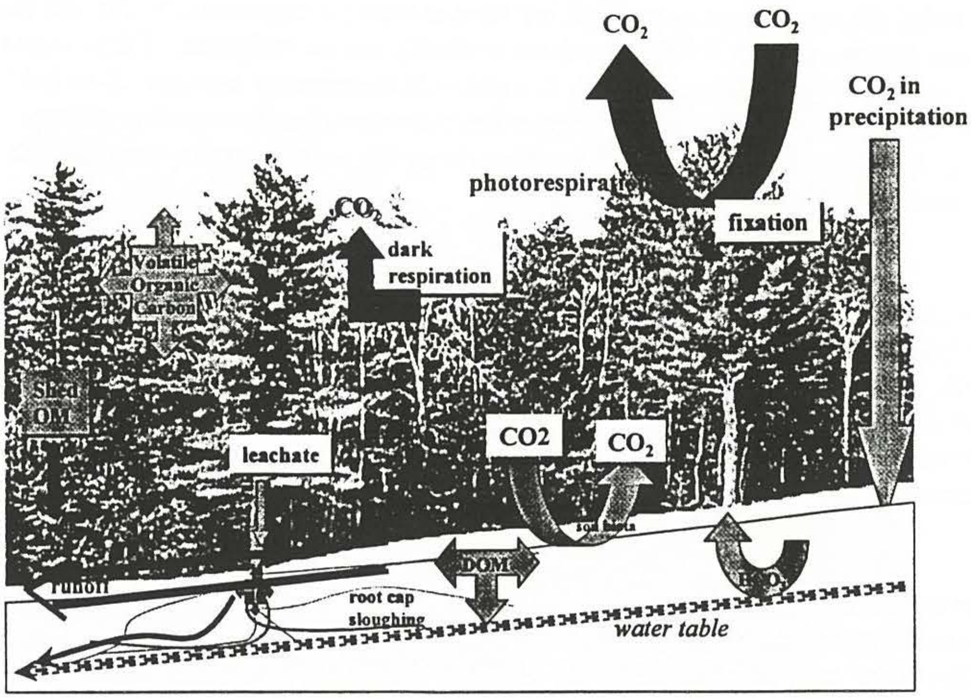

Figure 1. Above- and below-ground fluxes operating over the short term in forest ecosystems to determine import and export of carbon. See text for further explanation.

Tree roots are the primary recipients of photosynthate, but little of that received is actually accumulated as biomass. Much is lost to the rhizosphere as sloughing dead cells, slimy polysaccharides and foodstuff for herbivores. In addition to its load of dissolved CO_2 (see below), surface runoff in spring carries with it an abundance of other forms of DOM and also small particles of insoluble organic matter, particularly humic and fulvic acids (Bourbonniere, 1989; Bourbonniere and van Halderen, 1989). These transfers occur through as well as upon soil. Little is known about metabolism of DOM and insoluble organic matter in soils, but it is known that much of that matter flows to wetlands (Bourbonniere et al., 1995). Leaves, reproductive structures, twigs, branches and bark fall as forest-floor litter, and their myriad kinds of organic molecules serve not only to feed and provide habitat for organisms dwelling on the forest floor but to reduce evaporative losses and enrich both the organic and nutrient contents of soil.

The CO_2 cycle as it would hypothetically function in the absence of terrestrial biota can be seen as an exchange of CO_2 between the earth and its atmosphere, between gaseous and dissolved forms. CO_2 compared to most gases is remarkably soluble in water, and oceans are by far the major C sink, dissolved CO_2 (or 'carbonic acid', H_2CO_3) being converted into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. At sea level (760 mm pressure), the solubility, in ml CO_2 per 100 ml H_2O, is 171 at 0 °C and 88 at 20 °C (Budavari, 1989). Although CO_2 solubility increases as temperature decreases, it decreases with reduced pressure (i.e., elevation), so cloud precipitation rarely contains its full entitlement when it hits the earth. Nevertheless, atmospheric CO_2 literally falls onto Canadian soil every time it rains or snows, particularly abundantly during the winter months. Some attempt at quantifying annual total precipitation for Canada has been made (Hofman et al., 1998), but there evidently are no estimates of the magnitude of the associated C input. Precipitation C input will presumably increase if, as has been widely predicted, atmospheric CO_2 concentration increases over the coming century. Hofman et al. (1998) have summarized speculation about the many negative impacts this might have on ecosystems.

