CARBON RESERVES, CARBON CYCLING, AND HARVESTING EFFECTS IN THREE MATURE FOREST TYPES IN CANADA

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ABSTRACT

Three, mature, natural forest ecosystems on typical sites north and east of Lake Superior, Ontario, Canada, were contrasted in terms of their content and distribution of organic carbon (C). Total carbon reserves were lowest in an approximately 62-year-old jack pine *(Pinus banksiana* Lamb.) stand on a sandy outwash soil, highest in an old-growth (up to 300 years) sugar maple *(Acer saccharum* Marsh.) stand on an upland till soil, and intermediate in an approximately 110-year-old black spruce *(Picea mariana* [Mill.] B.S.P.) stand on a shallow upland till soil.

Annual net carbon fixation was substantially higher in the sugar maple than in the jack pine stand. Allocation of assimilated carbon varied: in the sugar maple stand, greater amounts went to the formation of leaves and fine roots; in the jack pine stand, new carbon was apportioned in the order—woody biomass > leaves > roots > flowers and fruits. Calculations of residence time (taking into account litter, fine root, and solution inputs) suggest that turnover of carbon is approximately three times more rapid in the sugar maple than in the jack pine forest floor. Residual carbon (taking into account inputs, accretion, and losses) for return to the atmosphere was likewise approximately three times greater in the sugar maple than in the jack pine forest floor. If not for respiration, all subsoil organic carbon could be accounted for by leaching inputs less outputs in approximately 100 years, indicating rapid turnover of carbon in the subsoil as well.

Removal of carbon by different harvesting methods was calculated. In general, conventional (shortwood or tree-length) systems would result in removals of approximately 20% of the total (organic) carbon reserve from either the maple or the spruce site, with more intensive harvesting systems removing up to 32–35%. In contrast, conventional harvesting in the pine stand would remove approximately 33% of the total carbon, with more intensive regimes removing around 38–44%. The impact of site preparation method varied. Jack pine and black spruce sites could be susceptible to fertility loss as a result of full-tree harvesting because of the large amounts of carbon and nutrients stored in the forest floor rather than in the mineral soil.

Keywords: biomass; forest floor; growth; primary production; productivity; *Acer saccharum*; *Pinus mariana*; *Pinus banksiana*.

INTRODUCTION

Jack pine and black spruce are major component species of the Boreal Forest Region (Rowe 1972) of northern Ontario, Canada. Together, they account for approximately 85% of the total softwood used by the area's extensive pulp and paper and lumber industries (Ontario Ministry of Natural Resources 1990). Both species occur naturally on a variety of sites, often in even-acred, disturbance-origin stands; jack pine is frequently associated with outwash sands and black spruce with upland tills. Sugar maple, on the other hand, is restricted mainly to the tolerant hardwood-dominated Great Lakes–St. Lawrence Forest Region (Rowe 1972), which extends on to the southern portion of the Precambrian Shield.

There, sugar maple is typically the dominant species in old-growth hardwood stands, with admixtures of species such as yellow birch *(Betula alleghaniensis* Britton), white spruce *(P. glauca* [Moench] Voss), or white pine *(Pinus strobus* L.). In the Turkey Lakes Watershed, which supports forest typical of the area, maples account for approximately 90% of the basal area of stands on upland sites (Jeffries *et al.* 1988). Where undisturbed, such stands are often uneven-aged to all-aged, and trees 250–300 years old are not unusual. While stem decay is common in Precambrian Shield sugar maple, the resource is nonetheless utilised extensively for lumber and veneer production.

Growth and nutrition of jack pine, principally on outwash sands, and of black spruce and sugar maple on shallow upland tills, have commanded our attention for some years. Questions have been raised regarding organic matter and nutrient losses associated with different harvesting and site preparation practices (Foster & Morrison 1987, 1989; Morrison 1990; Morrison & Foster 1979).

Forest managers have generally been indifferent to the role of organic matter in maintaining soil fertility. In harvesting, organic residues have been variously left on or removed from sites, influenced for the most part by operational considerations alone. The general replacement of conventional (shortwood or tree-length) logging, which leaves tops and branches on site, with "full-tree" logging, in which the entire above-ground portion is removed to roadside for delimbing, met little opposition from silviculturists, who frequently perceived excessive slash as an impediment to stand re-establishment. It has been suggested, however, that excessive removal of organic matter from sites already low in organic matter (such as many jack pine sites) may compromise the build-up of organic matter in the soil and, in the long term, lead to lower site productivity (Morrison & Foster 1979). It has also been suggested that, under conditions of humus accumulation as a result of slow turnover, excessive removal of logging residues may prolong the period of litter breakdown after harvesting by restricting the nutrient supply to decomposition organisms, thereby compromising site productivity (Maliondo 1988).

