# A Multiple Resource Inventory of Delaware Using an Airborne Profiling Laser

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An airborne profiling laser is used to monitor multiple resources related to landscape structure, both natural and man-made, across regions encompassing hundreds of thousands of hectares. A small, lightweight, inexpensive airborne profiling laser is used to inventory Delaware forests, to estimate impervious surface area statewide, and to locate potentially suitable Delmarva Fox Squirrel (*Sciurus niger cinereus*) habitat. Merchantable volume estimates are within 14% of US Forest Service estimates at the county level and within 4% statewide. Total above-ground dry biomass estimates are within 19% of USFS estimates at the county level and within 16% statewide. Mature forest stands suitable for reintroduction of the Delmarva Fox Squirrel, an endangered species historically endemic to the eastern shores of Delaware, Maryland, and Virginia, are identified and mapped along the laser transects. Intersection lengths with various types of impervious surface (roofs, concrete/asphalt) and open water are tallied to estimate percent and areal coverage statewide, by stratum and county. Laser estimates of open water are within 7% of photointerpreted GIS estimates at the county level and within 3% of the GIS at the state level.

Airborne lasers are used to acquire decimeter or centimeter-level ranging measurements from aircraft to targets beneath the aircraft (1). These ranging measurements are typically utilized for terrain mapping or to monitor/measure manmade objects (2). At this point in time however, laser altimetry has not been employed operationally for natural resource assessment, though some inroads are being made (3). The reasons for this are economic; lasers generally come with a significant pricetags and specialized data processing requirements.

The overall objective of this study is to demonstrate that an inexpensive airborne laser profiling system can be used to inventory multiple natural and man-made resources regionally, across areas comprising hundreds of thousands of hectares. The study was conducted primarily to formulate, assemble, and exercise all components needed to conduct a statewide forest inventory - the airborne laser system, the statistical design, ground sampling procedures, formulation of predictive equations, and data processing software to generate laser inventory results. The study has three specific subobjectives. First, report forest inventory, impervious surface and open water area, and habitat assessment results and provide examples of output products that can be generated using airborne profiling laser data. Second, assess the accuracy of the forest inventory, surface area, and habitat assessment results. Third, investigate the repeatability and precision of airborne laser estimates of stem count, merchantable volume, and dry biomass. Determine the flight line sampling intensities needed to reliably estimate different land cover types at the county and state levels.

The airborne data were collected using a portable, inexpensive laser specifically designed for this type of resource assessment work (4). The airborne profiler was built from off-the-shelf, commercially available components - laser transmitter/receiver, dGPS system, synchronized CCD videocamera, laptop computer, and integration software (LABView™) - any item of which may be replaced as needed to meet specialized requirements. The system was designed to be small, lightweight, transportable, and easy to install on small aircraft by one person to allow scientists to conduct laser investigations in isolated locales far from technical support - e.g., the circumpolar boreal forests, South America, the Congo, and Asia.

A Portable Airborne Laser System (PALS) was built and used to acquire over 5000 km of flight data over the state of Delaware during the summer of 2000. Approximately one fourth of this data set, 1306 km of flight data, has been analyzed to inventory the forestlands of Delaware, to estimate impervious surface area, and to map and quantify the amount of mature forest available to the Delmarva Fox Squirrel (DFS), an endangered species on the Delmarva. The results of the statewide multiresource analyses are reported below, and examples of output products available from the laser inventories are provided. Where possible, laser estimates are compared to independent estimates to judge the accuracy and reliability of the laser products.

**Statewide Forest Inventory:**

Fourteen flight lines spaced four kilometers apart were systematically flown north-south across the entire length of Delaware (Figure 1). The longest flight line segment was 163 km; the shortest was 1.3 km. Aircraft dGPS locations were recorded once every 2 seconds, or, at a ground speed of 50m/s, once every 100 m. The airborne laser provides a first-return ranging measurement 2000 times per second. This data stream was subsampled 10:1 (9 pulses discarded for every one recorded) so that laser ranges were recorded at 200 hz, providing an along-track post spacing of 0.25m. Spot size at target from 150m AGL was 0.3m (2mr divergence). The dGPS signal was routed to a laptop computer to be interleaved with the laser ranging measurements and also to the CCD video stream so that the video history was synchronized with the laser ranging data (Figure 2).

A ground line was defined for each of the flight lines (4) and a height was calculated for each pulse. The laser flight line was registered to an existing Delaware land cover map (5) and a stratum identity (i.e., land cover) and county identity was assigned to each pulse. Each flight line was parsed into segments ≤40 m and laser height and density measures extracted. These measurements were used as the independent variables in predictive, stratum-level linear models relating laser height and density measurements to stems $ha^{-1}$, basal area $ha^{-1}$, merchantable volume $ha^{-1}$, stem green biomass $ha^{-1}$, and total above-ground dry biomass $ha^{-1}$ (6). Individual segments were weighted by length, adjusted for the amount of impervious surface or open water area contained, and summed across strata and counties to derive statewide estimates. Table 1 lists the laser-based stratum and county per-hectare summaries and totals for stems, merchantable volume, and total above-ground dry biomass. Similar tables are available for basal area and stem green biomass, but are not reported here because no comparable figures are available for accuracy assessment.

The USDA - Forest Service - Forest Inventory and Analysis unit is responsible for decadal inventories of every US state. They inventoried Delaware in 1999, one year prior to the laser overflights. The FIA measured or remeasured 215 systematically located plots to calculate cover type, county, and statewide estimates of stems, merchantable volume, and total above-ground dry biomass (7). Though the FIA forest cover classes vary significantly from the forest classes established in the 1997 Delaware GIS (8), totals across forest classes are comparable. Table 2 compares laser and FIA estimates of total stem, merchantable volume, and total above-ground dry biomass, by county and state. To reduce sampling errors, the FIA concatenates results for the two smaller Delaware counties, Newcastle and Kent

As noted in Table 2, stem estimates vary up to 40% at the county level and over 25% at the state level. For one of the two counties (considering Newcastle and Kent as one) and statewide, laser stem estimates consistently fall outside of the 95% confidence interval surrounding the FIA stem estimates. Laser merchantable volume estimates are within 14 percent at the county level and within 4 percent at the state level; all laser estimates fall within the FIA 95% confidence limits. Laser biomass totals are consistently smaller than FIA dry biomass totals but are within 20% at the county level and 16% at the state level. One of the three laser biomass estimates fall within the comparable FIA 95% confidence intervals.

Based on a review of the literature and the results presented in Table 2, the authors put forth two hypotheses for consideration. First, models which predict ground-measured volume or biomass as a function of profiling laser variables are, in general, weaker (i.e., lower $R^2$ values) for hardwoods or hardwood-conifer mixes and stronger for conifers (9). Second, merchantable volume and biomass are predicted more accurately than basal area and stem counts using profiling airborne laser altimetry, and this predictive differential increases as the hardwood species component increases (10). The authors suspect that the consistent, relatively poor showing of east coast hardwoods is due to their deliquescient, multi-stemmed growth form. Trees which exhibit apical dominance, i.e., a single stem tendency, such as conifers, tend to exhibit stronger relationships between height and the volume or weight of wood in a tree. If the hypotheses are true, then laser-based inventory estimates will be more accurate in areas where tree growth forms tend towards apical dominance (e.g., coniferous forests of the SE US, circumpolar boreal forests).

Preliminary results suggest that profiling lasers might be at a disadvantage in environs which support predominantly deliquiscent canopies. However small-footprint (<1m) scanning laser altimetry might mitigate this prediction deficiency since high-resolution laser data can be used to delineate individual tree crowns, and overstory crown diameter might serve as a surrogate for dbh (11).

**Repeatability and Sampling Intensity:**

The use of an airborne laser to inventory forests has one distinct and significant advantage over ground-based inventory procedures. Once the ground-laser models (which predict, for instance, volume or biomass as a function of airborne laser measurements) are developed at time zero, no additional ground work is needed to conduct subsequent inventories at $t_1$, $t_2$, etc. The $t_1$, $t_2$ inventories only require the reacquisition of laser measurements along the same flight paths and the computer processing of those laser measures. Such a re-inventory/change detection scenario raises two questions. First, how repeatable are laser-based volume or biomass estimates (12)? Second, how intensively should a county or state be flown in order to generate precise results?

In order to answer these questions, stem, volume, and dry biomass estimates were calculated using all 14 flight lines, 2 sets of 7 flight lines, 3 sets of 5 flight lines, 4 sets of 4 flight lines, 5 sets of 3 , and 7 sets of 2 flight lines. The flight line subsets were constructed, as near as possible, to be mutually exclusive. Flight lines used in one subset were not used in other comparably-sized subsets. Exceptions were made in one of the three 5-line sets, in two of the 4-line sets, and in one of the 3-line sets. In each of these, one flight line was used in two subsets. The flight line subsets were selected to ensure broad, systematic, statewide coverage. The results

(Figure 3) illustrate 1) how stratum, county and state estimates vary as sampling intensity is reduced, and 2) how estimates vary within a given sampling intensity. Results are provided for Newcastle, the smallest county, for Sussex, the largest county, and for the entire State. Stem and merchantable volume results are similar in appearance to the Figure 3 dry biomass graphs and are not presented.

For a given cover type (ct) within county, an appropriate sampling intensity will be a function of that cover type's spatial extent, spatial distribution (random versus clustered), and intrinsic class variability. The more extensive the ct, i.e., the higher the percentage of the study area in that particular ct, the greater the likelihood that flightlines will intercept and representatively sample it. Likewise, the more randomly distributed a ct, the more likely it is to be representatively sampled by systematic transects. Finally, the lower the intrinsic variability of a ct, the smaller the number of times that it must be intercepted in order to be precisely characterized. In Figure 3 we look for convergence towards a stable value as sampling intensity increases, where sampling intensity equals kilometers of flight line intercepting the given ct per square kilometer of sampled area, e.g. the county or state area (13).