CO_2 is about 1.5 times as dense as air. In the absence of ground-level turbulence – a not uncommon occurrence in forest ecosystems particularly at night – atmospheric CO_2 density equilibrates to become most concentrated at the forest floor. Healthy forest soils are full of life, and respiration also contributes to the higher CO_2 concentrations that are almost invariably found at ground level. The C content in undisturbed forest soils is known to be high (Tarnocai, 1996); however, little is known about how elevated forest floor CO_2 levels influence soil C content and impact ecosystem functioning and health.

Forest soil generally is viewed as a major sink for insoluble organic carbon derived from litter and leachates, but the direct contribution made by precipitation CO_2 remains uncertain (Hofman et al., 1998). As indicated in Figure 1, dissolved CO_2 on the forest floor and within the soil can serve for metabolism and growth, CO_2 reduction in this case being driven dark-fixation enzymes, such as carbonic anhydrase, phosphoenolpyruvate carboxylase and various biotin-dependent enzymes, rather than enzymes of photosynthesis (Forneris and Savidge 2000). Dark-fixation enzymes are well established to be of common occurrence, not only in roots and other non-green tissues of green plants but in fungi, bacteria, and soil fauna. Inorganic C, as H_2CO_3 and HCO_3 serves to feed the soil biota, modify soil pH, warm the soil, influence root growth, and modify the inorganic environment of the soil during all seasons.

CO_2 assimilated through photosynthesis undoubtedly is the major component of forest ecosystem sink strength (Figures 1, 2). The CO_2 is reduced into C skeletons of water-soluble carbohydrates ("sugars"). To satisfy the energy demand needed to drive carbon reduction biochemistry, a large proportion of that soluble carbohydrate necessarily is oxidized to CO_2 through processes generically referred to as 'respiration.' Dark respiration (so called because, unlike photorespiration, it can occur in both darkness and light) and photorespiration are the principal mechanisms of CO_2 release in leaves and needles. The soluble carbohydrates not oxidized accumulate primarily as insoluble starch during warm daylight hours, and during the cooler night hours the starch is hydrolyzed back to soluble sugar which is exported from the leaves and translocated throughout the tree to support production of stable water-insoluble C compounds (i.e., biomass). CO_2 is also lost through dark respiration from non-green stem and root tissues, but in contrast to leaves and points of primary growth, the major respiratory pathways of secondary growth (i.e., wood formation) include the oxidative pentose phosphate and shikimic acid pathways (Figure 2). Tropical tree species are notably different from Canadian species in having high and strategically placed dark-fixation capacity, serving to minimize photorespiratory losses from their leaves and enabling them to tolerate warmer climates. However, as noted above, dark-fixation enzymes also function in temperate-zone species, although their contribution to reducing respiratory losses throughout the tree remains little known (Forneris and Savidge, 2000).

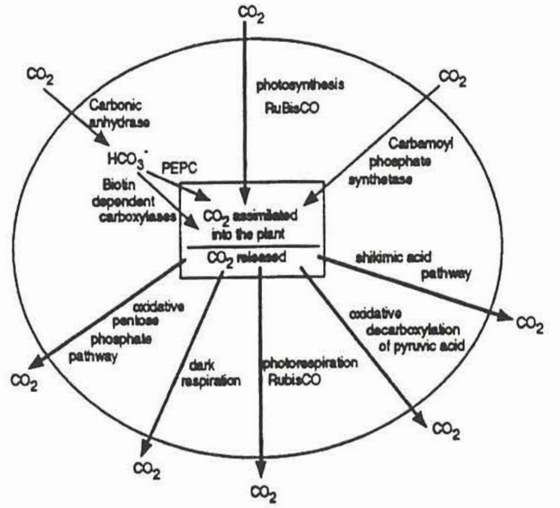

Figure 2. Some of the carbon cycle biochemistry occurring within forest organisms. RuBisCO, ribulose *bis*phosphate carboxylase/oxygenase, the key enzyme underlying both photosynthesis and photorespiration, is considered to be the most abundant biochemical catalyst on earth. RuBisCO catalytic activity is restricted to chloroplast-containing (i.e., green) plant cells exposed to light. Non-green plant cells (e.g., cambial and root cells), and cells of animals and microorganisms, share with green plant tissues the other CO_2 -fixing and -releasing pathways indicated in this figure. Net carbon assimilation is the difference between the number of CO_2 molecules assimilated and released. PEPC, phospho*enol*pyruvate carboxylase, HCO_3^-, bicarbonate anion (after Forneris and Savidge, 2000).

