Using the Forest Identity to grasp and comprehend the swelling mass of forest statistics

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SUMMARY

Valued attributes of forests encourage surveys and inventories of multiple attributes that need quantitative definition and integration followed by comprehensible presentation. The Forest Identity defines the four attributes of expanse, growing stock, biomass and carbon in terms of measurable forest area (A), forest density (D), biomass to growing stock ratio (B), and carbon concentration (C). The Identity connects and integrates them all, logically. Nearly constant C and a B varying fairly regularly with D allow a single synoptic chart to present the four changing attributes in many regions, as examples around the world demonstrate. The Identity simply and transparently audits complex estimates of sequestered carbon. Sensing biomass remotely would transfer the uncertainty of the ratio B from carbon to growing stock inventories. In whatever manner variables are measured, the Identity integrates them into attributes and permits synoptic charts of masses of data.

Keywords: Forest Identity, growing stock, biomass, carbon, change and transition.

Utilisation de l'identité de la forêt pour saisir et comprendre la masse croissante des statistiques forestières

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Les attributs appréciés des forêts encouragent études et inventaires d'attributs multiples qui ont besoin de définitions et d'intégration quantitatives suivies de présentation intelligible. L'identité de la forêt définit les quatre attributs de l'étendue, du stock en croissance, de la biomasse et du carbone en termes de zone de forêt mesurable (A), densité de la forêt (D), le pourcentage de la biomasse en stock en croissance (B), et la concentration de carbone (D). L'indentité établit des liens entre eux et les intègre tous logiquement. C presque constant, et un B en variation assez régulière avec D permettent à un tableau synoptique simple de présenter les quatre attributs changeants dans plusieurs régions, comme le prouvent plusieurs exemples à travers le monde. L'identité audite simplement, et de manière transparente, des estimations complexes de carbone sequestré. Une perception de la biomasse à distance permettrait de transférer l'incertitude du pourcentage B du carbone aux inventaires de stocks en croissance. Quelque soit le mode avec lequel les variables sont mesurées, l'identité les intègre en attributs, et permet d'établir des tableaux synoptiques d'un très grand nombre de données.

Uso de la identidad forestal para captar y comprender la cantidad cada vez mayor de estadísticas forestales

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Los atributos valiosos de los bosques se benefician de la investigación y la producción de inventarios de atributos múltiples que requieren una definición e integración cuantitativas, seguidas por una presentación comprensible. La "Identidad Forestal" define los cuatro atributos de extensión, stock en crecimiento, biomasa y carbono en términos de área forestal mensurable (A), densidad forestal (D), proporción entre biomasa y reservas en crecimiento (B), y concentración de carbono (C). La Identidad conecta e integra todos estos factores de forma lógica. Un valor de C casi constante y una relación oscilante pero relativamente regular entre B y D permiten que una sola tabla sinóptica presente los cuatro atributos cambiantes en muchas regiones, tal como demuestran diferentes ejemplos alrededor del mundo. La función de la Identidad se basa en auditar de forma sencilla y transparente cálculos complejos de carbono secuestrado. La captación remota de biomasa trasladaría la incertidumbre de la proporción B del carbono a los inventarios de reservas en crecimiento. Sea cual sea la forma de medir las variables, la Identidad los integra en atributos y permite la formulación de tablas sinópticas que incluyen grandes cantidades de datos.

INTRODUCTION

Strengthened public esteem for trees encourages more surveys and inventories to gauge the security of the valued forest attributes. More surveys multiply the variables surveyed and the mass of numbers reported. Repeating the surveys doubles the mass. FRA2005, the global Forest Resource Assessment (FAO 2005) exemplifies the variables and mass of numbers, as do national collections exemplified by Indian, German and American (Forest Survey of India 2005, Bundeswaldinventur 2008, Smith *et al*. 2002). Remotely sensed surveys will swell the mass further. At the same time that the mass multiplies, access grows easier. Without visiting a library, one can read the data on the Internet, and often avoid tedious typing by downloading spreadsheets. The many numbers, several variables, and easy access invite analysis.