More recently, observed increases in atmospheric carbon dioxide (CO_2) concentrations have focused attention on cycling of carbon in forest ecosystems, and on the potential impact of changing climate on forests (Harrington 1987). The role of forests and forestry in regulating atmospheric carbon dioxide has been discussed by a number of authors (Pollard 1985; Hendrickson 1990).

Documenting the carbon cycle in forest ecosystems is basic to understanding the role of soil organic matter in long-term forest productivity, as well as the role of forests in the global carbon cycle. The purposes of the present paper are (1) to document and compare the quantities and distribution of carbon in different components of three typical, mature, natural forest ecosystems in northern Ontario; (2) to compare patterns of carbon fixation and carbon cycling therein; and (3) to compare the outcomes of different harvesting intensities on carbon reserves.

STUDY AREAS

The jack pine study site (Table 1) was located approximately 25 km south-south-east of Chapleau, in northern Ontario (lat. 47°38'N, long. 83°15'W), within the Missinaibi-Cabonga Section of the Boreal Forest Region (Rowe 1972), and the Height-of-Land (between the Great Lakes and Arctic watersheds) Climatic Region (Chapman 1953). The average length of growing season, based on a 5.5°C index, is 161 days, roughly May through September inclusive. Mean total precipitation measured at the nearest weather station (Chapleau) was 834 mm annually, with approximately 53% of this falling during the growing season (Environment Canada 1982). Potential evapotranspiration has been estimated at approximately 480 mm annually (Chapman 1953). The soil, classified as Sultan sand, was an Orthic Dystric Brunisol (Canada Soil Survey Committee 1978) and has developed in silt loam over deep loamy sand of granitic origin, the latter commencing at a depth of approximately 30 cm below the organic-mineral interface. The stand was a typical, undisturbed, natural pinery, dating from a 1922 fire, making it 62 years of age at the time of study.

The black spruce site (Table 1) was located approximately 25 km east of Lake Nipigon (lat. 49°30'N, long. 87°50'W), within the Central Plateau Section of the Boreal Forest Region (Rowe 1972) and the Height-of-Land Climatic Region (Chapman 1953). The average length of the growing season was 152 days, roughly early May through early October. Mean total precipitation measured at the nearest weather station (Beardmore, Ontario) was 784 mm per annum with approximately 50% of this falling during the growing season (Environment Canada 1982). Potential evapotranspiration has been estimated at approximately 480 mm annually (Chapman 1953). The study stand occupied a gentle south-facing slope. The soil, an Orthic Humo Ferric Podzol (Canada Soil Survey Committee 1978), has developed in a shallow, stony silt ablation till over a compact sandy basal till, both of granitic origin. The stand was typical, undisturbed, upland black spruce of fire origin, dated at 110 years of age at the time of study.

The sugar maple site (Table 1) was located on the Turkey Lakes Watershed (lat. 47°03'N, long. 84°25'W), approximately 60 km north of Sault Ste. Marie, Ontario, and approximately 13 km inland from Batchawana Bay on Lake Superior. It was within the Algoma Section of

TABLE 1–Dimensions of mature jack pine, black spruce, and sugar maple stands at the time of the study.

	Jack pine	Black spruce	Sugar maple
Nominal age (years)	62	110	>250
Stocking (stems/ha)	1727	1200	682
Mean dominant height (m)	18.8	19.6	22.1
Mean dbh (cm)	14.7	14.8	19.5
Tree of mean B.A. (cm)	15.2	15.6	23.1
Basal area (m^2/ha)	31.5	23.0	28.6
Gross total volume (m^3/ha)	222.9	178.3	238.2
Gross merch. volume (m^3/ha)	184.4	164.6	219.8

the Great Lakes-St. Lawrence Forest Region (Rowe 1972), and the Superior Climatic Region (Chapman 1953). Total precipitation across the watershed during the 1981–83 period averaged 1300 mm per annum (Barrie *et al.* 1984). Growing season length was estimated at approximately 175 days, roughly from late April to October (Chapman 1953). Potential evapotranspiration was estimated at 500 mm annually (Chapman 1953). The topography was rugged, with approximately 290 m of relief within 1 km. The soil, an Orthic Humo Ferric Podzol (Canada Soil Survey Committee 1978), has developed in a bouldery ablation till of mixed basaltic-granitic origin. The stand was typical, uneven-aged, old-growth, sugar maple forest with yellow birch as a minor component. Individual trees in the stand were dated at >250 years of age.