The enzyme ribulose 1,5-diphosphate carboxylase/oxygenase is the key enzyme fixing CO_2 during photosynthesis in our Canadian tree species (Figure 2). However, RuBisCO is a dual function enzyme also catalysing photorespiratory release of CO_2 (RubisCO, Figure 2). Depending on environmental conditions, as much as 50% of gross CO_2 fixation can immediately be lost through photorespiration, but the losses can be minimized by growing trees under conditions where fixation prevails over photorespiration. Within a given light environment, whether RuBisCO fixes or releases CO_2 is largely determined by temperature and CO_2 availability, as they prevail immediately around RuBisCO. As temperature rises, the catalytic activity of RuBisCO in support of photorespiration is strongly favoured over its alternative catalytic activity as a CO_2 –fixing 'carboxylase.' As CO_2 concentration in photosynthetic cells increases, carboxylase activity is enhanced to the detriment of photorespiratory activity.

From first principles, therefore, a biochemical rationale exists for forestry to manipulate CO_2 assimilation through silvicultural practice. In Canadian tree species, respiratory losses overbalance photosynthetic gains when the temperature exceeds 30 °C. Thus, there can be no question that a key management objective, particularly in the face of the extreme global warming predicted for Canada over the next century (Maarouf et al., 1998), should be to maintain tree crowns cool during the growing season. Clearcuts are typified by intense late spring and mid-summer temperatures, and conifer needles are known to reach temperatures higher than 40 °C under such conditions. Moreover, relative humidity is low and evaporation losses are maximal in clearcuts, particularly when competing vegetation is removed. When water becomes limiting in needles or leaves, it leads to stomatal closure, shutting the door on atmospheric CO_2 uptake. Thus, drought-induced reductions in the CO_2:O_2 ratio of needles or leaves augment their CO_2 losses. Conversely, under shaded, higher humidity conditions created by a closed canopy environment, temperatures remain relatively cool, reducing the rate of dark respiration. The overshadowing canopy and undisturbed forest floor are also conducive to soil moisture content remaining relatively high. Consequently, CO_2 uptake and fixation are favoured, and evapotranspiration and photorespiration are reduced.

The present trend in Canada appears to be away from clearcutting toward selection cutting and shelterwood harvesting. If that trend continues and management focuses on shade-tolerant species and perpetual maintenance of closed-canopy stands, there can be no doubt that such a policy will aid existing tree species to continue within their present boundaries, and it will concomitantly minimize forest ecosystem greenhouse gas emissions and facilitate diameter growth in trees. Perpetual maintenance of closed-canopy stands will also confer immeasurable hydrological and habitat benefits in what otherwise is likely to become a parched landscape (Brown et al., 2001).

CO_2 Fixation and Wood Formation

In the language of plant physiology, locations such as green leaves where water-soluble sugars are synthesized are called "sources," and growing regions where those sugars (otherwise known as 'photosynthate') are used are termed "sinks". By analogy with the kitchen sink, the leaf or needle is the more-or-less open faucet, while organic compounds dissolved in water are the outflow streaming from that faucet through the piping of the tree. The sink comprises the cells accumulating the outflow in support of growth, and each has a drain plug in the form of its metabolism. Primary growth sinks include shoots, roots, developing leaves and reproductive structures, and during secondary or diameter growth the cambium and living cells in bark and wood are also sinks. The concept of 'sink strength' implies that the several sinks within the individual plant are not simply passively filled in parallel, rather have the wherewithal to attract and even modify the direction of movement of the outflow. In general, the phenology of Canadian trees reveals new roots growing in early spring, new shoots and reproductive structures in late spring and early summer, followed by another surge of root growth in late summer and early autumn. Depending on the species, cambial growth is or is not in synchrony with primary growth (Savidge and Wareing, 1981). The annual pattern of growth is highly repeatable in each species, clear evidence that the source outflow is indeed partitioned both spatially and temporally, and that the partitioning has a genetic basis.