Analysts will, of course, concentrate on the valued attributes that prompted the esteem for forests and encouraged the surveys. Some people will value the area sheltered, some the timber volume, some the biomass, and some the carbon sequestered. To grasp the state of multiple attributes in the mass of data, an analyst might weight those four attributes plus the antiquity of each forest and its abundance of animals, weighting them according to the value that the analyst assigns to each. Melding the weighted attributes might help comprehend diverse, dynamic, and multifaceted forests. It might answer, “Are things getting worse, secure, or passing a transition to better?”

The following paragraphs will comment on a system called the Forest Identity for first defining valued attributes of forests with measurable variables and then integrating them with logical weights. This Comment will discuss the simple, graphical presentation of the growing mass of data to grasp their meaning, illustrate its use on three continents (Europe, Asia and North America), and prepare for remote sensing.

DEFINING AND INTEGRATING VALUABLE ATTRIBUTES WITH MEASURABLE VARIABLES

The list of valued attributes of forests can be extended, indefinitely. For example, in its 2002 survey, Germany extended it with the ratio of forest edge length to forest area. Deadwood habitat, a shrub layer, and a comparison of present species to a natural community joined the list. The attributes of area and growing stock are fundamental, and FRA2005 reported their changes in 144 nations from 1990 to 2005. Area contributes the esthetic value of a forested landscape and the solitude of wilderness. It provides the physical value of watershed and erosion control. Growing stock equals the practical attribute of merchantable timber. The biomass attribute fuels forest ecosystems and can become biofuel. The fear of climate change has given value to the attribute of carbon. Forests remove carbon from the supply of carbon dioxide in the atmosphere and sequester or store it in the biomass. Symbols and dimensions for the four attributes are area (A, ha)), growing stock volume (V, m^3), biomass (M, Mg), and carbon (Q, Mg). Ha means hectares, and Mg means megagrams or tons.

Although these are only an elementary quartet of valued attributes, tabulating their condition in the 144 nations of FRA2005 in 1990 and 2005 requires 4 spreadsheets of attributes, 2 columns of times and 144 rows of nations. The consequent 1,152 values comprise a sufficient mass to digest. The Forest Identity (Kauppi *et al*. 2006, Waggoner and Ausubel 2007) defines the attributes by four measurable variables:

Area (A) again, density (D, m^3/ha), biomass ratio (B, Mg biomass per m^3 growing stock), and concentration (C, Mg carbon per Mg biomass).

A (ha) = A

V (m^3 of growing stock) = $A \times D$

M (Mg of biomass) = $A \times D \times B = V \times B$

Q (Mg of carbon) = $A \times D \times B \times C = M \times C$

Analysts might weight the attributes and variables, giving more weight to area than lumber in growing stock, or more to lumber than sequestered carbon. Because the weights would reflect preferences, they would be debatable. By relating the attributes and variables, one to another, with physical dimensions these Forest Identities have instead set the relative weights or values on a solid foundation. For example, physical instruments, measuring tapes and balances, measure the biomass ratio B, and chemical analysis measures the concentration C, without debate.

Making an attribute like Q the function of so many variables might propagate errors in the attribute. Uncertainty besets estimation of the variables, as Mather (2005) and Grainger (2008) found in the Forest Resource Assessments of the FAO. Because V is identical to A times D, however, the Forest Identity does not add more errors than those in reports of A and D. On the other hand, if biomass M is calculated from A and D or V, uncertainty about B does propagate uncertainty about M and Q.

B declines regularly with increasing D in many forests (Schroeder *et al*. 1997). Generally, estimation of B begins with the ratio of *above ground* biomass to growing stock. Called an allometric ratio or biological expansion factor, the ratio B falls from infinity, when no biomass qualifies as growing stock, toward the specific gravity of wood, when nearly all biomass becomes growing stock. Brown and Schroeder (1999) related B to biomass thus:

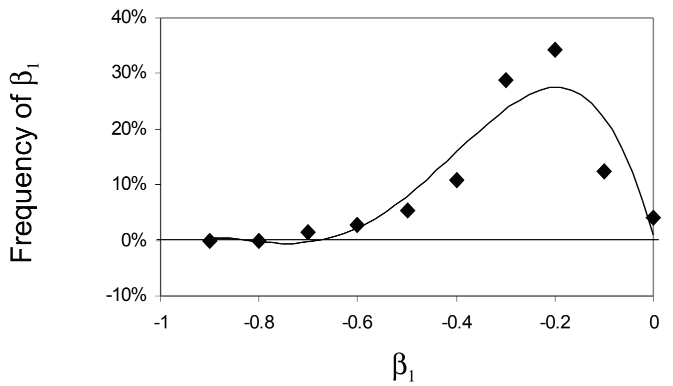
$$\ln(B) = \beta_0 + \beta_1 \ln(D)$$

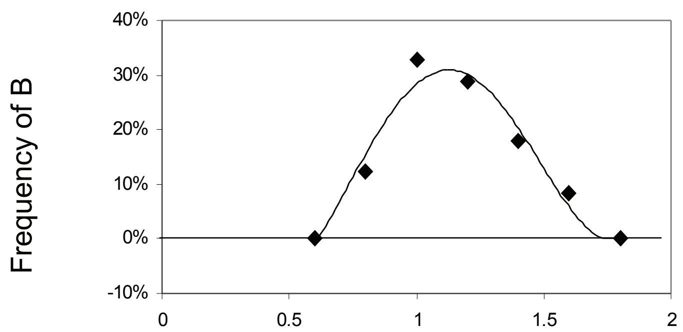
In an unpublished survey, Fang (2006) found β_1 from -0.5 in the USA through –0.3 and -0.4 in China, India and Japan to -0.1 in Europe and Russia. At a reference density of 100 m^3/ha, B varied from 0.7 to 1.7. IPCC default values of B at 100 m^3/ha range from 0.6 in boreal pines to 1.4 in natural forests in the humid tropics; between 100 and 300 m^3/ha among the same forest types, β_1 ranged from –0.05 to –0.4 (IPCC 2006).

Frequency distributions of β_1 and B appear in Figure 1

(Smith *et al*. 2003). The least biomass per growing stock was mostly conifers in Pacific regions, and the most was in more eastern regions. Bs were frequently near 1, reflecting a specific gravity near 0.5 and 50% of the biomass in growing stock. Explaining outlying β_1 is difficult. Six of the seven steepest decreases β_1 of the ratio B were found in one region, the South Central, but the outliers were both conifers and hardwoods. Twelve of the 13 flattest declines β_1 were in Pacific regions. The frequent β_1 near minus 0.3 suggests B often declines about 3% for a 10% growth of density D.
Reports of the German National Forest Inventory provide

FIGURE 1 *The frequency distributions of B and β_1 in 73 U.S. forest types. Seventy-three of 77 equations fitted to forest types by Smith et al. (2003) produced the estimates of B at 100 m3/ha and β_1 from density 100 to 300 m3/ha*





data for an exercise (Bundeswaldinventur 2008). In 2002, forests covered 7,610 k ha of the old Lander (states) of the Federal Republic with an average density of 342 m^3/ha. If B = 0.8 and C = 0.5, the forests of the old Lander had sequestered

Q = 7,610 k ha * 342 m^3/ha * 0.8 Mg/ m^3 * 0.5 Mg/Mg = 1,043 Tg or million tons carbon.

The forests of present Germany, hold 1,352 Tg carbon. To comprehend this orchard of carbon, compare it to 227 Tg of carbon that Germans emitted in 2002 (IEA 2006). Because the 1,352 Tg in forests is an accumulation, but 227 is an annual emission, logical comparison requires that the Forest Identity calculate annual changes as well as standing orchards.

CALCULATING CHANGES WITH THE FOREST IDENTITY

Gauging the security of the attributes requires knowing how fast they change, and whether they change for worse or through a transition to better. Convert the states of the variables in the Identities to their logarithms. The derivatives of the logarithms with respect to time almost equal the slow annual percentage changes symbolized by lower case letters.

$v = a + d$
$m = a + d + b$
$q = a + d + b + c$

Changes were measured in the eight old Lander of the Federal Republic of Germany. From 1987 to 2002, forest area expanded 0.07 %/yr and density grew 1.09 %/yr. Let *b* decline at 0.3 times *d*, and let *c* be 0.

$q = a + d + b + c$ =0.07 + 1.09 + (-0.3 * 1.09) + 0 = 0.83 %/yr.