The following preliminary findings might lend some guidance to those planning laser aircraft operations related to long-term monitoring of natural resources. The recommendations below apply specifically to the Mid-Atlantic, heavily dissected, coastal plain forests of Delaware, though they might be applied elsewhere in lieu of any alternate guidance. A rough conversion from range (provided below) to standard error may be calculated by dividing the range by 4 (14). Note that a sampling intensity of 0.05 km/km$^2$ corresponds to a systematic, parallel flight line spacing of 1 flightline every 20 km; 0.10 km/km$^2$ = 1 flightline every 10 km; 0.15 km/km$^2$ = 1 fl every 6.67 km.

1. To monitor dry biomass statewide (5200 $km^2$) in a specific forest cover type (e.g., conifer, 2.3% of the land area) or in forestlands in general (34.1% of the land area) within a range of ~20t/ha, a sampling intensity of 0.10 $km/km^2$ should be employed. The range decreases to ~7 t/ha at a sampling intensity of 0.15 $km/km^2$.

2. Consideration/enumeration of smaller, more dissected areas such as Newcastle County (1124 $km^2$) require higher sampling intensities for a given cover type. For instance, at a sampling intensity of 0.15 $km/km^2$, the range of dry biomass estimates for all forestlands (27.6% of the land area) is 30 t/ha. Reliable, stable biomass estimates of relatively rare cover types (e.g., conifer, 0.3% of the county area) in an area the size of Newcastle requires sampling intensities well in excess of 0.25 $km/km^2$; no evidence of coniferous estimate stability was noted in the sampling intervals considered in this study. . The conifer ct is the limiting factor in the county, since the conifer estimates bounce between 142 mtons/ha and zero, depending on whether or not the flight line subset considered included the single laser transect which intercepted one or more of the few conifer polygons Newcastle County.

3. For an area of the size and with the land cover characteristics of Sussex County, a mostly agricultural county, 2500 $km^2$, 36% forested, an SI $\approx$ 0.12 $km/km^2$ is appropriate to estimate volume and biomass in conifer, forest, nonforest, and for all strata. Higher SIs are needed to reliably measure residential wood resources, though an argument could be made that all five of these cover types could be precisely, repeatedly monitored with systematically-located flight lines spaced 4 to 8 km apart (15).

4. If a biomass estimate across all cover types is needed for the entire state, then a sampling intensity of 0.05 $km/km^2$ yeilds a range of biomass estimates of 13 t/ha where the average biomass statewide is 50 t/ha. A

sampling intensity of 0.10 $km/km^2$ produces a biomass estimate range of 10 t/ha; a si = 0.15 $km/km^2$ yeilds a range of 5 t/ha.

**Impervious Surfaces Area and Open Water Area:**

Line Intercept Sampling techniques (16) were used to estimate impervious surface and open water area, by county and state. The 14 laser flight lines were reviewed to identify segments of flight line which traversed roofs, asphalt/concrete, and open water. The laser flight lines were cropped at the Delaware River, the Delaware Bay, and the Atlantic Ocean so that open water estimates would not be skewed severely by these large water bodies which make up the eastern border of the State (17). Estimates of open water area then, include only that water west of the eastern State shorelines. Open water estimates do include the water areas of Rehobeth Bay, the Indian River Inlet and Bay, and Little Assawoman Bay north of Ocean City, MD, substantial bodies of salt/brackish water.

The estimation technique involves simple ratios. The area under roof in Newcastle County, for instance, is merely the county area multiplied by the ratio of the length of flight lines traversing roof in Newcastle divided by the total length of the flight lines flown over Newcastle. Once impervious surfaces and open water were flagged by manual inspection of the laser profiles and video record, flightlnes were automaticallly processed to estimate pervious (forest, nonforest), impervious (roof, asphalt/concrete), and open water area for the three counties and statewide. The results are presented in Table 3.

It is interesting to note that 11% of the surface area of Newcastle County, which includes the cities of Wilmington and Newark, the Interstate 95/295/495 corridors, and the industrial waterfronts along the Delaware River, is impervious. 3.5% of Newcastle County is under roof; 7.6% is under asphalt or concrete. Approximately 3% of the more rural/agricultural southern counties are covered by roof, asphalt, and concrete. In total, approximately 4.8% of Delaware is impervious, an area approximately 25% larger than Washington DC.

No independent estimates of impervious surface area have been found for comparison. The University of Maryland, under the auspices of the Mid-Atlantic Regional Earth Science Applications Center (18) is currently working on estimates of impervious surface area for Delaware based on the analysis of 30m Enhanced Thematic Mapper data (Landsat 7), but those estimates are not yet available. Independent open water estimates can be gleaned from the 1997 University of Delaware GIS used as the stratification base map in this study, since this GIS was not consulted while the laser flight lines were visually parsed into the respective surface classes. Comparison of laser and GIS open water percentage estimates, by county and statewide, are presented in Figure 4. The results indicate that laser and GIS open water estimates are comparable; percent differences ((GIS-Laser)/GIS) range from -4.8% (Kent County) to +6.9% (Newcastle County).

**Mapping Delmarva Fox Squirrel Habitat:**

The profiling airborne laser system measures forest canopy heights and canopy density. If these height measures or derived measurements (19) are related to habitat characteristics, then an airborne laser profiler can be used to map potentially suitable habitat and to monitor gains or losses over time. The Delmarva Fox Squirrel, an endangered species on the Delmarva, was endemic to mature, closed canopy forest stands with open understories and plentiful mast production (20). 1306 km of laser profiles were processed to categorize height classes and to locate contiguous forested areas at least 30 meters long with heights averaging over 20m and canopy closures exceeding 80%; those points are mapped in Figures 1 and 2. The areal distributions of forest height - canopy density classes were generated for each of the three counties (Figure 5).

Figure 5 connotes the fact that the majority of the forests >5m tall in all three counties are fully stocked, i.e., most forested tracts in all height classes host dense canopies with closures exceeding 90%. Acceptable DFS habitat will most likely be found in the taller, more mature forest stands with dense canopies. It is interesting to note that the smallest, most urbanized county - Newcastle - supports the greatest area of dense forest over 25m tall. The majority of these stands are interspersed amongst older residential suburbs of Wilmington and Philadelphia in the northern part of the County, one fourth (24.3%) of which is residential. Sussex County supports the greatest area of dense forest over 20m tall. The majority of these stands are situated in a county dominated by agriculture (47.2%) and forest (36.0%).

Summary statistics such as those illustrated in Figure 5 can be used to follow habitat gain/loss over time and to determine the political, e.g., county, affiliations of those gains/losses. Shifts in acreage out of the tallest height classes over time would indicate loss of potential habitat and might be grounds for revisiting developmental regulations in the particular counties supporting the losses.

The laser is a screening tool used to identify and locate potentially suitable sites. The first-return laser system used in this study gives no information concerning the understory characteristics of the highlighted stands, and this understory layer is important to DFS reintroduction and relocation efforts. Most of the contiguous patches of Delaware forest are cut regularly on rotation schedules on the order of 30-70 years, depending on species and site index (21). A dense understory of greenbriar is common in cut stands, and the presence of such a layer for the most part precludes reintroduction of the DFS. Ground visits are needed to verify suitability.

A preliminary study was conducted to determine the screening capability of an airborne profiling laser. Sixteen 40 meter laser transects identifed as having heights exceeding 25m and canopy closures exceeding 90% were visited in the field. Of these 16, all proved to be mature, tall, dense stands; 10 were judged to be capable of supporting DFS. The 6 judged insufficient had significant understory regrowth which would preclude reintroduction. A more rigorous habitat assessment project is currently underway to quantify DFS habitat suitability in different forest height and cover type classes. The study employs a USFWS mathematical model (22) which quantifies habitat suitability based on ground observations along a 5m x 200m sample transect. The results of this study will report screening efficiencies (i.e., number of laser segments found to be suitable for the DFS/number of laser segments visited) by height class and GIS cover type.

**Summary:**

A small, portable, inexpensive airborne laser profiler was used to inventory forests regionally, estimate and monitor impervious surface and open water area, and to locate potentially suitable DFS habitat. At the county level, merchantable volume agreed with USFS-FIA estimates within 14%, and within 4% at the state level. Total above-ground dry biomass laser estimates agreed with FIA estimates within 19% at the county level and 16% at the state level. Though impervious surface estimates could not be validated (due to the unavailability of comparable data), open water estimates were within 6.9% of photointerpreted results at the county level and within 2.3% at the state level. Results also indicated that the airborne laser data could be used to identify and map the location of areas potentially suitable for DFS reintroduction. Preliminary field visits to tall (>25m), dense (>90% canopy closure) stands indicate that over half of these sites (62.5%) would provide habitat suited to the DFS.

If lasers are to be used to detect changes to standing biomass and carbon stocks over time, then a sampling procedure must be employed to insure estimate stability within a particular temporal sampling window, i.e., at time $t_0$, $t_1$, $t_2$... Any change detection procedure which employs a small footprint (sub-meter) profiling laser such as the one used in this study will involve repeated sampling (over time) of established flightlines. It is important to note, however, that those flightlines cannot and will not be reflown exactly, since buffeting winds and pilot and GPS imprecisions will collectively introduce locational errors of 10s of meters (23). The stability of the laser estimates were checked by looking at various flightline subsets at the county and state level. Empircal observations suggest that forest dry biomass can be repeatedly estimated regionally (areas > 5200 $km^2$) within a range of ~7 t/ha with a systematic sample of flightlines spaced 6-8 km apart, i.e., a sampling intensity of 0.15 $km/km^2$. The range of the biomass estimate will decrease as the size of the study area considerd increases.

An airborne laser profiling system should be viewed as a regional assessment tool, to be used to monitor areas on the order of 100s of thousands of hectares or larger. Possible applications include inventory and monitoring of forest structure (e.g., height, canopy roughness/ variability, canopy density), timber volume, and above-ground biomass and carbon stocks and fluxes. Consideration should be given to the application of this technology to areas with little forest mensuration information and/or to areas undergoing rapid change, e.g., the circum-polar boreal forests, the Amazon, the Congo, Madagascar, SE Asia.

