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PRACE NAUKOWE – RESEARCH PAPERS

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ESTIMATES AND FORECASTS OF FOREST BIOMASS AND CARBON SEQUESTRATION IN NORTH AMERICA AND AUSTRALIA: A FORTY-FIVE YEAR QUEST

A half-century of forest inventory research involving statistically-valid field measurements (using statistically representative sample size and showing confidence limits) and well-validated forecasting methods are reviewed in this paper. Some current procedures overestimate global and large-scale forest biomass, carbon storage, and carbon sequestering rates because they are based on statistically-invalid methods (errors in estimates are unavailable and unreported), or they fail to consider key dynamic characteristics of forests. It is sometimes assumed that old-growth forests can serve as fixed, steady-state storage of biomass and carbon for indefinitely long periods, but it is shown by both modelling and remote sensing that forests are dynamic systems, the state of which can change considerably over as short a time as a decade. Forecasting methods show that maximum biomass and carbon storage in some important forest types occurs in mid-succession, not in old-growth. It is proposed, therefore, that realistic biomass and carbon storage estimates used for carbon credits and offsets be determined as the statistical mean minus the confidence interval and that practical carbon sequestering programs include specific timeframes, not indefinitely long periods of time.

Keywords: Forest modeling, forest inventory, biomass inventory, carbon sequestering, model validation

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Introduction

An invitation from IUFRO to the senior author (Botkin) provided an opportunity to reflect on almost half a century of work in forest ecology. This has involved trying to understand how forests work, to use that understanding to solve forest-related environmental problems, and come to know what our place within forests should be – what would be best both for humans and for forest ecosystems. Because this is primarily a personal research history, it does not attempt to provide an exhaustive review of the fields of study covered, but highlights the long-recognized need for justifiable estimates of forest stocks and growth.

The possible effects of human-induced climate change on forests have been a source of personal concern to the senior author since 1968, leading to the development of the JABOWA forest dynamics model [Botkin et al. 1970], the first well-known gap model. During the last 40 years, many tree-based forest growth models have been developed and evaluated [e.g. Pretzsch et al. 2002; Stage 2003; Valentine, Mäkelä 2005]. However, the JABOWA model concept is still considered valid [Long et al. 2014], is used [Ashraf et al. 2012, 2013] and has formed the basis for many other models [e.g. Monserud 2003; Hanson et al. 2011; Larocque et al. 2011]. The water relations of forests have also been a concern to forest ecologists, including the authors, in different parts of Australia for many years [e.g. Doley 1967; Ngugi et al. 2003]. This work became more relevant with the determination to expand native species hardwood plantations in parts of the country with relatively low rainfall in response to the threat of climate change [Ngugi et al. 2004]. In parallel, government forest management agencies in Queensland, Australia developed one of the most comprehensive long-term forest monitoring systems and databases in the developing world [Beetson et al. 1992]. These data have been used to validate a variant of the JABOWA model and to investigate carbon storage and uptake in selected Australian forests [Ngugi, Botkin 2011; Ngugi et al. 2011, Ngugi et al. 2013].

The need

Concern over the possibility of greenhouse-induced climate change drives the need for more quantitative knowledge of the global carbon cycle, including amounts and rates of change of carbon storage in major biomes. More generally, this knowledge is fundamental to the understanding of the dynamics of Earth's biosphere, which is itself fundamental to Earth System Science. However, in spite of repeated calls by scientists that such knowledge should be obtained, terrestrial ecosystem carbon storage and exchange remain poorly documented [e.g. Detwiler, Hall 1988; Canadell, Mooney 1999; Canadell et al. 2010].

Statistically based estimates of terrestrial carbon stocks have been obtained for only a few large areas, including boreal forests and eastern deciduous forests of North America [Botkin, Simpson 1990; Botkin et al. 1993; Brown et al. 1997; Hollinger 2008] and portions of temperate forests of Australia [Keith et al. 2010; Moroni et al. 2010; Moroni 2012] and tropical forests of the Amazon [Baker et al. 2004]. As a result, discussions about the global carbon cycle [e.g. Thompson et al. 2007] often rely on highly uncertain estimates of the size of national or regional carbon storage [IPCC 2006], and ignore the large range in carbon storage and annual rate of change across an extensive landscape.

The Intergovernmental Panel on Climate Change (IPCC) has compiled detailed biome-averages for carbon storage and uptake for plantation forests in major global biomes, but some of the largest forest areas are occupied by less intensively managed mixed species native forests subjected to varying degrees of disturbance [IPCC 2006]. Therefore, establishing baseline carbon storage and net rate of flux in natural undisturbed and disturbed native forests is crucial to estimating global greenhouse gas emissions and sequestration potential. Since carbon stocks vary across landscapes and vegetation types, a biome-average value cannot represent this variation adequately for an entire region or country [Gibbs et al. 2007], especially in Australia where the forests extend from wet coastal to dry inland regions and from temperate to tropical latitudes.

Ground-based baseline estimates of forest carbon stocks are needed to support carbon sequestration efforts through calibrating and validating remote sensing based estimates of the global carbon cycle and for successful implementation of climate change mitigation policies [Saatchi et al. 2011; Hoover et al. 2012].

Many estimates of carbon stocks are based on forest inventory data [Houghton 2005; Sierra et al. 2007; Mackey et al. 2008; Hu, Wang 2008; Keith et al. 2010; Keith et al. 2009]. However, because carbon stocks of managed or disturbed forests are dynamic in relation to the time since last disturbance, estimates of carbon stocks and changes may be difficult to relate to potential carbon storage.