METHODS

Adaptations of the method of Hegyi (1972) were used to determine tree and stand biomass. Briefly, trees spanning the range of sizes were felled, weighed fresh in the field, then subsampled by component (i.e., foliage, fruit, branches, stem bark, stem wood). The subsamples were sealed to prevent moisture loss, returned to the laboratory, and dried. Conversion factors between dry and fresh weights were determined and used to calculate individual tree dry weights for each component. Logarithmic regressions of tree and component weight on diameter at breast height (dbh) were used in conjunction with plot stand tables to calculate above-ground biomass per hectare. Below-ground tree biomass was likewise determined by the regression-stand table method (Morrison 1974). In the sugar maple stand, soil cores were also used to estimate fine-root production. For the current study, the jack pine regression equations used were based on 27 mature jack pine trees, with per-area biomass contents determined by applying these equations to stand tables derived from nine 0.04-ha permanent sample plots. The black spruce equations were based on 25 trees and were applied to 12 plots of 0.10 ha; equations for jack pine, understorey black spruce, and balsam fir (*Abies balsamea* (L.) Mill.), which formed a minor component of the stand, were also developed and applied separately (Foster & Morrison 1987). The sugar maple equations were based on 34 trees and were applied to four 0.10-ha plots; equations for minor components of yellow birch and other species were determined separately (Morrison 1990). The methods used to calculate the weights of ground vegetation and of litterfall have been described previously (Foster & Morrison 1987; Morrison 1990, 1991). Fallen log weight was determined by sampling and weighing all log material, distinguishable as such, on randomly located subplots distributed across the site. Separately determined carbon concentrations were used to calculate carbon content, by component and stand, from dry weights and were also used to calculate the carbon content of litter.

Forest-floor weights were determined by sampling, drying, and weighing 0.1-m^2 quadrats (Foster & Morrison 1987; Morrison 1990), with organic carbon concentrations determined by both loss-on-ignition and by chromic acid oxidation (Walkley 1947). The latter method was also used to determine organic carbon concentrations in mineral soil, by horizons, to a depth of 1 m (to bedrock in the black spruce stand), with per-area carbon content calculated using horizon weights. Precipitation, throughfall, and percolates were collected using the methods outlined by Foster (1985). Organic carbon concentrations in water were measured with a Technicon Autoanalyzer II system using industrial method number 451-76A/A. Carbon fluxes were calculated as the volume-weighted product of carbon concentration times the measured solution volume flux (or estimated volume flux for soil solution). Estimated soil solution flux was calculated according to a modified water balance equation (Thornthwaite & Mather 1957).

RESULTS

Storage of organic carbon on the sugar m ite (Table 2) greatly exceeded that on either the jack pine or black spruce sites. On all three sites, between 32% and 45% of on-site organic carbon occurred in living vegetation, with the remainder distributed between the forest floor and the mineral soil. Relative to the softwood sites, only a small portion of the total soil carbon on the sugar maple site was localised in the forest floor. The carbon reserve in the mineral soil beneath the sugar maple stand was approximately four times as much as the carbon reserves beneath the pine stand.

Annual net carbon fixation (Table 3) into woody biomass was slightly greater in the jack pine stand than in the sugar maple stand. However, with substantial quantities of carbon

TABLE 2–Carbon content of the vegetation, forest floor, and mineral soil of mature jack pine, black spruce, and sugar maple stands, in northern Ontario, Canada.