These inventory and monitoring applications take advantage of the primary strengths of an airborne laser forest inventory system. First, the ground work needed to relate volume, biomass, and carbon to laser metrics need only be done once for a particular study area. Once the predictive equations are established, subsequent laser deployments for re-inventory/monitoring purposes involve only the airborne sampling phase and the post-mission computer processing necessary to produce inventory estimates. Second, once the predictive regressions have been calculated for the first inventory, the data analysis sequence does not not involve analysts in any sort of interpretative role, thereby removing a potential, possibly significant, source of bias (24). If the predictive regression equations are unbiased, the laser-based inventory procedure will produce unbiased results at $t_0$, $t_1$, $t_2$... If, in fact, the regression equations are biased, then that bias remains constant between remeasurement periods, mitigating flux errors.

Generic relationships have been established between above-ground dry biomass and carbon (25), so, to the extent that biomass can be accurately measured and the generic biomass-carbon relationships hold, an airborne laser profiler can be used to estimate and monitor carbon regionally. Such a system may have utility as a carbon monitoring device when carbon become a globally-regulated commodity.

**References and Notes:**

1. J.C. Ritchie, T.J. Jackson, J.H. Everitt, D.E. Escobar, J.B. Murphey, and E.H. Grissinger, *J. Soil and Water Cons.* 47(1): 104-107 (1992); J.B. Blair, M.A. Hofton, *Geophys. Res. Lett.* 26(16): 2509-2512 (1999); W.B. Krabill, C.W. Wright, R.N. Swift, E.B. Frederick, S.S. Manizade, J.K. Yungel, C.F. Martin, J.G. Sonntag, M. Duffy, W. Hulslander, J.C. Brock, *Photogrammetric Eng. and Remote Sens.* 66(1): 65-71 (2000); R. Nelson, G. Parker, M. Hom, *Photogrammetric Eng. and Remote Sens., in press (2002).*

2. See http://www.airbornelasermapping.com for listing of corporate LIDAR providers and various applications, including terrain mapping beneath vegetation, highway, railroad, utilities (powerline, pipeline) mapping/monitoring, monitoring shoreline erosion.

3. E.P. Baltsavias, ISPRS *J. Photogrammetry and Remote Sens.* 54: 164-198 (1999).
4. R. Nelson, G. Parker, M. Hom, *Photogrammetric Eng. and Remote Sens., in press (2002).*
5. University of Delaware Spatial Analysis Laboratory, 1997 photointerpreted GIS product.
http://www.udel.edu/FREC/spatlab/
The 44 - 1997 land cover classes were concatentated into 8 classes.
6. R.F. Nelson, A. Short, M.A. Valenti, submitted to *Forest Science* ( 2002).
7. D.M. Griffith, R.H. WWidmann, Forest Statistics for Delaware: 1986 and 1999, Res. Bull. NE-151, Northeastern Res. Stat., USDA-FS, Newtown Square, PA, 58 p., (2001).
8. The USFS-FIA post-stratifies their systematic plots in order to develop land cover class estimates for common generic cover types (e.g., oak/hickory, beech/birch/maple, oak/pine). They sample plots/subplots in areas stocked with trees that are at least an acre in size and more than 120 feet wide. They do not sample trees in agricultural, residential, or urban areas unless the size criteria just mentioned are met. If the size criteria are met, then the wood production found in ag, residential or urban areas is considered "Forest land", not "Timberland", wood production. The 1997 Delaware GIS land cover classification, on the other hand, is based on photointerpretation results using 1m resolution 1992 CIR photography and 1997 B&W photography interpreted with a 4 acre minimum mapping unit. The 1997 University of Delaware map defines four forest classes - hardwoods, mixedwood, conifer, and wetlands. Much of the wetlands cover type is heavily forested inland and much is treeless marsh near the Delaware River, Delaware Bay, and Atlantic Ocean. Year 1999 USFS-FIA "Timberland" totals were compared with year 2000 laser "Forest" totals, where the laser "Forest" class consists of the 4 1997 GIS forest cover types.
9. Compare hardwood results reported in M.A. Lefsky, D. Harding, W.B. Cohen, G. Parker, and H.H. Shugart, *Remote Sens. Env.* 67: 83-98 (1999) to conifer results in M A. Lefsky, W.B. Cohen, S.A. Acker, G.G. Parker, T.A. Spies, and D. Harding, *Remote Sens. Env.* 70: 339-361 (1999). See also S.C. Popescu, R.H. Wynne, R.F. Nelson, ERIM Conf., 2nd Int. Conf. - Geospatial Info. in Ag. and For., Lake Buena Vista, FL, Jan. 10-12, Vol. II: 346-353 (2000); S.C. Popescu, Dissertation, Virginia Tech, Blacksburg, VA. 137 pp. (2002).
10. This point is arguable. The following citations support the hypothesis: M.A. Lefsky, W.B. Cohen, S.A. Acker, G.G. Parker, T.A. Spies, and D. Harding, *Remote Sens. Env.* 70: 339-361 (1999); E. Naesset, *Remote Sens. Env.* 80: 88-99 (2002). The following citations do not support the hypothesis, suggesting that, in western US coniferous stands, basal area, biomass, and volume models are essentially equivalent; $R^2$ values of 0.95 to 0.97: J.E. Means, S.A. Acker, D.J. Harding, J.B. Blair, M.A. Lefsky, W.B.

Cohen, M.E. Harmon, W.A. McKee, *Remote Sens. Env.* 67: 298-308 (1999); J.E. Means, S.A. Acker, B.J. Fitt, M. Renslow, L. Emerson, and C.J. Hendrix, *Photo. Eng. Remote Sens.* 66(11): 1367-1371 (2000).

11. S.C. Popescu, Dissertation, Virginia Tech, Blacksburg, VA. 137 pp. (2002).

12. Differences in volume, biomass, and mean canopy height estimates for repeated flightlines over a SE US pine forest ranged from 3-6%, R.Nelson, R. Swift, and W. Krabill, *J.Forestry* 86(10): 31-38.

13. Cover types were selected to reflect a wide variety of spatial distributions and forested states.

14. F. Freese. Elementary Forest Sampling, Agricult. Handbook No. 232, USDA-Forest Service, US Gov. Printing Office, Wash., DC. 91 p. (1962), pg. 25.

15. Since there is only one observation at SI = 0.25 km/ $km^2$, it is unknown whether or not estimates are stable at this si level. A subsequent study utilizing all 54 flightlines will permit us to look at the sampling intensity issue up to an SI ≈ 1 km/ $km^2$.

16. L. Kaiser, *Biometrics* 39: 965-976, (1983); P.G. DeVries, Sampling Theory for Forest Inventory. Springer-Verlag, New York. 399 p., (1986).

17. The eastern border of Delaware encompasses all of the Delaware River from the State's NE border to a point approximately 7km south of the Chesapeake and Delaware Canal. The New Jersey - Delaware border roughly bisects the southern portion Delaware River and the Delaware Bay.

18. Mid-Atlantic RESAC - http://www.geog.umd.edu/resac/

19. A varienty of derived measurements can be calculated based on the cumulative frequency distribution (CFD) of heights along specific segments of a profiling laser flight line. Specific quartile or decile heights as well as the slope of the CFD in different height quartiles or deciles have been related to stand maturity. Rumple, or the ratio of the profile length at the top of the canopy to the length of the vertical projection of that trace is also related to stand maturity in a closed canopy (G. Parker, pers. comm.).

20. P.R. Bender, G.D. Therres, *Amer. Midland Naturalist* 132(2): 227-233 (1994).

21. Loblolly pine sawtimber rotation is 40-50 years; softwood pulp is cut at ~30 years old. Poplar and oak rotations vary from ~40-70 years.

22. R.D. Dueser, J. L. Dooley, R. Taylor, G.J. Taylor, p. 414-421, In R. C. Szaro, K. E. Severson, D. R. Patton (eds.), Management of amphibians, reptiles and small mammals in North America, U.S. Forest Service Tech. Rpt. RM-166, Ft. Collins, CO (1988).

23. In this Delaware study, actual versus planned flightline divergences varied from 0.4 m - 77.1 m (n=50), with an average discrepancy of 24.5

meters. In a previous study, where 3 flight lines were marked by balloons and the lines repeated, as closely as possible, with a 4-engine turboprop aircraft flying at an altitude of 150 AGL, divergences ranged from 0m to 120m with average flight line divergences of 15m, 30m, and 60m - R. Nelson, R. Swift, and W. Krabill, *J. For.* 86(10): 31-38, (1988).

24. In the opinion of the primary author, one of the greatest weaknesses of satellite data processing for natural resources mapping and monitoring, and therefore one of the biggest reasons that satellite data analysis has not been collectively embraced by the natural resource community, is the non-repeartable nature of the data processing stream. For instance, given the same satellite data set, two different analysts may develop significantly different resource maps. The same may be said of the same analyst processing data sets of the same area acquired on two different dates. The airborne laser data processing stream involved in this study removes this potentially significant source of analyst bias.

25. Above-ground dry biomass to carbon conversion ratios reported in the literature vary, but 0.5 is typical (R.A. Houghton, pers. comm.). Tropical conversion factors of 0.45 (secondary tropical forest) and 0.5 (primary tropical forest) are reported (R.A. Houghton, D.L. Skole, C.A. Nobre, J.L. Hackler, K.T. Lawrence, W.H. Chomentowski, *Nature* 403(20): 301-304; R.F. Nelson, D.S. Kimes, W.A. Salas, M. Routhier, *Bioscience* 50(5): 419-431, (2000),Table 2). In boreal ecosystems, above-ground dry biomass to carbon multipliers of 0.5 (woody biomass) and 0.45 (foliar biomass) have been used (S.T. Gower, J.G. Vogel, J.M. Norman, C.J. Kucharik, S.J. Steele, T.K. Stow, *J. Geophys. Res.* 102(D24): 29,029-29,041 (1997). Estimates of below-ground carbon are more difficult to calculate due to variation induced by soil fertility (P.M. Vitousek, R.L. Sanford, *Annu. Rev. Ecol. Syst., 17:137-167;* P.M. Fearnside, W.M. Guimarães, *For. Eco. and Mgmt.* 80: 35-46, (1996)). If the 0.5 biomass-carbon conversion holds below ground, then generic multipliers can be used ta calculate below-ground carbon. R.A. Houghton, D.L. Skole, D.S. Lefkowitz, *For. Eco. Mgmt.* 38: 173-199, (1991) multiplied above-ground dry biomass by 0.2 to calculate generic below-ground biomass estimates in Latin America. R.A. Houghton, K.T. Lawrence, J.L. Hackler, S. Brown, *Global Change Biology* 7:731-746, (2001), working in the Amazon, report an above-ground living (dry) biomass to below-ground biomass conversion factor of 0.205. If dead above-ground forest biomass is included in the calculation, the total above-ground dry biomass to below-ground dry biomass conversion factor is 0.188.