Cambial growth is the primary mechanism for accumulating C (in wood) in branches and boles of trees. Thus, cambium has long been the primary producer of Canada's real wealth. Cambium is nevertheless a weak sink relative to roots, shoots and reproductive growing points. The available data (limited to a few $^{14}CO_2$ studies) indicates that more than half of the net photosynthate is translocated to the root system, where most of it is allocated to primary extension and exploitation of the soil environment. A relatively small fraction accumulates through secondary growth as woody biomass. Thus, the root system appears to be the strongest sink in forest trees. In addition to supporting root growth and maintenance metabolism, carbon skeletons allocated to roots fulfil two major functions:

- Enzymes combine the translocated sugars with nitrogen to produce amino acids which flow in the transpiration stream to the crown of the tree in support of above-ground growth; and
- Organic material is secreted from root tips and serves to maintain symbiotic relations with microorganisms in the rhizosphere.

The above analysis of relative sink strengths of shoot and root systems is based on research with small trees. As indicated in Figure 3, at a size or age (that varies by species) in the life of each tree, the above-ground system emerges as the better endowed end in terms of biomass. Do those biomass adjustments signal that sink strengths of the opposing poles have changed once a certain age, or stage of development, has been achieved, or is the dominance of the root sink maintained but secondary growth simply not a priority for the root system? Pathetically little is known about root – shoot photosynthate allocations as trees increase in size.

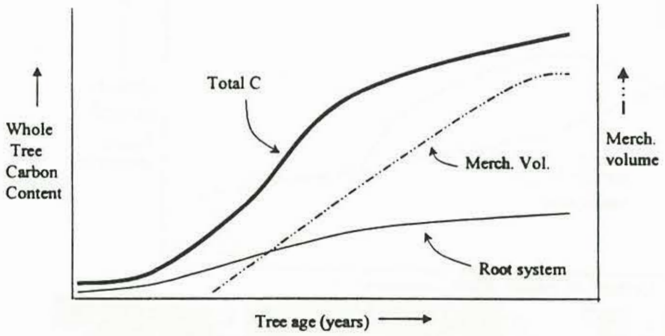

Figure 3. General representation of how biomass (thus, C content) between shoot and root systems changes with age, also showing the merchantable volume of wood in the bole.

The physiological explanation for the weak sink strength of cambium in above-ground parts of trees remains unknown. Indeed, very little of anything is understood with any finality in relation to wood formation (Savidge 2001). Sugar exported from leaves is translocated through phloem elements only a few cells removed from cambium and, in view of the abundant photosynthate allocated to roots, the strength of the cambial sink appears to be governed by the mechanism(s) controlling phloem unloading (Sauter 2000; van Bel and Ehlers 2000). Cambium sink strength, like that of buds and root apices, varies seasonally, but during cambial growth the cambium is sensitive to changing environments, reducing to zero in response to drought and temperature extremes, and increasing strongly when water is not limiting and warm day temperatures are followed by cool night temperatures.

Photosynthetic rates in sun and shade leaves in various Canadian tree species were recently reported (Catovsky and Bazzaz, 2000). In general that study confirmed earlier data indicating that shaded leaves and older needles capture CO_2 at lower rates than sun-exposed leaves and young needles, regardless of the season. The danger is that such findings may be projected, as they erroneously have in the past, to biomass accumulation in the tree: simplistically, young leaves and needles exposed to sunlight supposedly contribute more to wood formation than shaded leaves or older needles.

In fact, photosynthesis and wood formation are not at all tightly linked. Leaves and needles which through photosynthesis measurements are found to be below the compensation point (i.e., the point where CO_2 assimilated just equals respiratory losses of CO_2) are nevertheless fully capable of strongly promoting wood formation. The evidence indicates that older leaves and needles although less efficient photosynthetically make the greater contribution to woody biomass accumulation, whereas the younger foliage principally supports height growth, branch and root elongation and reproductive development (Kramer and Kozlowski, 1979; Savidge and Wareing, 1981; Savidge, 1985).