Component	Carbon content (kg/ha)		
	Jack pine	Black spruce	Sugar maple
Living trees			
Foliage	2 200	4 600	1 800
Fruit	500	1 700	200
Live branches	4 800	7 800	22 300
Dead branches	1 200	3 000	900
Stem wood	48 000	44 500	61 000
Stem bark	4 900	7 000	9 500
Stumps & roots	10 000	20 400	16 100
Total (living trees)	71 600	89 000	111 800
Ground vegetation	400	700	600
Dead trees, logs	19 800	1 800	5 400
Forest floor	20 300	69 600	16 100
Mineral soil	48 900	90 200	214 300
Total (all components)	161 000	251 300	348 200

TABLE 3–Net carbon fixation by mature jack pine and sugar maple stands, northern Ontario, Canada.

Component	Net carbon fixation (kg/ha/yr)	
	Jack pine	Sugar maple
Trees		
Woody biomass*	1790	1190
Leaves	731	1756
Flowers & fruits	150	134
Fine roots	529	2506
Total (trees)	3200	5505
Lesser vegetation	NA	75
Total fixed	3200	5580

* Based on gross growth.

going into the production of deciduous parts (mainly foliage and fine roots) in the sugar maple stand, overall net carbon fixation was substantially greater in that stand.

Transfers of organic carbon in solution are shown in Table 4. Taken as the difference between inputs and outputs, more organic carbon was leached from the sugar maple than from the jack pine canopy, whereas more organic carbon was removed from the jack pine than the sugar maple forest floor. On an annual basis, approximately equal amounts of organic carbon were leached from the overlying organic material into the mineral soil, with considerable retention in the uppermost mineral horizons.

Potential quantities and proportions of total carbon that could be removed from the sites using different harvesting options are given in Table 5. The options range from conventional (shortwood or tree-length) systems, in which only stems are removed, through full-tree harvesting, in which all above-ground parts are taken, to "complete-tree" harvesting, an extreme method in which even roots are extracted and removed. In the jack pine stand, conventional and full-tree harvesting could potentially remove 33% and 38%, respectively, of the total organic matter from the site.

TABLE 4–Total organic carbon flux in solution in mature jack pine and sugar maple stands, northern Ontario, Canada.

Solution	Organic carbon flux (kg/ha/yr)	
	Jack pine	Sugar maple
Precipitation	16.1	13.6
Throughfall	37.6	86.6
Forest floor	218.7	228.1
Soil (10 cm)	–	54.7
Soil (15 cm)	35.7	–
Soil (30 cm)	13.6	32.2
Soil (60 cm)	–	24.8

TABLE 5–Quantities and proportions of total carbon reserves removed from stands by conventional (stems only), full-tree, and complete-tree harvesting.

	Total carbon reserve (kg/ha)*		
	Jack pine	Black spruce	Sugar maple
Conventional†	52 900 (33%)	51 500 (20%)	70 500 (20%)
Full-tree	61 600 (38%)	68 600 (27%)	95 700 (27%)
Complete-tree	71 600 (44%)	89 000 (35%)	111 800 (32%)

* Percentage of total in parentheses.

† Shortwood or tree-length.

DISCUSSION

In terms of general order of magnitude, both the carbon content and net primary production (herein, "carbon fixation") data from the current study were similar to the values assembled by Powers & Van Cleve (1991) for semiboreal and cool-temperate forests. Differences in both carbon content and growth among the three stands in this study (all of which were at the same stage of maturity, were similarly stocked, and were on sites typical for their species) emphasise the need for caution, however, when preparing regional estimates.

Remeasurements of sample plots on the sugar maple and jack pine sites, for example, indicated little change in total yield over the respective study periods, with mortality offset by growth. On the sugar maple site, there was only a slight net gain in biomass of approximately 400 kg/ha (Morrison 1990) over a 5-year period in the early 1980s, while a net loss of approximately 2900 kg/ha occurred on the jack pine site over the same period of time. Gross growth, however, was substantial on both sites, with approximately 17 700 and 12 200 kg of living woody matter produced per hectare over 5 years by the jack pine and sugar maple stands, respectively. In addition to perennial woody matter, substantial carbon is also fixed annually in deciduous parts such as leaves, flowers, fruits, and fine roots. Together, the various processes accounted for the fixation of approximately 3200 kg C/ha/yr on the jack pine site and approximately 5580 kg C/ha/yr on the sugar maple site (Table 3), representing an annual removal of 11 700 kg CO_2 from the atmosphere for each hectare of mature jack pine and 20 400 kg CO_2 for each hectare of mature sugar maple forest.