Applied to the 2002 carbon stock of 1,352 in all present Germany, 0.83 %/yr produces an annual accumulation of 11.3 Tg. The sequestration of 11.3 Tg equals 5% of the annual 227 Tg emission from present Germany, a worthwhile contribution to balancing Germany's carbon account.
Across the European Union, Saikku *et al*. (2008) used the Forest Identity to compare sequestration and emission and reached a similar conclusion. Saikku's nation of Finland has extensive forests and no complication of changing boundaries. For 1990 and 2005 the same B and C used above and the FRA2005 reports for Finland produce 2005 carbon stock and 1990 to 2005 change:

Q = 22,500 k ha * 96 m^3/ha * 0.8 Mg/ m^3 * 0.5 Mg/Mg = 863 Tg
q = 0.09 + 0.73 + (-0.3 * 0.82) = 0.60 %/yr

Multiplied by the carbon stock of 863 Tg in 2005, the *q* means that Finnish forests sequestered 4.9 Tg, a considerable fraction of Finland's 2004 emission of 19.4 Tg carbon.

Although the above pertains to biomass above ground, the Forest Identity can be extended to all biomass, above plus below ground. In three hundred reliable observations in forests, Mokany *et al*. (2006) found that all biomass was 20 to 40% more than above ground. The exception was 60% in dry forests and plantations in tropical and subtropical region with less than 20 Mg/ha above ground biomass.

Observations of the 73 American forest types reported by Smith *et al*. (2003) and used above permit other estimates of B and also root-to-shoot ratios. At a reference density of 100 m^3/ha, all biomass exceeded above ground by 20%. Both above ground and all biomass decreased with a β_1 of -0.31. Evidently all biomass of trees is about 20% more than that above ground. Because the above ground and all biomass and carbon increase at equal rates, the identity for *q* above serves for both above ground and total biomass.

GRASPING MEANINGS

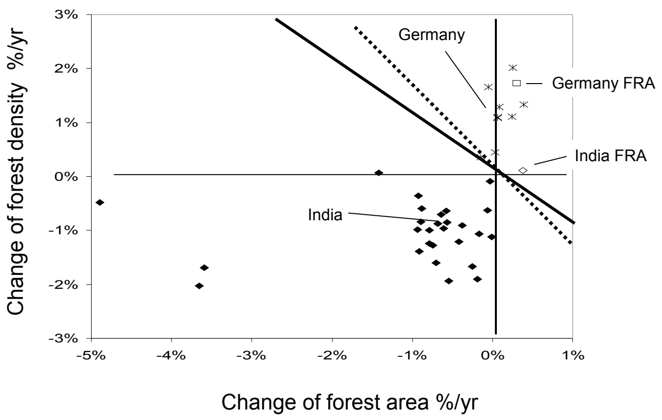
Moving from the state of attributes and variables at a single time to their change multiplies the numbers to comprehend. To grasp the patterns of change, Kauppi *et al*. (2006) drew a synoptic chart of the changes in the 50 nations with most forest. They mapped the annual percentage *a* of area as longitude and *d* of density as latitude. A diagonal boundary through the origin with a slope of minus 1 separated nations to the northeast that gained volume *v* from those southwest that lost volume. Another boundary that declines with a steeper slope equal to minus $1/(1+\beta 1)$ separated the gainers from losers of biomass and carbon (Waggoner and Ausubel 2007). The frequent $\beta 1$ near –0.3 makes the steeper slope minus 1/(1-0.3) or -1.4

The changes from 1987 to 2002 of forests in the old Lander of Germany illustrate a synoptic chart, Figure 2. Forest area expanded in six of the eight Lander. Their average also expanded. Growing density in Baden-Württemberg and Nordrhein-Westfalen compensated for shrinking area. The combinations of changing area and density placed all eight Lander northeast of the boundary between rising and declining growing stock and biomass and carbon, too. Reassuringly, the *a* and *d* calculated from FRA2005 reports for 1990 and 2000 fall within the range of those calculated from the Bundeswaldinventur.