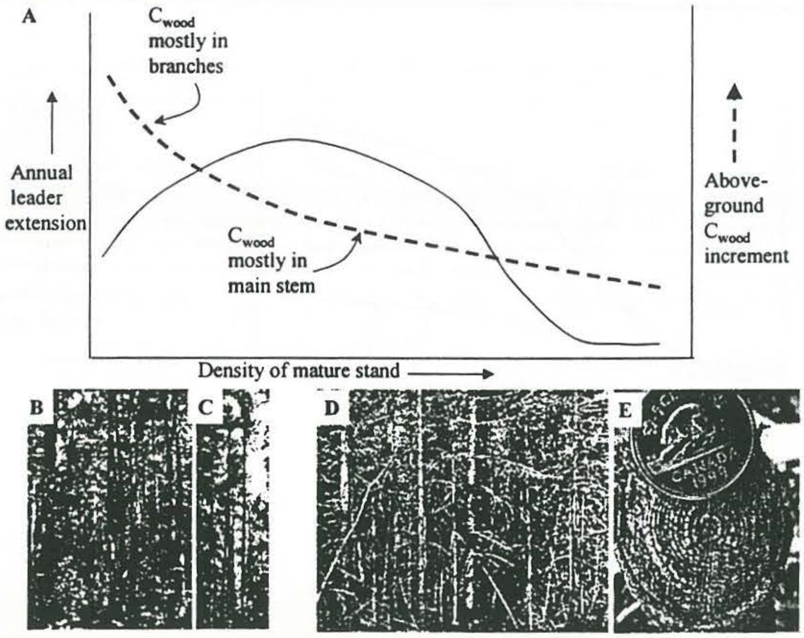

Figure 4. Height growth and C allocation to wood as functions of stand density. A) Height growth rate is reduced in deference to branch growth in open-grown trees. Leader extension is favored when trees are grown together but not too densely. Maximum biomass and C_{wood} accumulate in open-grown trees; however, biomass and C_{wood} are concentrated in the bole when trees are spaced sufficiently close to shade lower branches. B) Natural black spruce stand showing trees spaced 1 – 3 m apart, sufficient for strong height growth. C) Same stand as B showing tall slender trees with small crowns. D) Natural black spruce stand showing trees spaced 0.1 – 0.5 m apart. At this stocking density leader extension ceased at 4 m height. E) Ground-level stump of a more than 25-year old 'bole' of one of the trees shown in D. Although diameter growth of the main axis takes precedence over both branch and height growth, the rate is severely reduced.

As shown in Figure 4, there are also limits to the idea that secondary growth is favored when leaves or needles are shaded. Trees which cannot keep up with height growth rates of their cohorts, and trees which germinate beneath closed canopies, though fully tolerant of the shaded conditions nevertheless grow slowly in both height and diameter. The former evidently are genetically constrained; they cannot compete and tend not to be invigorated to gain in height after gaps are created through selection harvesting, whereas many of the latter will be released. Trees growing at excessively high stocking densities also grow slowly in both height and diameter (Figure 4). Such stands usually arise following fire, and the severe competition brings out the superior stock. Thinning to favor the larger diameter individuals can be effective.

C_{wood} has its origin in carbohydrate synthesized in photosynthetic tissues, starting with RuBisCO fixation of CO_2 in chloroplasts during daylight hours (Figure 2). The resulting photosynthate translocates as dissolved sugars from green tissue to sites of utilization. Carbohydrates allocated to cambium in support of wood formation are metabolized into polymers (cellulose, hemicelluloses and lignin) of woody cell walls, where the C remains indefinitely stable until the wood is burnt or otherwise oxidized. It is important to recognize that wood formation as a biological process is not rigidly determined, rather manifests as a plastic expression of interactions, at the level of each individual cell, between that cell's genotype and the surrounding environment (Savidge 1996, 2001). For example, branch wood and root wood both tend to be distinct from that of the wood in the tree's bole. "Normal" bole wood is very different in chemistry, hence appearance and properties, from reaction wood, and depending on the tree species the same often applies to sap and heart woods, early and late woods, and various other kinds of woods. Production of cellulose, hemicelluloses, lignin, lipids and other extractives making up wood is known to arise through the activities of distinct biochemical pathways, each of which has gene expression at its heart.