The 3200 and 5580 kg C/ha, approximately, fixed annually by the jack pine and sugar maple stands, respectively, eventually reach their forest floors as annual litterfall, root turnover, or dead trees. For the sugar maple and jack pine stands, residence times of carbon in the forest floor (an index of the rate of turnover) can be calculated. For the sugar maple stand, there is an annual input of 3730 kg organic matter/ha/yr to the forest floor in litter of all types (Morrison 1991), the equivalent of approximately 1865 kg C/ha/yr. To this may be added a contribution from root decay (for those roots in the forest floor), estimated at 693 kg C/ha/yr (based on sequential sampling of fine roots), and a small but significant contribution of organic carbon in throughfall, amounting to 73 kg/ha/yr. Total input is thus 2631 kg C/ha/yr. Dividing this figure into the total weight of organic carbon in the forest floor (16 072 kg/ha) yields a residence time of approximately 6 years. For the jack pine stand, a similar calculation can be made: the annual input of carbon in litter from the above-ground parts = 1048 kg/ha/yr; in root slough = 146 kg/ha/yr; in solution = 21 kg/ha/yr. Thus, total input is 1215 kg C/ha/yr. Dividing this figure into the total weight of organic carbon in the forest floor (20 270 kg/ha) yields a residence time of approximately 17 years, or about three times that of the sugar maple stand. Similar data were not available for the black spruce stand; however, with a forest floor that contains some 69 600 kg organic C/ha, an even longer residence time could be expected.

Although it was convenient to consider the forest floor as non-aggrading for the purpose of the above calculation, there was, in fact, some increase in forest floor weight over time. In 1991, the forest floor of the jack pine stand was estimated to contain 20 300 kg organic C/ha *versus* 15 600 kg/ha 20 years earlier, an increase of 4700 kg C/ha, for an average annual accretion of 235 kg/ha/yr. Combining this figure with an average annual loss through leaching of 219 kg C/ha/yr (Table 4) and, in turn, subtracting these from the average input total (above) leaves 761 kg C/ha/yr as the amount presumably oxidised and returned to the atmosphere as carbon dioxide. Making a similar calculation for the sugar maple stand (using an average annual accretion in the forest floor of 64 kg C/ha/yr), the average annual return to the atmosphere would be 2339 kg C/ha/yr, approximately three times greater than for jack pine. Carbon removed from the forest floor through respiration exceeded that lost through leaching in both the jack pine and sugar maple stands. In the jack pine stand, however, aqueous transport accounted for approximately 22% of the loss in comparison with less than 10% for the sugar maple stand. In another comparison, the ratio of carbon respired to that fixed within the jack pine forest floor was approximately 3:1; in the sugar maple forest floor it was approximately 36:1. This greater turnover by the sugar maple forest floor is presumably consistent with its greater nitrogen content (Foster 1989). Carbon dioxide returned to the atmosphere annually through forest-floor respiration, then, should be of the order of 2800 and 8600 kg C/ha for jack pine and sugar maple forests, respectively. These figures are generally less than those obtained from direct measurements of soil respiration in other forest systems (e.g., Reiners 1968; Schlentner & Van Cleve 1985). However, the present estimates are probably comparable in that (1) they do not include root respiration, which can account for 50% or more of soil respiration (Wiant 1967; Hendrickson & Robinson 1984), and (2) they do not include subsoil respiration.

All sites exhibited podzolic-type soils with a distinct LFH layer with minimal faunal mixing, such that accretion of carbon in the subsoil would be by downward movement in solution and by root decay. Were it not for respiration, and barring other losses, the entire carbon content in the subsoil of either the jack pine or the sugar maple stand could be accounted for in approximately 100 years as follows: the standing stock of carbon in the subsoil divided by the sum of the annual input of carbon by leaching plus input by subsoil roots less that lost by deep leaching. The fact that the entire carbon content could be accounted for in so short a time, even though the soils have been developing for a much longer period, suggests a fairly rapid carbon turnover in the subsoil as well. As solution inputs were similar between the jack pine and sugar maple sites (Table 4), the difference in carbon accumulation is probably more related to root decay than to solution input. Wildfires probably have some effect in reducing forest-floor organic matter in jack pine stands, although if solution transport is not the major source of subsoil carbon, it is difficult to see how even repeated fires could account for the very low (subsoil) carbon reserves commonly associated with natural jack pine stands. Indirectly, however, impoverishment of soils with respect to other elements (possibly nitrogen) as a result of fire can produce less-vigorous root growth, which may be related to lower levels of subsoil carbon.