One point here needs qualification: While global estimates lack the necessary statistical validity, today in the United States there is research in local areas – forested areas covering 12,000 or more hectares – which is following legitimate, scientific and statistical methods based on both combinations of inventories, remote-sensing and biophysical measurements [e.g. Hoover 2008; King et al. 2011; Huntzinger et al. 2012; Ashraf et al. 2013]. But for many smaller areas, the goals remain local and are aimed at selling carbon credits from these forests.

Problems

There are four major problems with existing estimates of forest biomass and carbon storage:

1. A lack in estimates of variance: Many global, biome, and large-area forest storage estimates in use by the IPCC and in major scientific literature are based on estimates without indications of confidence limits. The lack

of any estimate of sampling or observation error makes them scientifically invalid.
2. Not comparable methods: Global estimates use data from a variety of small area estimates, which do not use consistent methods and are therefore not strictly or directly comparable.
3. Data from studies whose purpose was not global biomass or carbon storage: Most of the estimates are from isolated studies not originally carried out to seek large-area estimates.
4. Steady-state old-growth assumptions: Most, perhaps all, estimates assume that storage can be achieved in a steady-state system, stored indefinitely or at least for a very long time.

The solution

1. Develop an international program that uses comparable, if not uniform, methods to estimate forest biomass.
2. Ensure these methods include statistically valid estimates of stocks and confidence intervals.
3. Base realistic estimates of carbon sequestration credits and offsets on agreed calculations, such as the mean minus the confidence interval.
4. Determine how close the international scientific community is to achieving these methodological goals.

The first statistically testable estimates of biomass and carbon storage for any large area of Earth

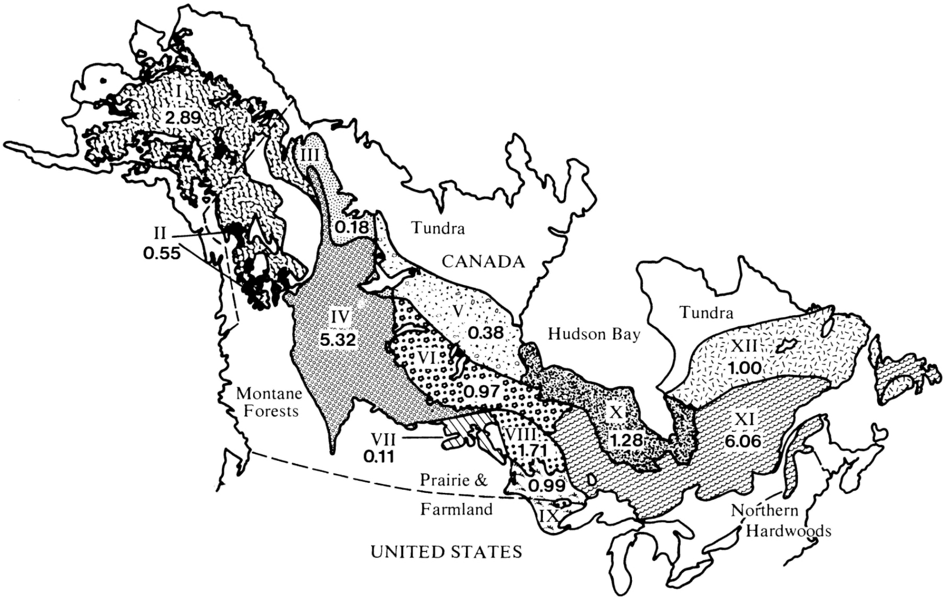
Starting in the 1980s, one of the authors (Botkin) realized that it was necessary to begin to develop statistically testable estimates of biomass and carbon storage for large areas. While the measurement of biomass is conceptually simple, the logistics of a valid sampling scheme over a large area are complex, as has been indicated in recent works [Gregoired Valentine 2008; Mandallaz 2008]. The North American boreal forest was selected for a first estimate because: it was understood to contain a sizable fraction of the Earth's organic matter; it is floristically simple; and, although encompassing some of the most remote regions of the globe, it had good available transportation. Furthermore, oven-dry biomass equations of all trees and most shrubs were available, which greatly simplified measurement procedures.

Direct ground-based measurements involved two steps. The first was dimensional analysis in which the height and diameter of a tree was measured, and then, ideally, cut down and all the parts were weighed. This was repeated for the range of tree sizes found for each tree species of interest. From these data equations were developed to estimate biomass and carbon storage for each tree in a plot, and the sum of all trees was extrapolated to an estimate for a forest.

As discussed in Woods et al. [1991], the most cost-effective and long-term solutions to increasing the precision of biomass estimation are sacrificing more trees to fit models or sampling larger areas of forests. Both of these approaches require investments that many land managers are loath to make. Consequently, caution is necessary when relying solely on results from general allometric estimates, particularly in relation to the implementation of climate change mitigation policies, such as the reduction of emissions from deforestation and degradation [Saatchi et al. 2011].

Field sampling

The second step is to carry out non-destructive sampling. The technique of "survey sampling," commonly used in agriculture and forestry, was employed to obtain reliable estimates of crop yields and timber volumes. Environmental features were used to delineate the outer boundaries of the North American boreal forest region because there is no agreement on the exact present boundaries of the boreal forest in North America. The area was subdivided into 12 strata whose boundaries were defined by climate, geology, and soil patterns (fig. 1). July mean temperature isotherms delineated north and south boundaries; other climatic factors, along with geological and soil features, delineated east-west boundaries. Some strata were also delineated by accessibility as determined by a Canadian study [Bonnor 1985].