A major concern in contemporary Canadian forest management – one rarely if ever considered previously due to the abundance of mature and overmature stock – attends the increasing appetite of industry for and consumer acceptance of small wood. Now that the large-diameter trees have been largely depleted, plantations in their early years of exponential juvenile growth fragment the landscape. By the year 2030 the majority of such stands will be 50 – 60 years old, large enough to provide lumber. By present standards they will be considered "mature," but they will not have begun to reach either their maximum volume or their full C storage capacity. This early harvesting problem is exacerbated by the fact that consumer demand for the higher qualities of wood (i.e., the more expensive end products) is small, providing little incentive for maintaining growing stock (Figure 5). This represents a fundamental attitude change in society. A century ago and earlier, "mature wood" was the heartwood from the cores of large diameter trees, and the pale sapwood was considered inferior, not worthy of carpentry (Evelyn, 1729). Recycling and refabricating wood and paper represent major societal and industrial opportunities to offset greenhouse gas emissions. Canadians can contribute to the C sink level of the nation by ensuring that paper and wood products have longer in-service lifetimes.

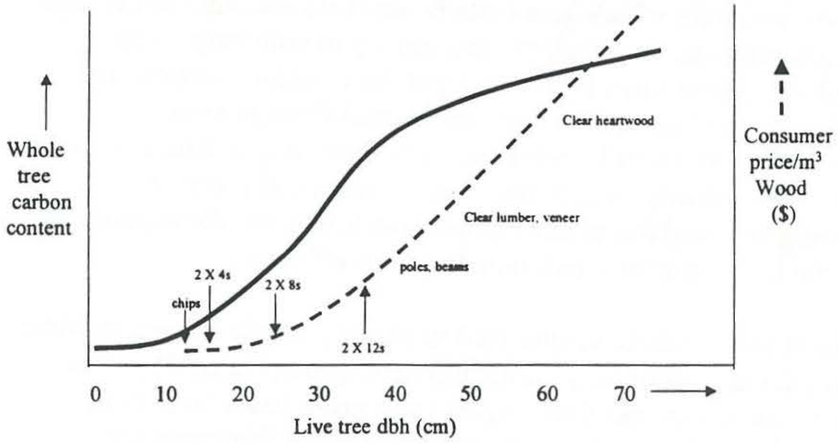

Figure 5. A hypothetical diagram to show whole tree C content and the end cost to consumers as functions of log diameter breast height (dbh).

Carbon content, whether determined as total C_{wood} or the proportion locked up in any particular macromolecular class, can be viewed as the phenotype, determined by an interaction between the genes and the environment. This is the classical concept of G *x* E = P, where G is the genome (or genotype), E is the environment, and P is what we detect, the phenotype. At present, 50% by dry weight is widely promulgated as a generic C_{wood} value. However, it has to be noted that despite more than two centuries of forestry and wood properties research, evidently not a single study has ever specifically addressed the question of variation in total carbon content of wood as it exists in the forest in relation to changes in either G or E. Total C determined by elemental analysis in my laboratory revealed that C_{wood} actually varies substantially among species as well as within individual trees (S. Lamlom and R.A. Savidge, unpublished data). C_{wood} of oven-dried material is significantly lower than C_{wood} when woods are dried at ambient temperature, not surprising but important in relation to the 50% value because evidently all past research on C_{wood} has investigated oven-or kiln-dried woods. Our data indicate that C_{wood} in mature stems of Canadian hardwood species ranges from 46.32 to 49.97 %, and for softwood species from 47.21 to 55.20 %. If this hardwood – softwood C_{wood} difference is universal, there appears to be scope to argue additional C storage capacity in Canadian softwood forests vis-á-vis those of nations growing principally hardwoods.

A general principle in forestry is that anything altering the environment of the tree will also change the properties of its wood. Silviculture, tree improvement and genetic engineering have focussed on modifying not only growth rate (i.e., productivity) but also yield of cellulosic fibres. The impact that selection for those "improved" trees has had on the C_{wood} sink is unknown, C_{wood} being little more than curiousity knowledge until the advent of climate change planning. Cellulose has relatively low C content; thus, it could be that we have inadvertently selected against C_{wood} sink strength. We are currently attempting to determine if changes in total C_{wood} have occurred in response to changing climatic conditions and selection pressures.