Table 1 Airborne laser profiling estimates of (A) stems/ha, (B) merchantable volume/ha, and (C) total above-ground dry biomass/ha, by cover type, county, and state.

A. Stems per hectare:

| | Newcastle | Kent | Newcastle /Kent | Sussex | Delaware |
|---|---|---|---|---|---|
| Hardwood | 1090.69 | 1233.33 | 1134.44 | 1298.45 | 1147.66 |
| SEE | 18.61 | 25.73 | 15.13 | 50.28 | 14.49 |
| Mixedwood | 1065.39 | 1424.22 | 1387.41 | 1425.22 | 1417.72 |
| SEE | 89.15 | 19.87 | 20.04 | 11.97 | 10.38 |
| Conifer | 1617.03 | 1815.38 | 1773.37 | 1900.15 | 1886.36 |
| SEE | 192.18 | 66.10 | 66.12 | 33.95 | 31.10 |
| Wetlands | 460.11 | 824.50 | 732.68 | 1031.68 | 872.55 |
| SEE | 19.68 | 14.43 | 11.88 | 12.05 | 8.47 |
| Forestland | 825.15 | 976.42 | 921.85 | 1278.78 | 1105.85 |
| SEE | 13.39 | 11.27 | 8.67 | 8.50 | 6.07 |
| Agriculture | 144.47 | 75.69 | 96.87 | 106.84 | 102.04 |
| SEE | 8.42 | 4.15 | 3.87 | 4.21 | 2.87 |
| Residential | 376.82 | 332.91 | 362.64 | 460.26 | 396.46 |
| SEE | 10.83 | 15.88 | 8.95 | 14.44 | 7.69 |
| Urban | 228.88 | 159.12 | 210.14 | 322.28 | 241.57 |
| SEE | 13.46 | 19.32 | 11.13 | 23.90 | 10.44 |
| Nonforest Land | 243.55 | 115.96 | 173.31 | 170.07 | 171.81 |
| SEE | 6.01 | 4.15 | 3.54 | 4.19 | 2.72 |
| Water | 108.08 | 75.35 | 91.08 | 50.42 | 64.06 |
| SEE | 20.52 | 14.70 | 12.47 | 7.30 | 6.41 |
| Total: | 400.53 | 421.81 | 412.84 | 563.91 | 486.52 |
| SEE | 5.62 | 4.79 | 3.64 | 3.96 | 2.68 |

## B. Merchantable Volume per hectare (cu. meters per ha):

| | Newcastle | Kent | Newcastle /Kent | Sussex | Delaware |
|---|---|---|---|---|---|
| Hardwood | 174.74 | 167.52 | 172.53 | 141.86 | 170.06 |
| SEE | 2.41 | 2.83 | 1.88 | 5.16 | 1.78 |
| Mixedwood | 150.39 | 151.99 | 151.83 | 145.72 | 146.93 |
| SEE | 10.41 | 2.17 | 2.22 | 1.19 | 1.05 |
| Conifer | 170.30 | 135.55 | 142.91 | 129.15 | 130.64 |
| SEE | 19.43 | 7.42 | 7.15 | 2.81 | 2.62 |
| Wetlands | 71.65 | 77.41 | 75.96 | 95.50 | 85.10 |
| SEE | 3.64 | 2.04 | 1.78 | 2.03 | 1.34 |
| Forestland | 129.99 | 100.35 | 111.05 | 118.30 | 114.79 |
| SEE | 2.05 | 1.54 | 1.23 | 1.16 | 0.85 |
| Agriculture | 15.86 | 12.07 | 13.24 | 11.46 | 12.31 |
| SEE | 0.80 | 0.49 | 0.42 | 0.37 | 0.28 |
| Residential | 56.90 | 47.22 | 53.77 | 57.74 | 55.15 |
| SEE | 1.51 | 1.71 | 1.16 | 1.49 | 0.92 |
| Urban | 27.78 | 17.95 | 25.14 | 28.80 | 26.16 |
| SEE | 1.58 | 1.75 | 1.25 | 1.96 | 1.05 |
| Nonforest Land | 32.71 | 17.21 | 24.18 | 19.08 | 21.82 |
| SEE | 0.72 | 0.47 | 0.41 | 0.38 | 0.28 |
| Water | 17.28 | 5.56 | 11.19 | 1.85 | 4.99 |
| SEE | 3.88 | 2.15 | 2.17 | 0.61 | 0.83 |
| Total: | 59.16 | 46.61 | 51.90 | 54.02 | 52.93 |
| SEE | 0.76 | 0.62 | 0.48 | 0.48 | 0.34 |

C. Total Above-Ground Dry Biomass per hectare:

| | Newcastle | Kent | Newcastle /Kent | Sussex | Delaware |
|---|---|---|---|---|---|
| Hardwood | 158.60 | 156.22 | 157.87 | 136.88 | 156.18 |
| SEE | 1.76 | 2.09 | 1.38 | 4.40 | 1.32 |
| Mixedwood | 139.73 | 147.33 | 146.55 | 142.49 | 143.29 |
| SEE | 8.31 | 1.63 | 1.69 | 0.95 | 0.83 |
| Conifer | 142.17 | 116.03 | 121.56 | 115.94 | 116.55 |
| SEE | 13.54 | 5.18 | 4.99 | 1.98 | 1.84 |
| Wetlands | 60.05 | 73.44 | 70.06 | 91.58 | 80.13 |
| SEE | 2.78 | 1.55 | 1.35 | 1.43 | 0.98 |
| Forestland | 115.83 | 95.02 | 102.52 | 113.52 | 108.19 |
| SEE | 1.54 | 1.17 | 0.93 | 0.84 | 0.62 |
| Agriculture | 15.80 | 11.13 | 12.57 | 11.39 | 11.96 |
| SEE | 0.69 | 0.41 | 0.36 | 0.32 | 0.24 |
| Residential | 54.33 | 44.85 | 51.27 | 56.94 | 53.23 |
| SEE | 1.34 | 1.54 | 1.03 | 1.38 | 0.83 |
| Urban | 27.06 | 17.58 | 24.51 | 30.31 | 26.14 |
| SEE | 1.31 | 1.47 | 1.04 | 1.71 | 0.89 |
| Nonforest Land | 31.64 | 16.12 | 23.10 | 19.01 | 21.20 |
| SEE | 0.62 | 0.40 | 0.36 | 0.34 | 0.25 |
| Water | 14.21 | 5.15 | 9.50 | 2.44 | 4.81 |
| SEE | 2.96 | 1.39 | 1.60 | 0.46 | 0.62 |
| Total: | 54.42 | 44.01 | 48.40 | 52.27 | 50.29 |
| SEE | 0.61 | 0.49 | 0.38 | 0.36 | 0.26 |

Table 2. Comparison of FIA and Laser results, A. total stem counts; B. total merchantable volume; and C. total above-ground dry biomass.

A. FIA-laser stem totals comparison:

| | Newcastle/Kent | Sussex | Delaware |
|---|---|---|---|
| FIA Total | 76525300. | 187473800. | 263999100. |
| FIA SEE | 7882106. | 18559906. | 20327931. |
| FIA-1.96*SEE | 61076372. | 151096384. | 224156356. |
| FIA+1.96*SEE | 91974228. | 223851216. | 303841844. |
| Laser Total | 79279587. | 117010993. | 196290580. |
| Laser SEE | 745962. | 777500. | 1077481. |
| Percent Difference: (FIA-Laser)/FIA | -3.60 | 37.59 | 25.65 |

B. FIA-laser merchantable volume (cubic meters) totals comparison:

| | Newcastle/Kent | Sussex | Delaware |
|---|---|---|---|
| FIA Total | 8417365. | 11180685. | 19598050. |
| FIA SEE | 892241. | 1140430. | 1450256. |
| FIA-1.96*SEE | 6668574. | 8945442. | 16755549. |
| FIA+1.96*SEE | 10166157. | 13415927. | 22440551. |
| Laser Total | 9550026. | 10825004. | 20375030. |
| Laser SEE | 105915. | 106384. | 150118. |
| Percent Difference: (FIA-Laser)/FIA | -13.46 | 3.18 | -3.96 |

C. FIA-laser total above-ground dry biomass (metric tons) totals comparison:

| | Newcastle/Kent | Sussex | Delaware |
|---|---|---|---|
| FIA Total | 10106636. | 12673364. | 22780000. |
| FIA SEE | 1111730. | 1039216. | 1526260. |
| FIA-1.96*SEE | 7927646. | 10636501. | 19788530. |
| FIA+1.96*SEE | 12285627. | 14710227. | 25771470. |
| Laser Total | 8817107. | 10387101. | 19204209. |
| Laser SEE | 79919. | 76592. | 110695. |
| Percent Difference: (FIA-Laser)/FIA | 12.76 | 18.04 | 15.70 |

Table 3. Surface area percentages for Delaware, by county, as estimated using airborne laser profiling data and LIS techniques. These percentages may be converted to area by multiplying by the county and state areas - 112412 ha, 154234 ha, 253896 ha, 520543 ha for Newcastle, Kent, Sussex Counties and Delaware, respectively.