Source: Botkin, Simpson [1990]

Fig. 1. Sampling strata for the North American boreal forest

An equal-area map was produced from which the location and size of each stratum, as well as the overall size of the study area, could be calculated (table 1). The total area was found to be approx. 5 million km^2. Each stratum was sampled with primary sampling units (PSU) of equal size (24 × 24 km) each representing an 8 × 8 pixel square on a digital image on the geographical information system (GIS). The number of PSUs allocated to a stratum was proportional to the stratum's relative size. However, to achieve an unbiased estimate of the variance, at least 2 PSUs were allocated to each stratum.

PSUs were randomly selected within the strata using the GIS and a table of random coordinates. Each PSU was then subsampled with four randomly located secondary sampling units (SSU) for a total of 152 SSUs. Each SSU consisted of five non-independent plots, so that a total of 760 plots were measured. SSUs were selected using a table of random Universal Transverse Mercator (UTM) Grid system coordinates representing all possible locations of SSUs within a 24 × 24 km primary sampling unit (UTM coordinates locate areas of equal size in contrast to latitude/longitude coordinates which delineate areas of decreasing size with increasing latitude). Each set of coordinates represented a 400 m^2 area of the PSU.

The northwest corner of the 400 m^2 area was used as the center-point for the SSU. To locate them in the field, SSUs were plotted on topographic maps (Canada – 1:50,000; US – 1:24,000). All terrestrial sites were accepted regardless of present use, condition, or cover, except that points occurring on bodies of water were excluded (Canada is approx. 7.6% water [Bonnor 1985]).

Field crews traveled to each secondary sampling unit, which consisted of five sub-plots: one 20 m diameter circular sub-plot located at the center and four 20 m diameter sub-plots located tangentially to the central sub-plot, one in each cardinal direction. This layout resulted in an overall sample size of 1571 m^2 per SSU. The center point of each secondary sampling unit was located in the field using maps and aerial photographs. Where possible, established SSU centers were then located with satellite navigation devices or by aerial photography to a precision that would allow them to be correlated later with remote sensing data. Field measurements were obtained during the summers of 1987 and 1988. The diameter at breast height (DBH) (1.3 m above the ground), total height, and species were recorded for all trees with DBH > 2 cm in each sub-plot. A 2-m diameter micro--plot was established at the center of each sub-plot within which the species and stem diameter at the base and 15 cm above the ground were recorded for all shrubs and for trees with DBH < 2 cm.

Data analysis

Oven-dry biomass for each stem was estimated from diameters and heights using dimensional analysis relationships available at that time [Whittaker 1966; Aldred, Alemdag 1988]. Biomass equations for trees were developed by the Canadian Forestry Service [Evert 1985]; those for shrubs and seedlings were obtained from a variety of sources [Stanek, State 1978; Ribe 1979; Smith, Brand 1983]. It was assumed that the estimates from these equations were accurate for trees and shrubs throughout the boreal forest region [Evert 1985]. The total biomass of an SSU was calculated by summing the individual stem results from the biomass equations for all plots. Biomass density per hectare was calculated by dividing the total SSU biomass by the SSU area.

The mean oven-dry biomass per unit area (kg/m^2) of the boreal forest and its 95% confidence interval was calculated with a set of standard survey-sampling equations based on the sample design [Yamane 1967]. The mean and total biomass equations weighted the SSU results by strata and sample size. Variance equations used strata and sample sizes to weight variance that was partitioned into PSU components, allowing comparisons within units and between units. In this study, carbon content was taken to be 45% of the oven-dry biomass following Whittaker [1975].

North American boreal forest results

The above ground biomass of trees and shrubs for the North American boreal forest averaged 4.18 ± 1.01 (95% C.I.) kg/m^2 and totalled $21.5 \times 10^9 \pm 5.2 \times 10^9$ (95% C.I.) metric tons for the 5,126,427 km^2 (table 1). This estimate is as little as one-fourth of the previously published estimates for above ground biomass (12 to 18 kg/m^2) used in analysis of the global carbon budget (table 2), and is significantly lower (95% C.I.) than all the others.

Table 1. Estimates of above-ground biomass and carbon in the North American boreal forest

Source	Biomass [kg/m^2]	Carbon [kg/m^2]	Total Biomass [10^9 MT]^c	Total Carbon [10^9 MT]^c
Botkin, Simpson [1990]	4.2 ±1.0	1.9 ± 0.4	22 ± 5	9.7 ± 2
Ajtay et al. [1979]	17.5	7.9	90	40
Whittaker, Likens [1973]	15.4	6.9	79	35
Olson et al. [1978]	14.8	6.7	76	34
Olson et al. [1983]	12.4	5.6	64	29
Bonnor [1985]	5.9	2.7	30	13.8

Sources for previous studies are given in Botkin, Simpson [1990]

Carbon content was calculated to be 1.9 ± 0.4 kg/m^2 and totalled $9.7 \times 10^9 \pm$ $\pm 2.3 \times 10^9$ metric tons (table 1). This value is much lower than previous estimates of carbon content used in analyses of the global carbon budget, which range from 12 to 18 kg/m^2 for above-ground biomass and up to 7.9 kg/m^2 for carbon content (table 1). Only the biomass inventory directed by the Canadian Forestry Service gave values close to Botkin and Simpson [1990], with a mean biomass value of 5.9 kg/m^2 for all of Canada [Bonnor 1985]. The Canadian Forestry Service estimate was the most reliable prior to the one presented in the study, but was acknowledged to be not statistically reliable for the entire boreal forest region because it was based on the results of a number of different studies using a variety of methods. That estimate also included all Canadian forests, which accounts, at least in part, for a value slightly higher than the one presented and was related to political rather than natural areas.