Estimating the Mass of Stable Carbon in Canada's Forest Ecosystems

As discussed above, accurate determination by direct measurements of the total C flux balance of a forest ecosystem is not a simple matter. It requires a major ongoing commitment of personnel and resources for data acquisition in the field and application of complex models embodying all kinds of assumptions in the office. In the end, the errors attached to the estimates may be unacceptably large. Canada comprises 997.1 million hectares (ha), with 417.6 in forest, 75.5 as fresh water and 504 as non-forest. Of the 417.6 million ha of forested land, 173 million are classified as unproductive and 244.6 million as productive. A hectare is an area of 100 m X 100 m, approximately the size of two football fields. One hectare well stocked as a closed canopy stand would contain approximately 1000 trees. Thus, a starting point in estimating forest C would be to determine how much C is contained in a single tree, and how that content changes with time. Note that an under or over estimate on a single tree has the potential to be multiplied 1000 X 417.6 million times, so precision and attention to detail (i.e., variation within forest ecosystems) obviously are critically important for accurate estimates.

In forestry the only biomass sufficiently of interest to merit reasonably accurate quantitative estimation at the ecosystem scale has, so far, been the above-ground volume of wood in the boles of trees. Merchantable volume of itself cannot provide an accurate estimate of the total C in living trees within forest ecosystems because roots, branches and small above-ground organs also contain C. Also, the early pre-commercial thinning years tend to be overlooked because of the focus on merchantability. Nevertheless, C in merchantable wood (C_{wood}) is a starting point. C_{wood} estimates allow indirect, low-cost, facile and accurate estimation of the CO_2 sink strength of trees growing in forest ecosystems. The C_{wood} approach does not overestimate, and it enables standardized comparison between forest ecosystems worldwide.

Mass unit conversions:
1 kilogram (Kg) = 10^3 g
1 megagram (Mg) = 10^3 Kg
1 gigagram (Gg) = 10^3 Mg
1 teragram (Tg) = 10^3 Gg
1 petagram (Pg) = 10^3 Tg

1 tonne (t) = 10^3 Kg
1 kilotonne (Kt) = 10^3 t
1 megatonne (Mt) = 10^3 Kt
1 gigatonne (Gt) = 10^3 Mt
1 teratonne (Tt) = 10^3 Gt

Tables 1 and 2 estimate C_{wood} in merchantable timber of softwood and hardwood species on Canada's 244.6 million ha of productive forest lands. Table 1 indicates that Canada has 4.8 X 10^{12} tonnes of C in merchantable softwood, and Table 2 yields 1.6 X 10^{12} tonnes of C in merchantable hardwood, for a total of 6.4 Tt of C_{wood}. To arrive at total C within the living trees, that value could be doubled on the assumption that the C in roots, branches, foliage and other non-merchantable parts is equivalent to that in the bole.

Presently, more than 100 million hectares of Canada's productive forest area consist of immature and regenerating stands, and their C is not included in this estimate of 12.8 Tt of merchantable tree C for the year 1991. In addition, there are 173 million ha of "unproductive" forest land in Canada containing an unknown amount of C. Any complete estimate of forest C must also include the massive amounts contained in soils, peats and waters.

Table 3 indicates that in 1998 Canada extracted 45 million tonnes (45 Mt) of C_{wood} from 0.5% of its more than 244 million hectares (ha) of productive forest area. That annual harvest contained less than 0.001% of the 6.4 Tt of C_{wood} existing in boles of merchantable trees in 1998. If the mass of C_{wood} removed was replaced through the process of wood formation in the remaining trees during 1998, there was no net gain or loss of C_{wood}.

Those figures compare interestingly with what IIASA calculated as the total C flux balance (including both industrial sectors and the terrestrial ecosystem) for Russia in 1990. Russia was a net source of 527 Tg C (1 Tg = 1 Mt). In other words, emissions to the atmosphere exceeded fluxes out of the atmosphere. When the energy and industry sectors were excluded and only the interaction between the atmosphere and the terrestrial ecosystem considered, Russia acted as a sink of –149 Tg C in 1990 (Nilsson et al., 2000), slightly more than three times the mass of merchantable wood extracted in Canada in 1998.

Harvesting over the last three centuries has reduced C content in Canada's productive forests to a level that very likely is well below 50% of their pre-1700 sink capacity. Thus, there is enormous opportunity to gain carbon credits. To refill the sink, it is proposed that a ceiling of 50 million tonnes C_{wood} be set as the annual allowable cut.

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Table 1. Merchantable volumes, biomass and C content of conifer stock growing in Canada, by province and territory, in 1991.