Laser Transect Surface Report,
by County and for the State (percent)

| | Newcastle | Kent | Sussex | Delaware |
|---|---|---|---|---|
| Forest | 27.92 | 26.85 | 33.66 | 30.40 |
| SEE | 0.71 | 0.50 | 0.39 | 0.31 |
| Nonforest | 58.26 | 67.83 | 58.92 | 61.42 |
| SEE | 0.58 | 0.53 | 0.37 | 0.28 |
| Pervious Subt: | 86.18 | 94.68 | 92.58 | 91.82 |
| SEE | 0.25 | 0.39 | 0.24 | 0.13 |
| Roof | 3.45 | 1.13 | 1.04 | 1.59 |
| SEE | 0.05 | 0.08 | 0.06 | 0.02 |
| Asphalt/Concr: | 7.57 | 2.21 | 1.77 | 3.16 |
| SEE | 0.11 | 0.12 | 0.09 | 0.05 |
| Imperv. Subt: | 11.02 | 3.35 | 2.82 | 4.75 |
| SEE | 0.15 | 0.15 | 0.12 | 0.06 |
| Water | 2.80 | 1.97 | 4.61 | 3.43 |
| SEE | 0.21 | 0.37 | 0.22 | 0.12 |
| TOTAL: | 100.00 | 100.00 | 100.00 | 100.00 |

## LIST OF FIGURES

Figure 1. Laser flightlines flown over Delaware, summer 2000. A. 1306 km of linear airborne laser profiles were collected and analyzed in this study; 282 km were collected over Newcastle County. B. A portion of the Sussex County flightlines south of Cape Henlopen. dGPS GMT times are listed in the upper left picture. The red line is the planned flight line; the white line marks the actual flight path. The blue and red points along the flight lines identify mature stands which might support Delmarva fox squirrel sub-populations. All points have canopy closures exceeding 80%. Blue points mark stands with average canopy heights > 20m tall; red points mark stands >25m tall.

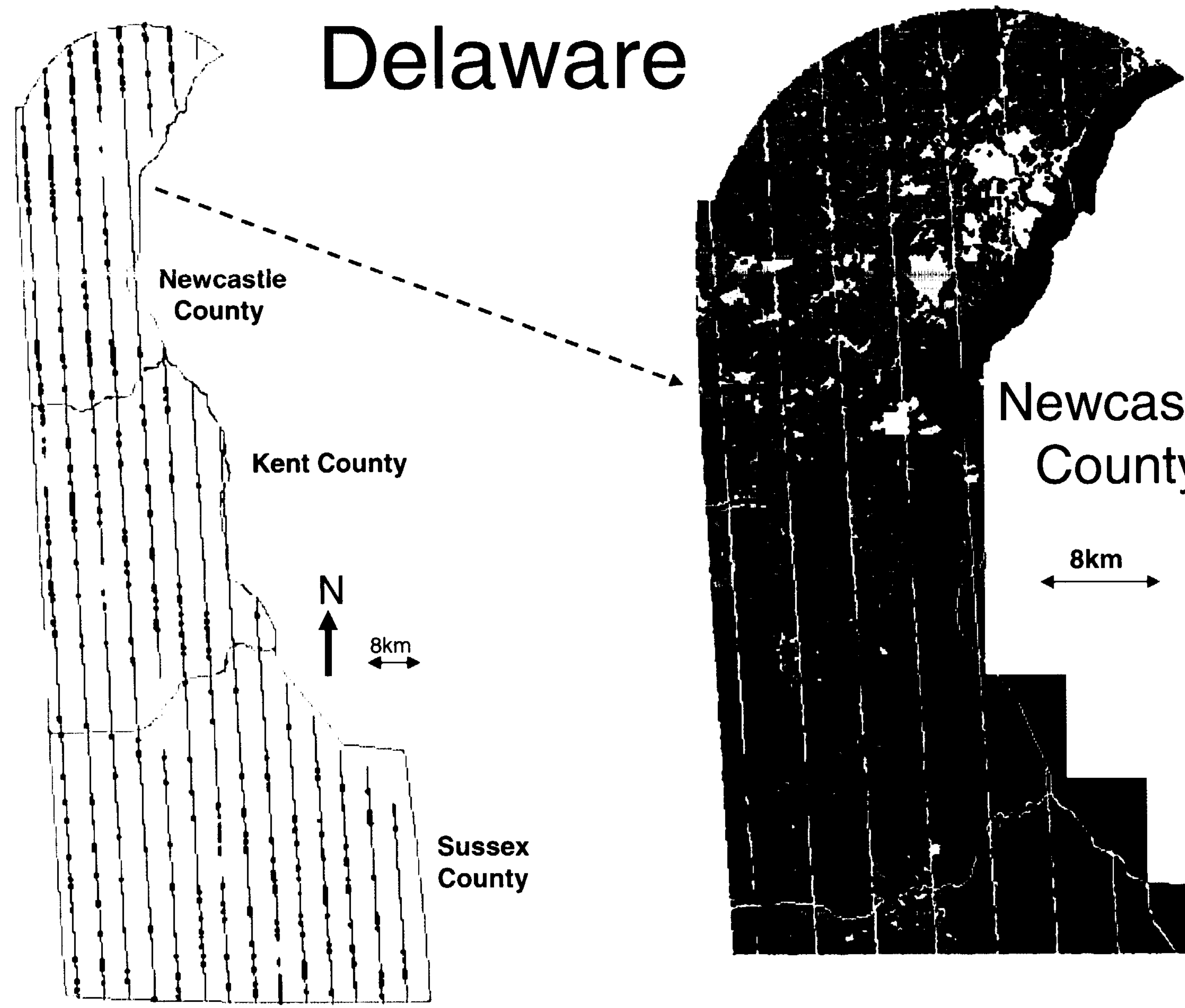
Figure 2. An example of the airborne laser profiling data used in this study; 1.2 km of laser profiling data are shown. The flight path is laid atop a 1992 CIR ortho-photo used to develop the initial statewide GIS (later updated using 1997 B&W photography). The actual flight line is in yellow, as are the dGPS GMT times. The white dotted line is the planned flightpath. GIS polygons are outlined on the photo, blue - wetlands, green - hardwoods. The spiked returns (right side of profile, ~181004 GMT) are laser pulses without a range return. Open water in the wetlands absorbs the 0.905 um near-infrared laser pulse.

Figure 3. Areal estimates of total above-ground dry biomass for 5 cover types - conifer, forest, residential, nonforest, all strata - in A) Newcastle County, B) Sussex County, and C) Delaware.

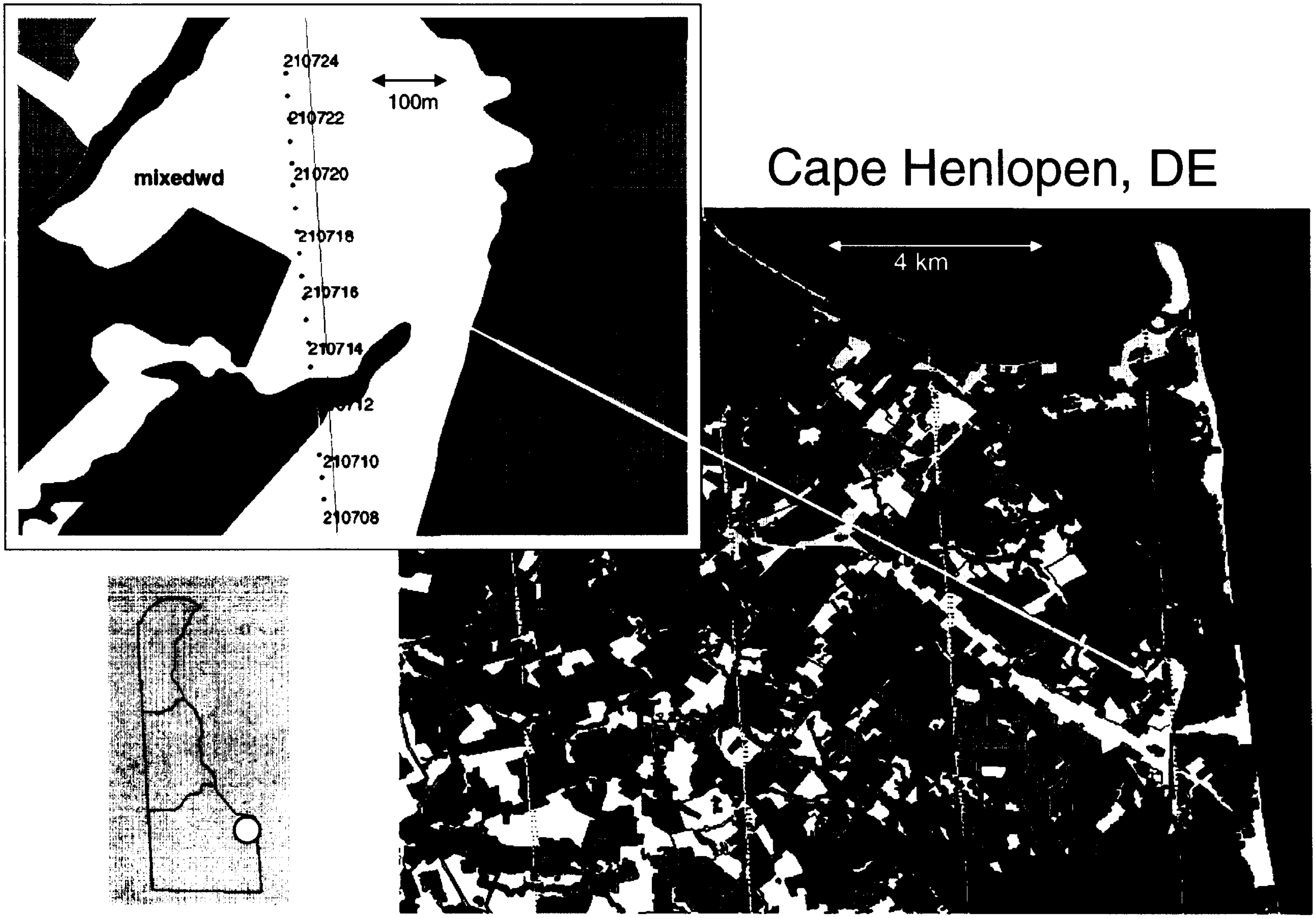
Figure 4. 1997 University of Delaware GIS versus airborne laser estimates of open water for the three counties and the State.