Biomass and carbon storage of North American eastern deciduous forests

Using the same methods, Botkin and Simpson [1990] obtained an estimate of the above-ground biomass and carbon storage for the eastern deciduous forest of North America (table 2). The results are consistent with those from the North American boreal forests: mean values are much lower than have been reported commonly in literature, and the statistical confidence intervals are a similar percentage of the mean (table 3) [Houghton 2005].

Table 2. Above-ground carbon in temperate deciduous forests of North America

Data sources	Carbon density [kg/sq m]	Total carbon [gigatons]	Ratio to Botkin and Simpson results
Botkin, Simpson [1990]	3.6 ± 0.6	8.1 ± 1.4	1.00
Presettlement			
Minimum	4.2 ± 0.7	9.3 ± 1.4	
Maximum	7.3 ± 1.2	16.1 ± 2.6	
Previous studies			
Atjay et al. [1973]	9.7	22	2.72
Whittaker and Likens [1973]	10.4	23	2.84
Olson et al. [1978]	7.7	17	2.10
Olson et al. [1983]	7.7	17	2.10
Houghton et al. [1983] Undisturbed	10.4	23	2.84
Houghton et al. [1983] Secondary	7.7	17	2.10

Source: Botkin, Simpson [1990]

Table 3. Comparison of Houghton [2005] and Botkin and Simpson [1990] (for North America boreal forest); Botkin and Simpson [1993] (for North America deciduous forest)

Region	Forest area [106 km^2]	Forest Total living biomass [Pg C]	Average forest biomass [Kg Cm^{-1}]	Source
Canada (Boreal)	316	12.9	4.1	Houghton [2005]
Canada + USA (Boreal)	512	9.7 ± 2	1.9 ± 0.4	Botkin, Simpson [1990]
United States (Eastern Deciduous)	212	13.3	6.3	Houghton [2005]
United States (Eastern Deciduous)	223	8.1 ±1.4	3.6 ± 0.6	Botkin, Simpson [1993]

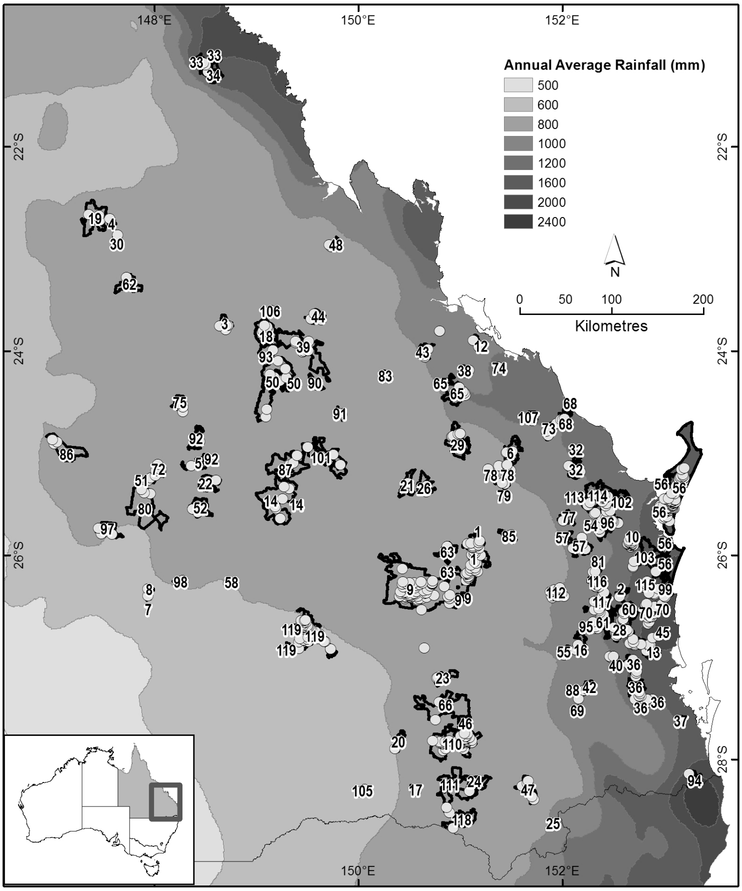


Fig. 2. Map of Australia showing Queensland State, the study area, annual rainfall zones, and distribution and location of forest plots

Forest carbon storage monitoring in Queensland, Australia

This study involved 2.6 million hectares of state-owned uneven-aged mixed species native forests in sub-tropical Queensland, between latitudes 21° and 29°S and longitudes 146° and 154°E, including a rainfall gradient from 500 mm/yr to 2,000 mm/yr (fig. 2). Within this forested area, 604 long-term permanent inventory plots were established, commencing in 1936 and measured up to 2011. The sampling procedure used a subset of a systematic inventory grid, resulting in an average sampling intensity of 1 plot per 43 km^2. Systematic sampling was the necessary consequence of operational simplicity and economy but it has been justified in recent analyses [Valentine et al. 2009].