Considering removals by harvesting (Table 5), approximately 20% of on-site carbon would be removed from either the sugar maple or black spruce sites and approximately 33% from the jack pine site by conventional (stems only) logging, exclusive of further site preparation. With the increasingly common "full-tree" option, these values increase to 27% and 38%, respectively. As well as removing more organic matter in total than conventional harvesting, full-tree systems remove much of the readily decomposable foliage and fine branch slash, leaving a surface dominated by mainly recalcitrant forms of carbon only. Shear-piling (using shear blades and rakes to remove surface debris from the planting site and pile it into windrows) in combination with full-tree logging could reduce total carbon on the jack pine, black spruce, and sugar maple sites by 63%, 56%, and 34% of the original carbon reserves, respectively. However, if solution transport is not the major source of subsoil carbon, as above, any adverse effects of excessive forest-floor removal are more likely to be related to nutrients than to carbon.

Some advantages in response to both soil fertility and climatic concerns could occur as a result of on-site conservation of organic carbon, though the same strategies might not work in all instances. For example, maintaining high levels of growing stock might have distinct advantages so far as reducing atmospheric carbon dioxide, but would probably have little effect on maintaining site fertility. Leaving slash distributed evenly over a site after harvest could have advantages with respect to fertility maintenance since nutrients contained therein would be rapidly mobilised upon decomposition of the slash. Windrowing or piling it might be a preferable option in terms of sequestering carbon since decomposition of slash piles would be slower. However, incorporating at least part of the forest floor into the underlying mineral soil may possibly be an advantageous option in most cases.

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BOOK REVIEW

PINUS RADIATA—BIOMASS, FORM AND GROWTH

by H. A. I. Madgwick

Published by H.A.I.Madgwick, 36 Selwyn Road, Rotorua, New Zealand. 1994. 428 pages.
ISBN 0-473-02375-X. NZ$50-00 (Australia, A$50-00; W.Europe, £25-00; other, US$45-00)

Students of the worldwide literature dealing with forest biomass research over the past several decades will know that H.A.I.Madgwick has published some of the most significant manuscripts on the subject. The book "*Pinus radiata*—Biomass, Form and Growth" is no exception, and has been written with the thorough approach and style typical of Madgwick. Beyond its high value as a comprehensive compilation, the greatest significance of this work is in the quantitative synthesis and critique of the worldwide literature on biomass, form, and growth of *Pinus radiata* that has been provided for each subject area addressed.

In the foreword, Madgwick has highlighted that one of the biggest problems associated with a synthesis of the literature arises from the inconsistencies in methodology used in forestry research. This problem was addressed by the International Union of Forestry Research Organizations (IUFRO) working party on forest biomass studies in several proceedings published in the early 1970s by Dr. Harold E. Young, University of Maine at Orono, and colleagues. However, it appears that their call for standardisation in units of measure has been ignored. The problem is greatest, of course, when one attempts to ask common questions of all published research in any subject area. Many researchers have not reached the point in their careers where they have attempted something the magnitude of this book, so will not have realised the pitfalls of taking a novel approach to their measurements. Perhaps this is a reflection on the urgency of the times, or on the failure of many scientists to synthesise the literature before undertaking an area of investigation. Perhaps repeating the plea for increased consistency in forestry research methodology will have an impact in the future. Madgwick has tried to overcome the inconsistencies by standardising the units in the book, and using oven-dry weights, unless otherwise noted, and converting all logarithms to base e.

The original aim of the book was to include all literature on the ecology of *Pinus radiata*. As this proved impossible for this effort, the literature dealing with concentration and content of nutrients in *Pinus radiata*, and cycling of nutrients, organic matter, and water may be compiled in a second volume. We hope so, given the contribution of this book. "*Pinus radiata* - Biomass, Form and Growth" is based on some 1100 publications drawn from books, journals, proceedings, and technical bulletins and reports. The 14 chapters and three appendices include:

I Estimation of Individual Tree Weight;
II Estimation of Stand Weight;

III Biomass of Stands;
IV Tree Form—Stems;
V Tree Form—Foliage;
VI Tree Form—Branches and Cones;
VII Tree Form—Roots;
VIII Stand Form;
IX Growth;
X Site Studies;
XI Physical Factors Affecting Growth;
XII Soil Nutrients Affecting Growth;
XIII Biological Factors Affecting Growth;
XIV Forestry Operations Affecting Growth;
Appendix I Field and Laboratory Methods;
Appendix II Stand Biomass;
Appendix III Mychorrhizae of *Pinus radiata.*