Figure 5. 3-D surface of forest height classes:
X axis - height classes: 5-10m, 10-15m, 15-20m, 20-25m, >25m
Y axis - cc classes: 0-35%, 35-70%, 70-85%, 85-100%
Z axis - area, hectares

A. Newcastle County
B. Kent County
C. Sussex County

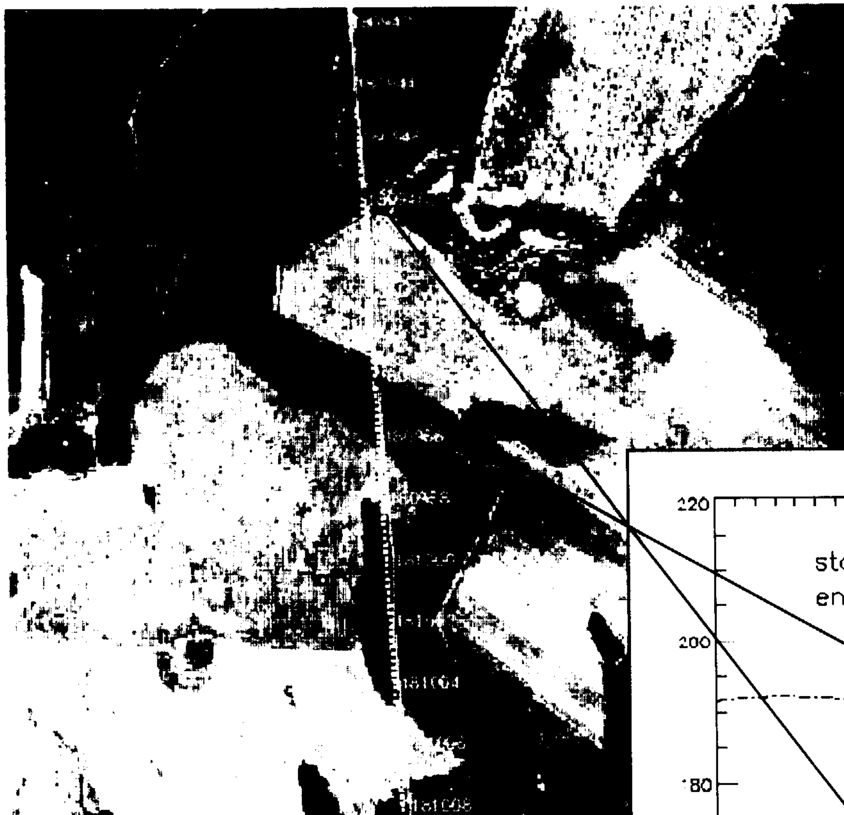

Delaware
Newcastle County
Kent County
N
8km
Sussex County
Newcastle County
8km

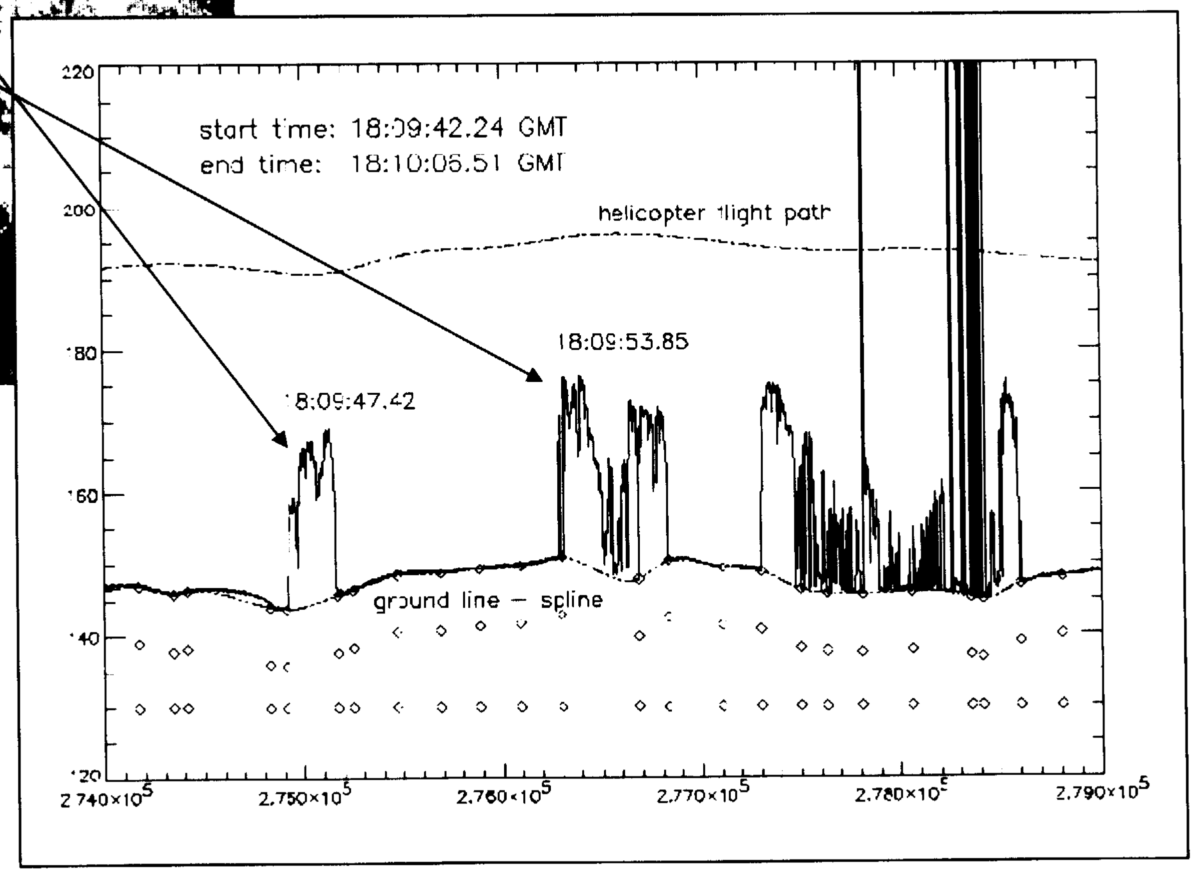
# Cape Henlopen, DE

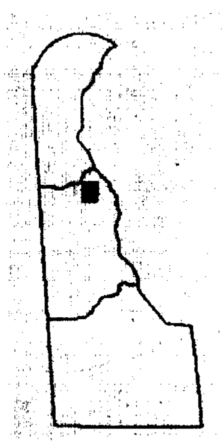


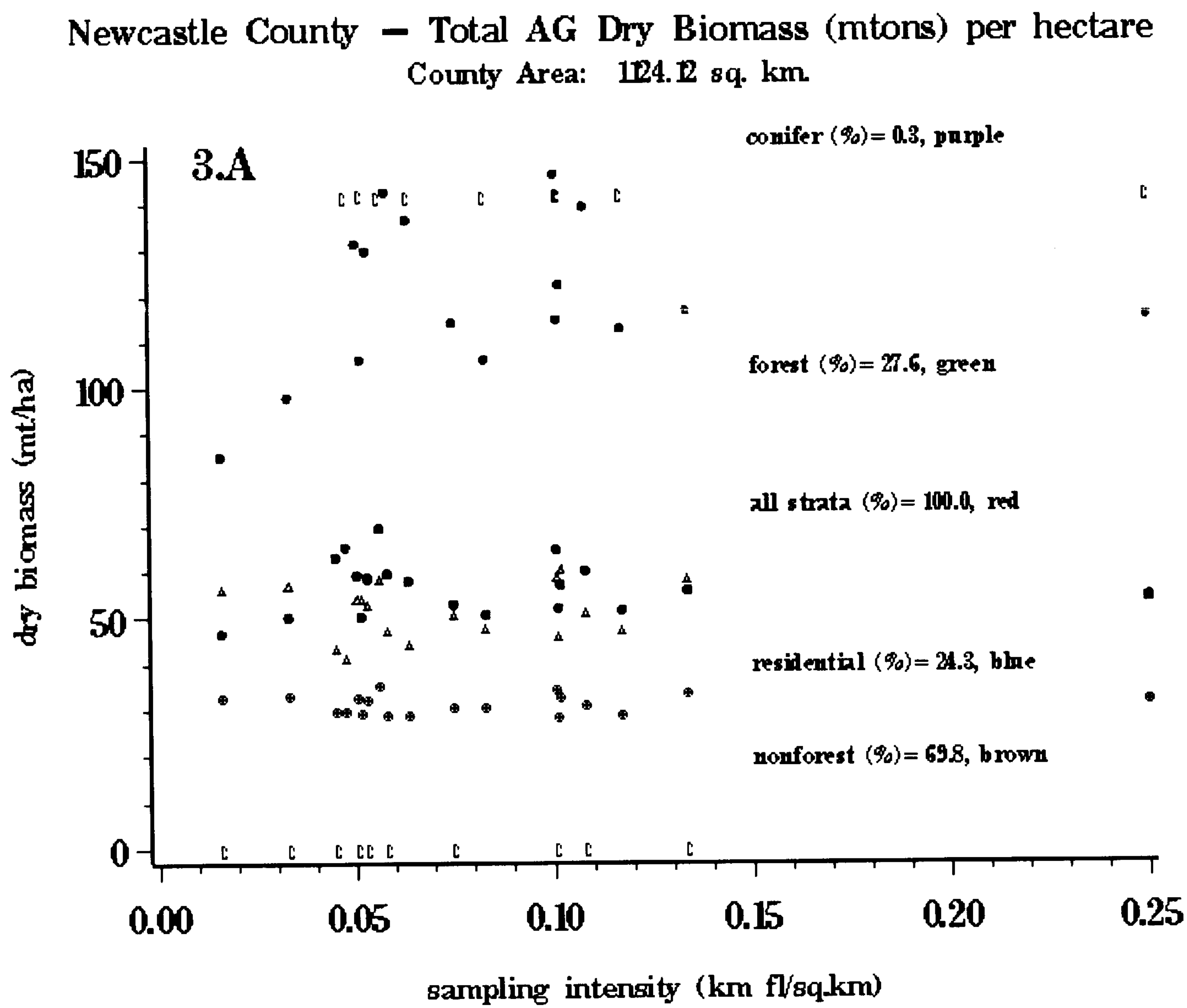
# PALS Data

Segment of flightline 18, Delaware, June 2000