Queensland data analysis

In this and an earlier Queensland study [Ngugi et al. 2013], conversion of biomass dry weight to live above-ground carbon stock was based on the assumption that woody tissue is 50% carbon [Gifford 2000]. (Note the slight difference (45%) used in the North American studies discussed earlier.) Since all the plots had a history of human disturbance, the long-term data sequence was examined from each of the 604 plots for the entire sequence. Data collected post-1993 were used to estimate carbon stocks, basal area, and the stem density component of trees < 10 cm DBH. The mean basal area and live above-ground carbon stock for each plot were calculated as the respective means of all measurement occasions for the plot for its entire measurement history.

The net annual changes in basal area and live biomass were calculated as the difference in observed attributes between two consecutive measures divided by change in time (the length in years of the measure interval). The plot statistics were then aggregated using rainfall zone and broad vegetation grouping to provide respective mean estimates for each group. Data management and calculations of carbon stocks were undertaken using R programming language [R Development Core Team 2011] and errors expressed as a 95% confidence interval (CI) of the mean.

Queensland results

Live above-ground tree carbon stocks and change across a rainfall gradient

This study provided empirical estimates of live above-ground carbon stocks and their annual net changes based on over 355,000 tree measurement records. Table 4 shows the mean plus and minus the 95% CI. A benchmark value for each rainfall zone was estimated as the mean maximum carbon stock for each plot across the entire inventory period of up to 70 years. This carbon stock value varied from 43.4 ± 3.4 to 138.1 ± 14.4 t C ha^{-1} (table 4).

Table 4. Estimates of mean (± 0.95 CI) live above-ground carbon (C) stock and annual change for trees with DBH > 5 cm in six annual rainfall zones in Queensland.

Rainfall zone [mm]	Sample size	Mean C stock [t ha^{-1}] ± CI	Conservative C stock [t ha^{-1}] ± CI	Benchmark C stock [t ha^{-1}] ± CI	C stock change [t ha^{-1} yr^{-1}]
500–600	41	29.4 ± 1.3	28.1	43.4 ± 3.4	0.67 ± 0.05
600–800	277	38.1 ± 0.7	37.4	50.0 ± 1.6	0.70 ± 0.03
800–1000	55	60.8 ± 4.3	59.4	67.8 ± 7.5	0.96 ± 0.18
1000–1200	102	57.4 ± 3.1	54.3	78.8 ± 7.9	1.01 ± 0.08
1200–1600	89	119.2 ± 6.9	112.3	138.1 ± 14.4	1.94 ± 0.20
1600–2000	40	101.8 ± 6.6	93.2	116.5 ± 12.7	2.21 ± 0.29

The important point here is that 95% CI is a sizable percentage of the mean. One can use these values to derive minimum and maximum carbon storages and then to consider what is reasonable to use for the determination of carbon offset credits, whether it should be the benchmark, the mean, or the mean minus the 95% CI to get the minimum likely storage. While one could use the benchmark or the mean plus the 95% CI, the authors consider that either of these estimates would be an unreliable basis for the making of long-term investment decisions. Instead, using the mean minus the 95% CI (the Conservative estimate in table 4) is recommended; it may be 20% to 50% lower than the benchmark estimate, but is more realistic for less than ideal environments. It is relevant that the discrepancy is greater for the lower rainfall areas, which constitute the bulk of land potentially available for carbon storage.

The mean live above-ground carbon stock increased with increasing mean annual rainfall from 600 mm to 1600 mm, then decreased slightly from the 1600 mm to the 2000 mm rainfall zone (table 4). The relationship between the conservative estimate of live above-ground carbon stock (LAC_c, t ha^{-1}) and mean annual rainfall (R, mm) is given by a quadratic equation, $LAC_c = -54.13 + 0.165R - 0.00004R^2$, $r^2 = 0.82$. Across most rainfall zones, the annual carbon increment was slightly less than 2% of the standing carbon stock.

Queensland net carbon stocks and change among broad vegetation groups

Queensland forests growing in comparable geology, geomorphology and soil conditions have been classified within the last 20 years into Broad Vegetation Groups (BVGs). Their mean carbon stocks range from 33.6 ± 0.9 t C ha^{-1} in *Callitris* forests (BVG 20a) to 146.4 ± 11.1 t C ha^{-1} in wet tall open forests (BVG 8a) (table 5). Note that the highest BVG carbon stock (146 t C ha^{-1}) observed in wet tall forests (BVG 8a) is substantially greater than the mean value for the entire 2000 mm rainfall zone (101.8 t C ha^{-1}, table 4), reflecting the fact that a range of forest types occur in this rainfall zone, and these do not all share the same high carbon stock values. This difference has important implications for the selection of an appropriate target value for carbon sequestration in a particular region. Therefore, classification of forest locations on both rainfall and forest type is essential for the development of reliable carbon inventories.

The mean live above-ground carbon net change ranged from about 0.7 t C ha^{-1} yr^{-1} or less in forests characteristic of rainfall zones of 1000 mm yr^{-1} or less (BVGs 10a, 12a, 18b and 20a) to 2.92 ± 0.25 t C ha^{-1} yr^{-1} in BVG 8b (open forest dominated by tall individuals of *E. pilularis* Sm.). The overall mean live above-ground carbon net change among all the broad vegetation groups and rainfall zones was 0.95 t C ha^{-1} yr^{-1}, due to the bulk of the forest sites being located in the lower rainfall zones.