Changes from 1920 to 1980 in 26 Indian states were discouraging, Figure 2. The Forest Identity transformed Richards and Flint's (1994) changes of carbon into changing densities of growing stock. Solving the Identity for *d* and assuming $c = 0$ and $\beta_1 = -0.3$ produces *d* to chart versus *a*:

$$d = (q-a)/(1+ \beta_1) = (q-a)/0.7$$

FIGURE 2 *The annual percentage changes of area a and density d in the old Lander of Germany from 1987 to 2002 and in Indian states from 1920 to 1980. The solid boundary separates increasing and decreasing v, and the dashed boundary separates m and q. Lines identify the national rates of the two collections of rates. The national rates reported by FRA2005 provide reference. Sources: Richards and Flint 1994, Bundeswaldinventur 2008, FRA2005*



Delhi and Haryana/Chandigarh, a new city and an industrial region, lost forest area faster than 3% per year. Forests on the 3,200-ha tropical atolls of Lakshadweep shrank even faster. With the exception of the Punjab's slow increase of density and Jammu/Kashmir's slow loss of both area and density, the changing areas and densities lie well into the southwest quadrant of Figure 2. A line in the Figure identifies the 26-state average. The chart presents a grim picture of lost forest area, density, growing stock, biomass and carbon during the 60 years before 1980.

Fortunately India experienced a forest transition. For the 15 year span 1990 to 2005 the published FRA2005 reports of area and growing stock on Figure 2 correspond to $a = 0.38$, $d = 0.11$ %/yr. These markedly improved rates lie safely above the boundary between losses and gains of growing stock and carbon, Figure 2. Indian forests expanded faster from 1990 to 2005 than forests in all German Lander except Schleswig-Holstein, 1987 to 2002.

USING THE FOREST IDENTITY

The Forest Identity graphically emphasized the improving forests in many nations that global sums cloak, and displayed the general improvement of forests around the Mediterranean, but not around the Caribbean sea. It found no correlation between logging for timber and deforestation. It quantified the sparing of natural forests by harvesting in fast-growing warm forests and plantations (Kauppi *et al*. 2006, Waggoner and Ausubel 2007). Further examples follow.

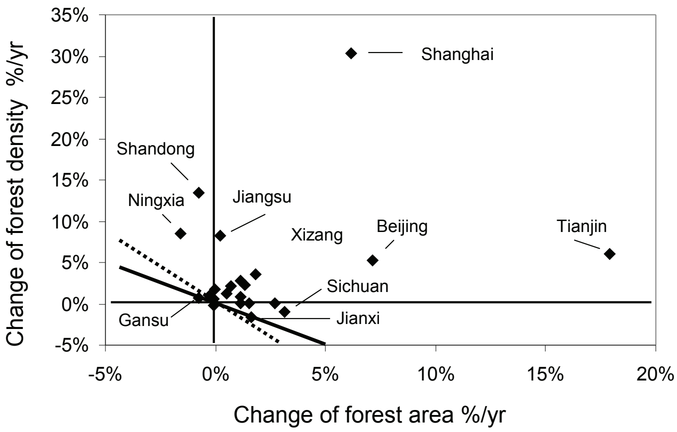
Europe

In Europe, Saikku *et al*. (2008) assayed the sustainability challenge of meeting carbon dioxide targets by 2020, using the Forest Identity to examine efficiently how much forest sequestration helped. To fulfil its obligation, Europe would have to dematerialise its use of energy and decarbonize the production of energy 2 to 3 times faster than during the past decade. Accordingly, the annual 126-Tg forest sequestration provided needed help. The annual sequestration equalled 11% of fossil emissions.

Asia

From China, Jingyun Fang of the Peking University supplied Figure 3 from an unpublished lecture in 2007 (Fang 2007). He opened a synoptic view of the diverse changes in forest area and forest density in Chinese provinces during the 1980s and 1990's. Shanghai's 6,340 km^2 and Beijing's 16,801 km^2 experienced rapid expansion of area and growth of forest density. The Sandification program expanded forests briskly in Tianjin. In three provinces with shrinking or scarcely expanding forest area, increasing density increased growing stock. Most provinces are safely above the boundary between winners and losers of growing stock.