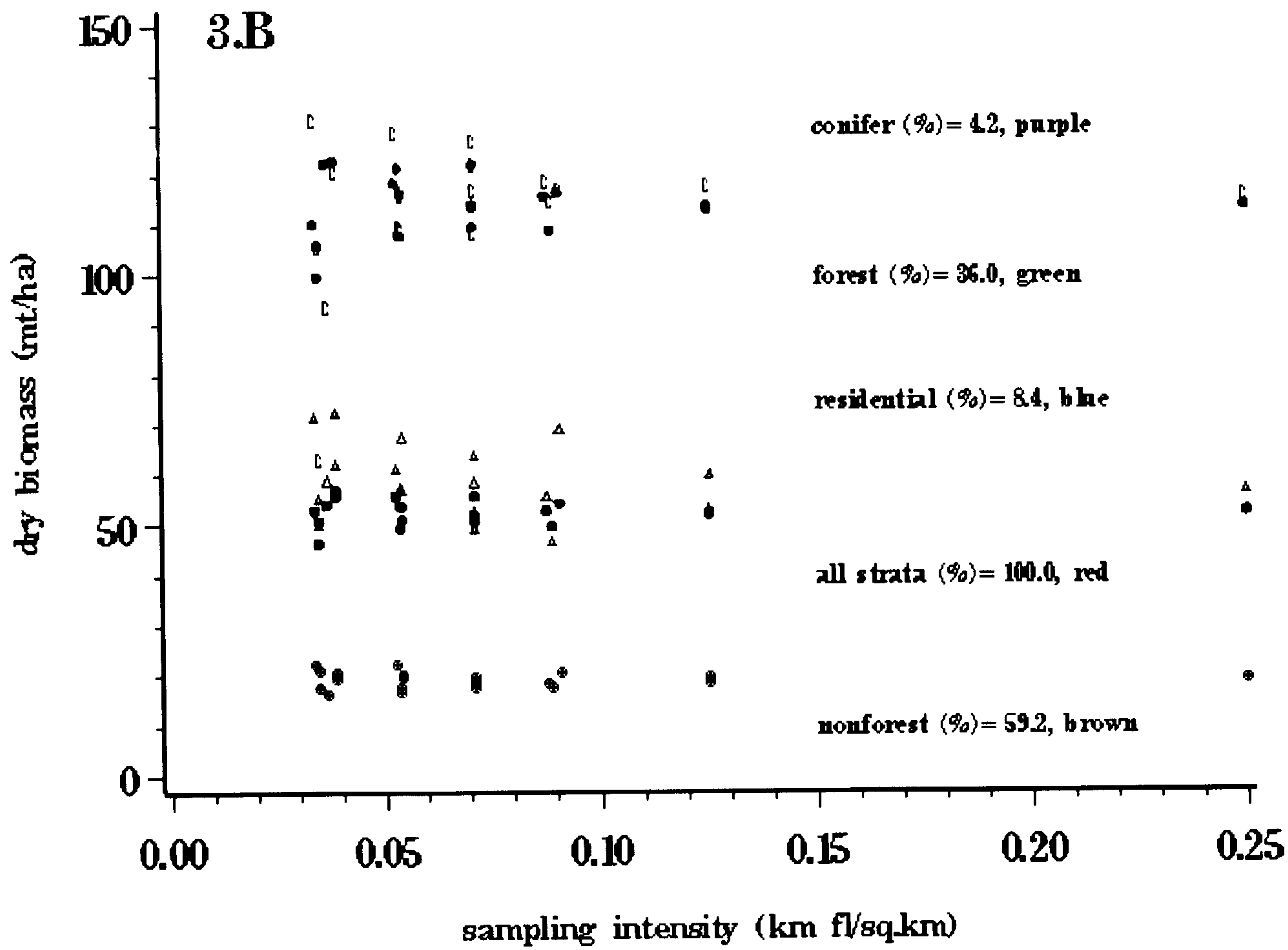





Newcastle County — Total AG Dry Biomass (mtons) per hectare
County Area: 1124.12 sq. km.
3.A
conifer (%)= 0.3, purple
forest (%)= 27.6, green
all strata (%)= 100.0, red
residential (%)= 24.3, blue
nonforest (%)= 69.8, brown
dry biomass (mt/ha)
150
100
50
0
0.00
0.05
0.10
0.15
0.20
0.25
sampling intensity (km fl/sq.km)

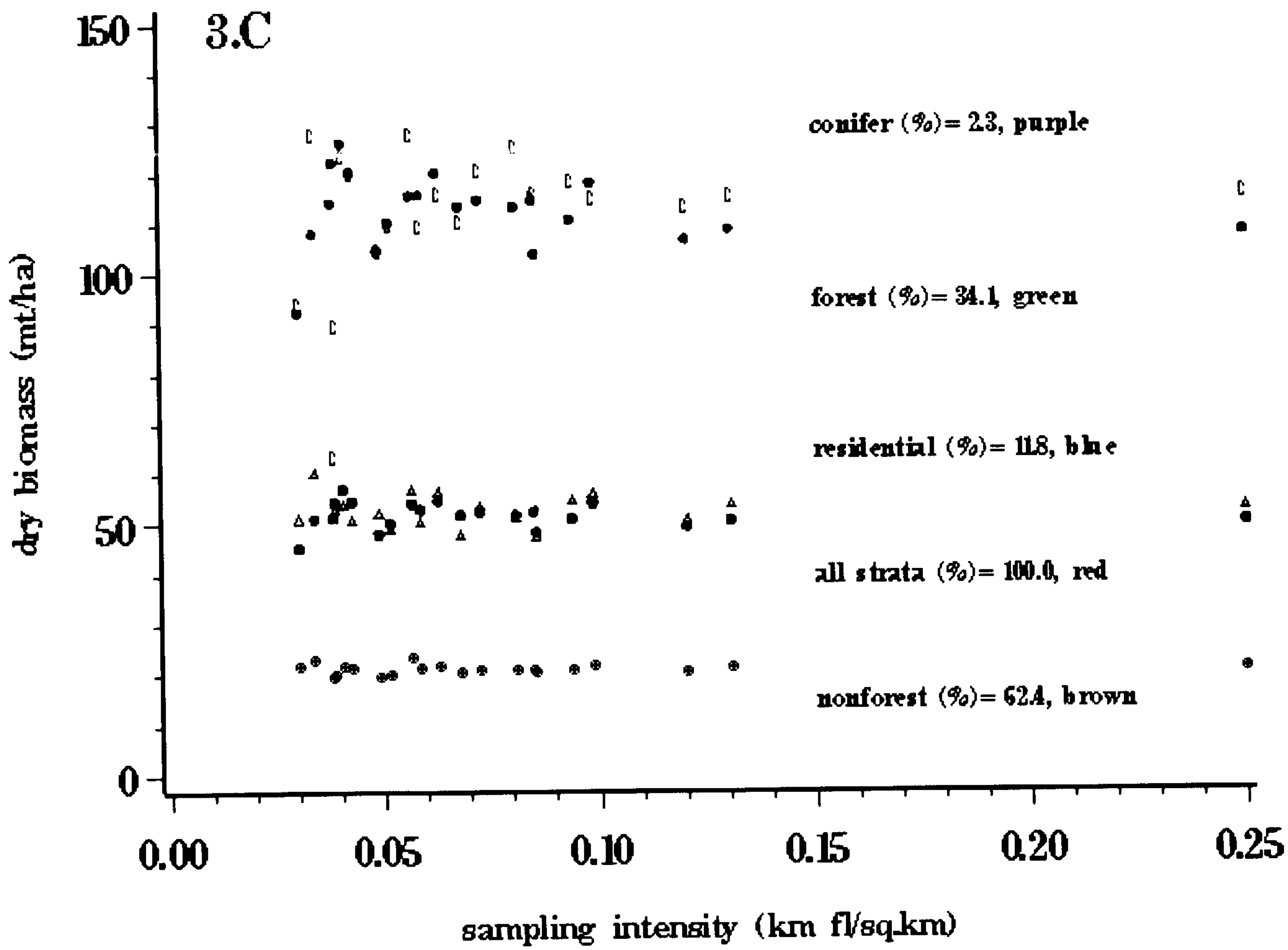
Sussex County – Total AG Dry Biomass (mtons) per hectare

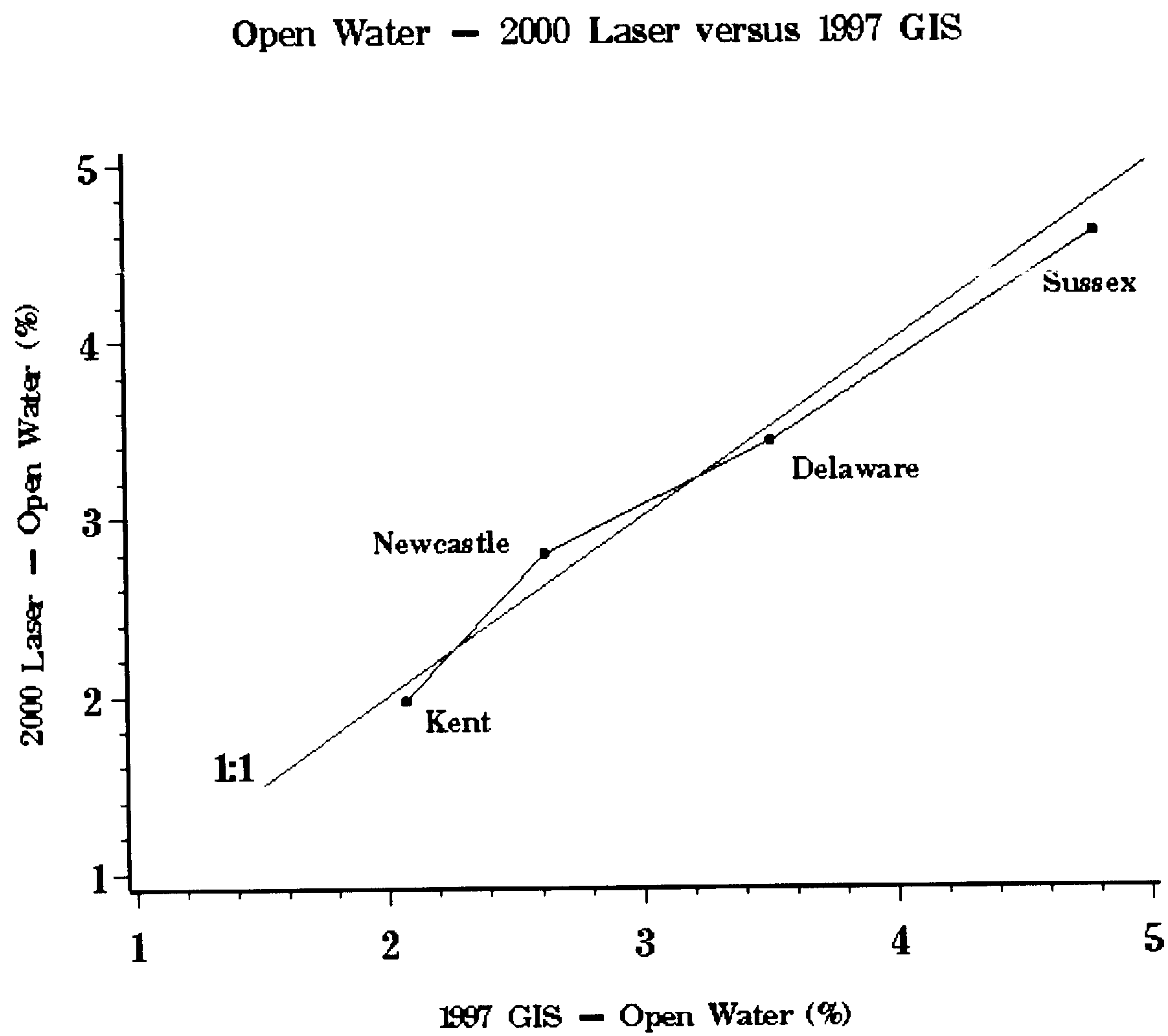
County Area: 2538.96 sq. km.