Table 5. Mean and annual net change in live above-ground carbon (C) stock for forest type

Broad Vegetation Group (BVG)	Rainfall zone [mm]	Number of plots	Mean C stock [t C ha^{-1}]	Annual net change C stock [t ha^{-1} yr^{-1}]
8a Wet tall openforests	1000–2000	41	146.4 ± 11.1	1.96 ± 0.22
8b Moist open forests	800–2000	55	136.0 ± 9.3	2.92 ± 0.25
9a Moist to dry open forests	600–2000	116	60.7 ± 2.2	1.12 ± 0.08
10a *Corymbia citriodora*	600–1000	113	39.3 ± 1.3	0.66 ± 0.06
10b Moist open *Corymbia* spp	600–1600	40	46.3 ± 2.5	0.85 ± 0.09
12a Mixed eucalypts	600–1200	28	46.2 ± 2.5	0.71 ± 0.13
18b *Eucalyptus crebra*	500–800	32	41.5 ± 1.8	0.70 ± 0.07
20a *Callitris glaucophylla*	500–800	115	33.6 ± 0.9	0.70 ± 0.03

Mean estimates ± 0.95 confidence interval

Implications for global estimates

There are two important points here: that it is possible to give statistical confidence to these estimates, and this should be done for all estimates so that realistic expectations about the range of carbon storage become available; and that these statistically valid estimates are generally significantly lower than those in common use. To reinforce these conclusions, the results presented here were compared with the 2006 IPCC report values (table 6). Since rainfall has a major influence on forest growth, live above-ground carbon within our rainfall gradient was estimated and these estimates were compared with the biome averages for forests more than 20 years after disturbance compiled by the IPCC [IPCC 2006]. It can be noted that several IPCC estimates are based primarily on available single-measure estimates from a variety of sources using a variety of methods, and as a result there is no ability to calculate a statistically-valid mean and variance. The statistically-expected range for each of the three Queensland rainfall regimes that could be compared with the IPCC studies are given. This range is the lowest mean minus its 95% confidence interval and the highest mean plus its 95% confidence interval. In all cases, the entire range reported for the Queensland forests is considerably lower than the 2006 IPCC values. The statistically-valid minimum for Queensland subtropical humid forest is 66% of the 2006 IPCC value, while even the statistically--valid Queensland maximum is 87% of the IPCC value. The statistically-valid Queensland subtropical dry forest minimum is 67% of the 2006 IPCC value, while even the statistically-valid Queensland maximum is 81% of the IPCC value. The statistically-valid Queensland steppe minimum is 80% of the 2006 IPCC value, while the statistically-valid Queensland maximum is 10% higher than the IPCC value. Only the range of the Queensland steppe includes the IPCC estimate.

The Queensland results are consistent with the North American boreal and eastern deciduous forest findings. Together, these show that there appears to be a fundamental deficiency in the quality of information that is being used to make decisions, even though the necessary methods are readily available. Moreover, realistic carbon sequestering programs should be adjusted for these ranges. The most conservative estimate, the lower mean minus the 95% CI is the most practical, but more importantly, international carbon sequestering programs should select one of the statistically-valid values as the planned standard.

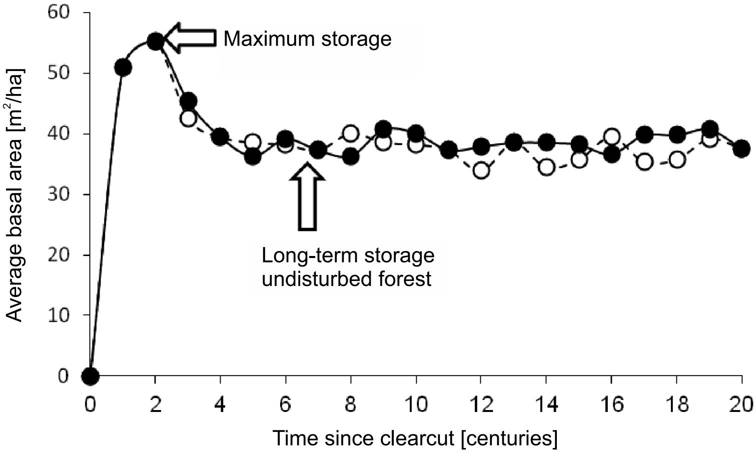
Table 6. Comparison of IPCC [2006] and Queensland study estimates of carbon storage. Within each of the rainfall ranges in Queensland, low is the mean minus the 95% confidence interval (CI) for the lower stock and the high is the mean plus the CI for the higher stock of the rainfall range

Biome and annual rainfall range estimates [mm/yr]	Source	Carbon storage	
		low [t C ha^{-1}]	high [t C ha^{-1}]
Subtropical humid 1600–2000	IPCC	145	145
Subtropical humid 1600–2000	Queensland	95.2	126.1
Subtropical dry 1000–1200	IPCC	80	80
Subtropical dry 1000–1200	Queensland	54.3	65.1
Subtropical Steppe 600–800	IPCC	35	35
Subtropical Steppe 600–800	Queensland	28.1	38.1

Can forests store maximum biomass and carbon over a long time?

The assumption underlying proposals for carbon trading is that one can obtain credit for a single value of the amount of carbon stored in a forest. A further common assumption is that to store carbon one simply allows a forest to grow whereupon it will reach its maximum biomass and carbon storage, and remain at that level indefinitely, not being subjected to any external disturbance such as forest fire, storms, or disease.