FIGURE 3 *A synoptic chart of changing forests during the 1980s and 1990s in Chinese provinces. The horizontal axis or longitude is the relative change a of forest area, and the vertical axis or latitude is the relative change d of growing stock density. In provinces above the diagonal line, growing stock grew at v %/yr. Source: Fang (2007)*



America

For America, the Forest Identity provides a transparent, robust audit of governmental estimates of carbon sequestration by forests, an obligation of Parties to the United Nations Framework Convention on Climate Change. In February 2008, the United States offered its 1990 to 2006 estimates for public comments (U. S. EPA 2008). Its Table 7-8 reported that biomass above ground in forests annually sequestered an average 92 Tg of carbon during 1990 to 2005. It also reported that biomass below ground increased as a steady 20% of that above ground.

In the Identity, the annual addition to carbon Q equals the change in growing stock V multiplied by the allometric ratio B and the carbon concentration C of the biomass. If B is 1 and C is near 0.5, then the annual Tg of carbon sequestered equals half the V million cubic meters grown. FRA2005 reported that U.S. growing stock increased an average 196 M m^3, sequestering an average 98 Tg carbon annually from 1990 to 2005. The U. S. Forest Service (Smith *et al.* 2002) reported that growing stock on the two-thirds of U.S. forests called *timberland* increased an annual 140 M m^3, sequestering 70 Tg carbon annually from 1987 to 2002. The estimate of 92 by EPA and 98 by FRA2005 in U.S. forests, and the estimate by the U.S. Forest Service of 70 on U.S. timberland may be as close as practical for estimates of carbon sequestration. The Identity simply and robustly tests magnitudes of complicated estimations.

THE FOREST IDENTITY AND ALTERNATIVE INVENTORIES

The order of variables in the Identity from area to carbon concentration manifests the history of forest estimations. When interest in biomass and sequestered carbon emerged, the allometric factor B made their estimation from the available inventories of forest area and merchantable timber eminently practical. Nevertheless, Figure 1 illustrates that uncertainty about B lingers. (The well-known and steady carbon concentration C introduces little uncertainty.) If the goal becomes knowing carbon rather than merchantable timber, however, estimating biomass and carbon directly would be preferable to measuring growing stock and interposing an uncertain B to estimate them. Despite imperfections (Lu 2006, DeFries *et al.* 2007), remotely-sensed estimates of carbon have been reported (Dong *et al.* 2003). Remotely sensed estimates of Q Tg of carbon need only be divided by 2 to know M Tg of biomass, which in turn need only be divided by B to know V m^3 of growing stock. Because carbon concentration changes little, the changes of *q* of carbon and *m* of biomass are nearly equal. Growing stock changes at *v*, which equals the biomass change *m* less the change in *b* caused by changing density. Carbon and biomass density change at *q-a* and *m-a* percent annually. On a synoptic chart with dimensions *q-a* versus *a* rather than *d* versus *a*, boundaries can still be drawn between winners and losers of carbon, biomass and growing stock.

The relative uncertainty of the variables in the Identity becomes germane at this point. For each state, the U.S. land-based inventory was designed to be accurate within 3 to 5% for timberland area, 10% for forest land area and 5% for growing stock volume (Smith *et al.* 2002). In each Lander except Saarland, the German inventory reported sampling errors of 1 to 4% for area and 2 to 8% for growing stock (BundeswaldInventur 2008). For a region as large as an American state with 50% forest cover, Hame *et al.* 2006) proposed a system to sense forest area remotely with a coefficient of variation of 1 to 2%. Grainger (2008) called attention to differences as high as 23% among three Forest Resource Assessments of the 1990 area of Asian-Pacific tropical forests. A synoptic chart of 50 nations constructed from FRA2005 highlighted nations reporting the same growing stock density in 1990 and 2005 (Kauppi *et al.* 2007, Waggoner and Ausubel 2007). At a biomass density of 100 Mg/ha, the remotely- sensed normalized difference vegetation index (NDVI) ranged 18% above and below a central value (Dong *et al.* 2003). Compared to these uncertainties, the standard deviation of the 73 American B displayed in Figure 1 is 20% of their average.

Flying over a forest is preferable to slogging through it. Also, the direct measurement of biomass shifts the uncertainty about B from carbon to growing stock inventories. Nevertheless, ground truth must be established for remote sensing, and the uncertainty of translating remote signals into carbon emerges. For this Comment about the Forest Identity, the last words can be, "However the variables are measured, the Identity can integrate them quantitatively into forest attributes and present masses of data on comprehensible synoptic charts."

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