# Delaware – Total AG Dry Biomass (mtons) per hectare

State Area: 5205.43 sq. km.

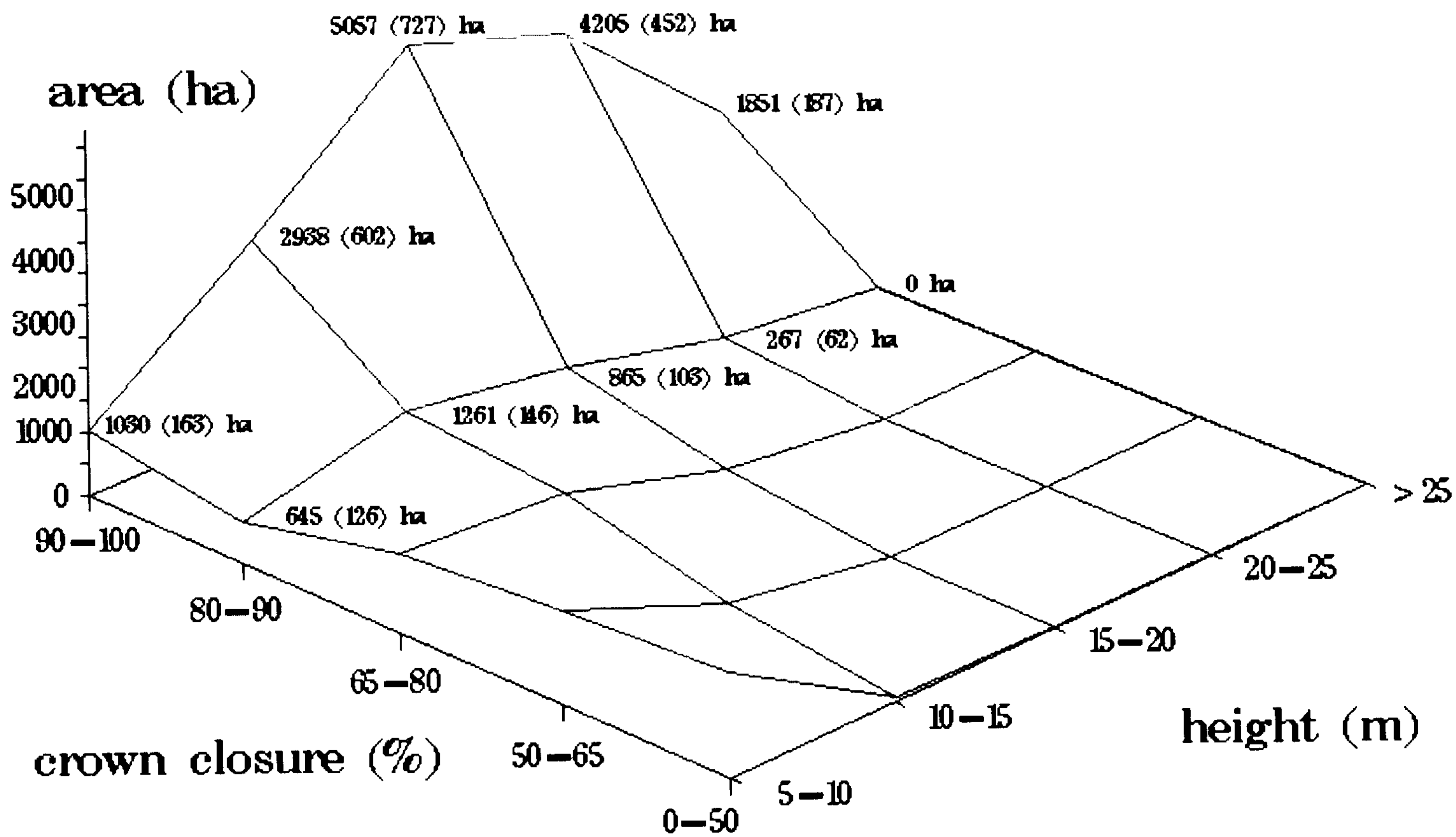




Open Water — 2000 Laser versus 1997 GIS
2000 Laser — Open Water (%)
1997 GIS — Open Water (%)
1:1
Sussex
Delaware
Newcastle
Kent
1
2
3
4
5

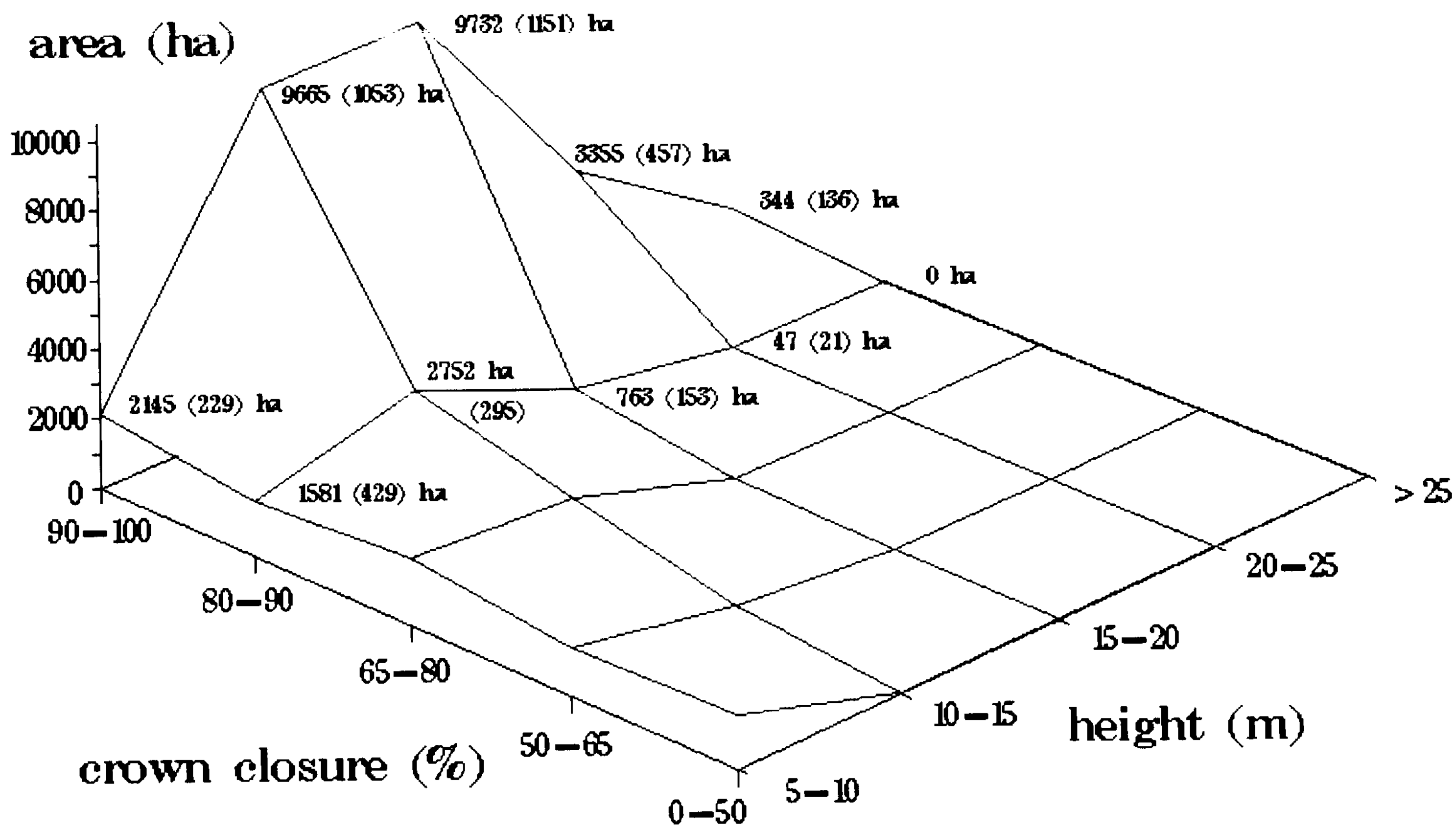
**Newcastle County Height—Closure Areas**

County Area: 112412 ha



**Kent County Height–Closure Areas**

County Area: 154234 ha



**Sussex County Height—Closure Areas**

County Area: 253896 ha