To the best of the authors' knowledge, this is not how even undisturbed forests exist over time. Here is output from the forest model that Botkin developed and a version of which is used by all the authors for simulating the growth of a forest from clearing or undisturbed state for several thousand years (fig. 3).

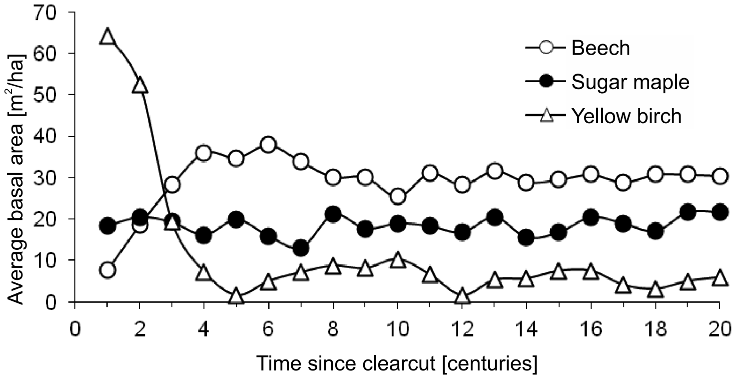


Source: Botkin et al. [1973]

Fig. 3. Computer simulation of long-term forest growth. Two long-term predictions of average basal area per plot of the model at 610 m elevation. Each line represents the average of 100 plots with identical site conditions, including a deep, well-drained soil and constant climate, but starting with different pseudo-random numbers

The model forecasts that the basal area, which is a good indicator of biomass and carbon storage, increases rapidly at first to a maximum, and then declines [Botkin et al. 1972; Botkin 1993; Botkin 2013]. For the North American eastern deciduous forests, which are modeled here, the maximum occurs between the first and second century after clearing. Thereafter, the forest never remains in a constant state, but varies over a range, which is considerably lower than the maximum. In the case shown, the long-term value averages approx. 70% of the maximum, while the variation over the long-term ranges from approx. 55% to 78%. Note that one can talk about the persistence of carbon storage around a mean value. Since the model involves stochastic birth and death, there are some random variations, but within a zone.

The early successional species are highly productive and rapidly growing (fig. 4). Yellow birch in particular adds biomass rapidly. Meanwhile, in the understory, sugar maple and American beech add more biomass to the forest, but more slowly than yellow birch. The forest maximum occurs at approx. 200 years, when there are many mature yellow birch and some sugar maple and American beech. But then yellow birch and the other early and mid-successional species are much diminished, and the shade-tolerant species become dominant.



Source: Botkin et al. [1973]

Fig. 4. Graphs for three species in the computer simulation of long-term forest growth: yellow birch, an early to mid-successional species, and sugar maple and American beech, which are characteristic of older forests. These show why this maximum and the decline in fig. 3 occur

Short-term forest dynamics influence carbon storage

It is commonly assumed that late stages in forest succession change little if at all and if there is change, it occurs very slowly. Remote sensing of successional stages in the boreal forest contradicts these assumptions. Landsat images ten years apart were used for two large study areas: the boreal forest in the U.S. Boundary Waters Canoe Area (BWCA), 4046.9 km^2 (1 million acres) in northern Minnesota, bordering Canada, which has its own large wilderness, Quetico Provincial Park, Ontario, covering 4.760 km^2, and contiguous with the BWCA, and the adjacent U. S. Superior National Forest, which covers 12.141 km^2 (3 million acres). Thus, a comparison was possible between an area protected from forest logging and one in which logging had taken place and was continuing at the time of the study (fig. 5) [Hall et al. 1991].

The Landsat images were calibrated carefully against field measurements obtained by field crews. The data comprised height and diameter measurements of all trees on circular plots 60 meters in diameter, representing twice the area of a Landsat pixel. Helicopters carried the same sensor that was in the Landsat satellite, and these measurements were used to calibrate the Landsat sensor against forest conditions. There were also high altitude aircraft carrying the same sensor, and then Landsat images were captured.

It was possible to measure five distinct states of forest succession: clearings, regenerating, broadleaf only, mixed deciduous and conifer, and spruce-fir only. Landsat images of these same areas in 1977 and 1987 were then overlaid. From these it could be determined how each pixel had changed state in ten years. It is interesting that in all cases, 1973, 1983, and in the wilderness and non-wilderness, more that 55% of the forest was in the two oldest stages (table 7).