Region	Softwood Volume[1] ($m^3 \times 10^6$)	Wood Biomass[2] ($t \times 10^6$)	C Content[3] ($t \times 10^6$)
NF/Lab.	491 893	221 353	117 316
NS	156 312	70 340	37 280
PEI	16 003	7 201	3 817
NB	434 127	195 357	103 539
QC	2 937 481	1 321 866	700 589
ON	2 399 324	1 079 696	572 239
MB	611 910	275 360	145 941
SK	460 553	207 249	109 842
AB	1 921 627	864 732	458 308
BC	9 883 607	4 447 623	2 357 240
YT	572 298	257 534	136 493
NWT	333 175	149 929	79 462
Canada	20 218 310	9 098 240	4 822 066

1) Source of volume data: *Canada's National Forest Inventory* (CanFI 91, V.94), *Gross merchantable volume on stocked timber productive forest land.*

2) Volume converted to biomass by applying a generic density of 0.45 t m^{-3}. (see Panshin and de Zeeuw 1980)

3) Biomass converted to C content by assuming 0.53 % (w/w) C, as per our data on Canadian woods (Lamlom and Savidge 2001)

Table 2. Merchantable volumes, biomass and C content of hardwood stock growing in Canada, by province and territory, in 1991.

Region	Softwood Volume[1] (m^3 x 10^6)	Wood Biomass[2] (t x 10^6)	C Content[3] (t x 10^6)
NF/Lab.	39 800	19 900	9 552
NS	106 157	63 694	30 573
PEI	10 029	6 017	2 888
NB	211 941	127 165	61 039
QC	1 320 215	792 129	380 222
ON	1 384 017	830 410	398 597
MB	326 049	195 629	93 902
SK	435 192	217 596	104 446
AB	1 198 264	599 132	287 583
BC	711 014	355 507	170 643
YT	65 664	32 832	15 759
NWT	132 861	66 430	31 887
Canada	5 941 203	3 306 441	1 587 091

1) Source of volume data: *Canada's National Forest Inventory* (CanFI 91, V.94), *Gross merchantable volume on stocked timber productive forest land.*

2) Volume converted to biomass by applying a density of 0.50 t m^{-3} to regions having principally poplars and white birch, and a density of 0.60 t m^{-3} to regions growing oaks, maples, ashes, birches and poplars (see Panshin and de Zeeuw 1980)

3) Biomass converted to C content by assuming 0.48 % (w/w) C, as per unpublished data on Canadian woods from my laboratory (S. Lamlom and R.A. Savidge)

Table 3. Mean density, mean C_{wood}, merchantable biomass and C content removed from Canadian forests each year as industrial roundwood, by province and territory.

Region	Mean density[1] (t/m^3)	Mean C_{wood} (% w/w)	Wood removed[2] (t x 10^6)	C removed[3] (t x 10^6)
NF/Lab.	0.46	52.7	0.87	0.46
NS	0.51	50.7	2.96	1.50
PEI	0.51	50.4	0.26	0.13
NB	0.50	50.9	5.76	2.93
QC	0.49	51.4	20.30	10.43
ON	0.50	51.0	11.85	6.04
MN	0.47	51.4	.99	0.51
SK	0.48	50.4	1.97	0.99
AB	0.48	50.7	8.13	4.12
BC	0.44	52.6	33.84	17.80
YT	0.46	52.3	0.12	0.06
NWT	0.52	50.8	0.10	0.05
CANADA			87.15	45.02

Data of Table 3 were derived from a report on *The State of Canada's Forests, 1999-2000 Forests in the New Millennium* (2000): http://www.nrcan.gc.ca/cfs/proj/ppiab/sof/sof00/trend1.shtml. For each Province, that report's figure of industrial roundwood volume harvested in a single year was the starting point. Unfortunately, the year varied (1997, 1998, or 1999) depending on the Province. To estimate the mass harvested, mean density was calculated on the assumptions that "softwood" density is 0.45 g cm^{-3}, "mixedwood" density 0.5 g cm^{-3}, and "hardwood" density 0.6 g cm^{-3}, and that the proportion of each being harvested was equivalent to its relative abundance. Mean C_{wood} percentages were calculated using unpublished data from my laboratory on the simplified basis that "softwood" contains 53% C, "mixedwood" 50% C and "hardwood" 47% C, and assuming that the proportion of each type being harvested was equivalent to its relative abundance. Note that the harvest level for fuelwood or firewood is not included; the report notes that for a single province it may range as high as "2.2 million m^3".

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