Most chapters follow a similar format, where Madgwick has aggregated the literature according to significant factors affecting the response of *Pinus radiata.* In each subsection, Madgwick has sought unifying theories to explain tree or stand responses, has provided a critique of individual papers and the state of knowledge in each area, and has provided summary recommendations and statements which could serve to stimulate further research. The most significant, and the most personally disappointing, departure from this approach is in Chapter X on "Site Studies" where the text diverged into a list format for nine published papers. It is not clear if this was an oversight or intentional. In any case, the outline format used in Chapter X detracted from an otherwise consistent and useful style found in other chapters. I also found Chapter XI on "Physical Factors Affecting Growth" to be one of the weaker chapters in the book, containing a rather abrupt ending without the customary summary section found in other chapters.

Madgwick published this book in a paperback format on A4 size paper using a word processor. Figures and tables are neat, and easy to comprehend. Most figures have reasonable clarity; however, the symbols on many two dimensional graphs were printed with fine line width and a light tone, which makes them a bit hard to distinguish. Similarity of font in figure and table titles and footnotes and text can detract from the flow of reading afforded by different fonts. Overall, the book contains few technical or typographic errors, and the quality of presentation is very adequate. While commercial publishing and editorial review would have improved the appearance and reduced the number of errors, this should not detract from the significant contribution of the book.

The book will be highly useful to quantitative ecologists, silviculturists, and mensurationists. While *Pinus radiata* is the sole focus, the principles applied and the approach taken to the analysis of the literature are instructive for application to other species. The highly intensive research programme on *Pinus radiata* conducted by New Zealand and Australia must be unequalled by research programmes associated with any other species worldwide. The intensive focus on one species has provided information concerning relationships affecting the growth and development of *Pinus radiata* that may provide useful insight for scientists working with other species. The text is not a fast read, given the highly quantitative treatment of the subject matter. For each subject area, Madgwick has asked questions concerning the assumptions behind the various studies, the state of knowledge, and the bias associated with various estimates. This systematic evaluation of the factors affecting various relationships contributes to the usefulness of this publication. For example, Chapter 1 on "Estimation of Individual Tree Weight" contains a systematic evaluation of how the foliage weight:sapwood ratio (w_f/s_o) varies with variation in age, stocking, pruning, nutrition, and clone.

While the real strengths of the book are to be found in the area of sampling theory and in the statistical evaluation of the quality of various estimates, the wider perspective of an ecologist collaborator might have provided a more sensitive analysis of the ecology of *Pinus radiata*. The potential for improvement can be seen in the treatment of the relationship of foliage mass to various site-related variables in Chapter III on "Biomass of Stands". One might argue that the quantitative style of presentation and synthesis of the literature is not appropriate, or overdone, for some subject areas. For example, in Chapter V on "Tree Form—Foliage", quantitative treatment of the literature on the number of chlorophyll and stomates in tree foliage may not be adequate without consideration of the factors relating to the ecology of the species and the physiological significance of variation in the relevant parameters, as can be found in the physiological ecology literature. Having said that, I should point out that Madgwick frequently comments on the biological relevance of various published equations and models.

For students of forest biomass research, this book will provide valuable insight to the developmental benchmarks of one of the leading scientists in forestry science. We hope the rewards from this effort will stimulate Madgwick to complete the second volume on the ecology of *Pinus radiata*. We hope that the current trend towards confidential reports and private ownership of research results will not preclude the forestry scientific community from insisting that the measure of scientist productivity be based on manuscripts published in internationally available journals. This book would not have been possible without such standards.

C. Tattersall Smith

CORRIGENDUM

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HOW WILL NEW ZEALAND'S FORESTS RESPOND TO CLIMATE CHANGE? POTENTIAL CHANGES IN RESPONSE TO INCREASING TEMPERATURE

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For—

For the 10 most productive sites in the country (defined by a mean annual increment in excess of 40 m^3/ha/year) the mean annual temperature range is between 9.8° and 13.7°C and the mean annual rainfall between 1100 and **1200** mm (New Zealand Meteorological Service 1983).

Read—

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