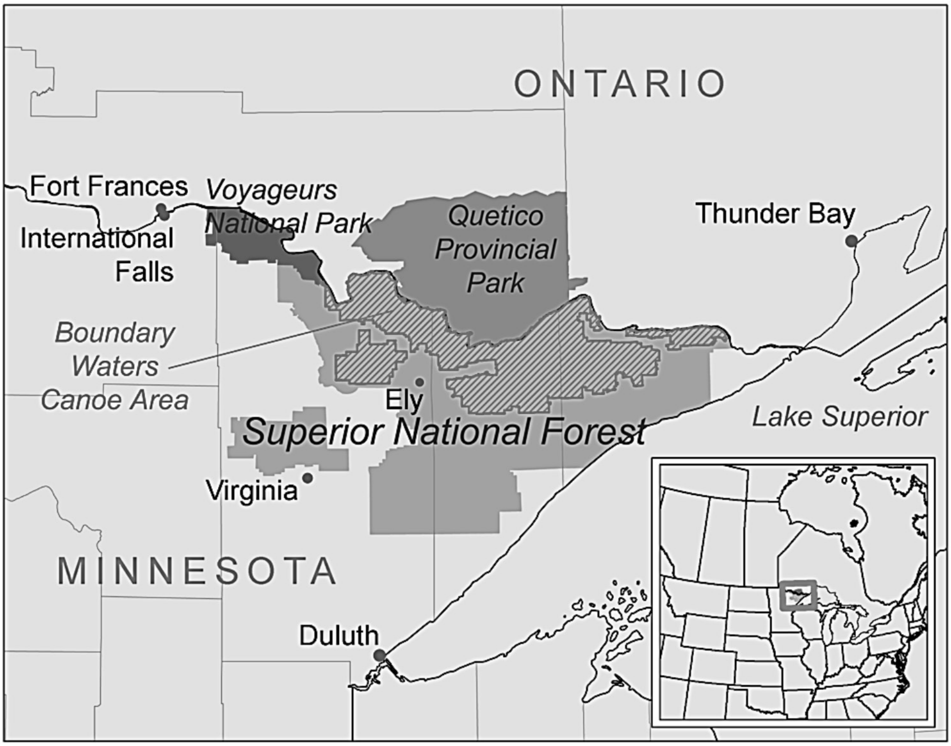


Fig. 5. Map showing the Boundary Waters Canoe Area, U.S. Superior National Forest, and Quetico Provincial Park, Ontario, Canada

Table 7. Landsat derived boreal forest areas in different successional stages, for the Boundary Waters Canoe Area and adjacent U.S. Superior National Forest

Ecological State class	Percent of land area by class*			
	1973 BWCA	1973 Superior Forest	1983 BWCA	1983 Superior Forest
	wilderness	non-wilderness	wilderness	non-wilderness
Clearings	3.91	8.95	1.93	7.35
Regeneration	11.2	15.2	13.4	22.2
Broadleaf	22.6	17.9	20.8	13.6
Mixed	37.9	33.5	40.6	35.4
Conifer	24.3	21.5	26.2	21.5
Percent mixed & conifer	62.2	55.0	66.8	56.9

*Water and clouds are omitted; hence some columns do not total 100%

As one would expect, the percentage in clearings was much higher in the national forest, where logging has been permitted, but also the most recent forest fire was concentrated in this forest rather than in the wilderness.

In the BWCA, 17% stayed as clearings and 45.54% changed to the regenerating (the second) successional stage (table 8).

Table 8. Transition matrices for Boundary Waters Canoe Area showing changes in ecological state in wilderness and surrounding non-wilderness area calculated from satellite images between 1973 and 1983. For an area of 534 km^2, with 14406 landscape elements, in protected wilderness of Boundary Water Canoe.

State	Clearings	Regenerating	Broadleaf	Mixed	Conifer	Other
Clearings	17.09	45.54	16.72	15.20	5.22	0.12
Regenerating	4.55	30.83	16.93	37.27	10.03	0.36
Broadleaf	1.12	19.72	47.06	27.61	4.16	0.28
Mixed	0.52	6.81	11.28	58.11	22.55	0.72
Conifer	1.04	4.37	1.81	31.02	57.80	3.93
Other	0.53	3.14	3.19	8.60	13.38	71.06

Diagonal elements are retention frequencies; off-diagonal are transitions from the state in column 1 to each of the states named in the adjacent columns

More than 50% of each of the two oldest stages stayed the same, but surprisingly, the rest changed state in this short time. Most of the transitions for these two stages were between one another. Thus 81% of the conifers remained in either conifer or mixed, while 80.66% of mixed remained either in conifer or mixed. But 20% of what were supposed to be old-growth stands changed to very different, much earlier successional states, in just ten years. This is a remarkably rapid rate of return to an earlier successional stage.

Conclusions

Concern over the possibility of greenhouse-induced climate change drives a need for more quantitative knowledge of the global carbon cycle, including amounts and rates of change of carbon storage in major biomes. This knowledge is fundamental to the understanding of the dynamics of Earth's biosphere, which is itself fundamental to Earth System Science. However, in spite of repeated calls by scientists that such knowledge should be obtained, terrestrial ecosystem carbon storage and exchange remain poorly documented.

It has been shown that statistically-valid estimates of carbon storage can be obtained using well-known ground-based methods, which have been used in North America and Australia. The North American results show substantially different and statistically lower carbon storage values from those widely adopted in scientific literature, while more recent studies of forests in Queensland, Australia, yield results more similar to those of the IPCC, but still different and mostly lower. Resulting mean values are considerably lower than those in wide use and the confidence interval is greater than 20% of the mean.

Furthermore, it is common to assume that forest storage of carbon can be treated as a single, scalar quantity — that forests will grow to a maximum carbon storage and remain at that storage indefinitely. Here the opposite is shown – that even in undisturbed environments, long-term forest patterns include a peak in what is usually termed late ecological succession and a continued variation within well--specified, but lower, bounds. Moreover, remote sensing of millions of pixels in the boreal forest of North America show the surprisingly rapid turnover of forest stands in just ten years. Therefore, realistic estimates of carbon storage must take into account the mean and the statistical confidence interval. It is recommended that the mean minus the confidence interval becomes the standard value for carbon sequestration offset calculations. Also, carbon storage must be planned for specific time-horizons rather than indefinite futures.

These results show that a global program using straightforward, relatively simple and consistent methods could yield far more accurate carbon storage values, and greatly improve any carbon trading, carbon sequestering, and scientific information about biomass and carbon storage and exchange.

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