2 The Forest Inventory and Analysis Sampling Frame

Gregory A. Reams, William D. Smith,
Mark H. Hansen, William A. Bechtold,
Francis A. Roesch, and Gretchen G. Moisen[1]

2.1 Overview of Forest Inventory and Analysis Sampling Design

2.1.1 Forest Inventory and Analysis Populations

For purposes of sampling and estimation, Forest Inventory and Analysis (FIA) subdivides the total land area of the United States into mutually exclusive **populations**[2] and **subpopulations**. Populations are usually defined by county **boundaries** or by public ownerships that may or may not cross county boundaries (e.g., national forests). In cases where the sample size for individual counties is insufficient, groups of counties may be combined into a **super-county** to form a single population with adequate sample size. Based on user request, counties occasionally are split into subpopulations to accommodate enumerated (known) acreages supplied by public agencies (e.g., National Forest System and The Bureau of Land Management). This is done to ensure that FIA totals match the county-level acreages reported by the requesting agencies. Each FIA population and subpopulation has a known number of **plots** and a known area of land, obtained from the U.S. Census Bureau, from which population estimates are derived. Each is sampled and processed as a separate entity, so estimates of grand totals and their variances for groups of populations and subpopulations are additive. For example, State-level estimates are obtained by totaling the estimates from all populations and subpopulations bounded by the State.

Note that FIA estimation is based on land area which excludes **census water** (4.5 acres in size and at least 200 feet wide). Census water is thus subtracted

---

[1] Gregory A. Reams, FIA National Program Manager, USDA Forest Service, 1601 North Kent Street, Arlington, VA 22209; William D. Smith, Research Quantitative Ecologist, USDA Forest Service, Southern Research Station, Research Triangle Park, NC 27709; Mark H. Hansen, Research Forester, USDA Forest Service, North Central Research Station, St. Paul, MN 55108; William A. Bechtold, Research Forester, USDA Forest Service, Southern Research Station, Asheville, NC 28802; Francis A. Roesch, Mathematical Statistician, USDA Forest Service, Southern Research Station, Asheville, NC 28802; and Gretchen G. Moisen, Mathematical Statistician, USDA Forest Service, Rocky Mountain Research Station, Ogden, UT 84401.

[2] First use of a glossary term in each chapter is in bold face.

from the total area of land and water at the beginning of the estimation process. We anticipate that estimation eventually will be based on total area, including census water, when precise digitized census water boundaries become available from the U.S. Census Bureau. The capacity to tabulate the area of census water from digitized data will improve FIA's ability to generate forest statistics for user-defined polygons.

FIA engages in three types of sampling—**Phase 1**, **Phase 2**, and **Phase 3**. All three types are performed for each population or subpopulation of interest. The sample points associated with each phase are subsets of the previous phase, but from the descriptions that follow it should be clear that this is not intended to be an application of classical three-phase sampling.

2.1.2 Phase 1

Phase 1 is designed to reduce variance through **stratification**. Although the details have differed among FIA units, all have used **double sampling for stratification** since aerial photography became widespread in the 1950s. For a given population of interest, a supplemental grid of Phase 1 sample points (i.e., photo points or satellite **pixels**) is superimposed over the Phase 2 sample points, such that Phase 2 can be viewed as a subset of Phase 1. All sample points, both Phase 1 and 2, are then assigned to **strata** based on their classification from remote-sensing imagery.

The remote sensing medium selected to accomplish Phase 1 is left to the discretion of the FIA regions, but satellite imagery is replacing aerial photography as discussed in section 2.1.2.1. The number of photo points or pixels classified and the frequency of Phase 1 sampling are regional decisions. The number of strata, if any, and the definitions of these strata also are left to the discretion of the regions, but most recognize a minimum of two—**forest** and **nonforest**. Factors influencing the details of Phase 1 stratification include the homogeneity of the population; the timing, availability, and cost of remote imagery; and the availability of personnel available to perform the work. Nationally **prescribed core** methodology related to Phase 1 is limited to:

- If available, acquisition of new imagery at least once for each new cycle of panel measurements (e.g., every 5 years for States on a 5-year panel system)
- Application of the double sampling for stratification estimation techniques described in chapter 4

The only difference in estimation techniques associated with the details of Phase 1 sampling is whether the strata weights are treated as estimated or known. With wall-to-wall satellite classification, strata weights are known. When photo points or satellite pixels are sampled, strata weights are treated as estimated. Even when wall-to-wall imagery is available, pixels are often sampled to ease the computational burdens of working with high-resolution imagery and multiple data layers. FIA units thus can choose between two approaches to stratified sampling:

1. The double sampling for stratification approach used when strata weights are estimated (sec. 4.2.2)
2. The **stratified estimation** approach used when the weights are known (sec. 4.2.1)

The choice is largely based on local efficiencies, but most units are moving toward the latter as satellite imagery replaces aerial photography.

2.1.2.1 Aerial Photography vs. Satellite Imagery

Since the 1950s and prior to satellite imagery, FIA used aerial photography to assign plots to strata at Phase 1 and in some cases to estimate forest area (Bickford 1952). The intensity of photo plots has varied over time and among FIA regions, ranging from one photo point per 230 acres in the South and Northeast, to one point per 248 acres in the Rocky Mountain region (assuming that each photo point has a radius of 50 feet). Photo points usually were established by overlaying a systematic grid on 1:40,000 black-and-white aerial photos, although other scales (e.g., 1:20,000) and media (e.g., color infrared) also have been used. Decisions regarding scale and media have been based on availability, timing, price, and coverage. A good historical overview of FIA Phase 1 sampling is provided by Frayer and Furnival (1999).

All FIA units have begun replacing photo-point classifications with satellite-based (pixel) classifications of land use. The primary source of FIA Phase 1 satellite imagery is the Landsat Thematic Mapper (TM) series. The TM sensor has a repeat cycle of 16 days and a swath width of 115 miles. This multispectral sensor has 6 nonthermal bands—three in the visible, one in the near infrared, and two in the midinfrared, all with 100-foot resolution. TM is the remote sensing platform of choice due to:

- Historic and planned continuity of wall-to-wall land cover classifications
- Moderate spatial and spectral resolution of the sensor
- A scale of resolution appropriate for matching ground-truth units to pixels for the computation of standard error estimates

Because TM satellite imagery has been used more often and with more success for forest assessments than any other satellite sensor, there is a vast body of literature on classification algorithms using various analytical approaches including **unsupervised**, **supervised**, and various **hybrid classification** approaches. From this work it is known that land cover classification accuracies > 80 percent are difficult to achieve with satellite imagery, which is notably less than the 95-percent accuracies attained by experienced FIA photo interpreters. This difference in accuracy should not be disregarded because the gap is even wider when classification is attempted beyond forest and nonforest cover types. It also means that aerial photography will remain a useful tool even after the transition to satellite imagery is complete. Although photo classification is demonstrably more accurate than satellite classification on a point-by-point basis, satellite classification has several distinct advantages when compared to aerial photos (Wayman and others 2001, Wynne and others 1999):

- Satellite classification accuracy is expected to improve as classification algorithms and ancillary ground-truth data improve.
- The gain in precision from 80 percent accuracy with wall-to-wall satellite coverage offsets the 95 percent accuracy attained from a comparatively small sample of photo points.
- Satellite-derived thematic maps usually are generated from objective and consistent processes (although some human interpretation is needed to label classified cover types and other land features).
- Satellite imagery provides an opportunity for more frequent updates.
- Spectral change detection is relatively easy and particularly useful when analyzing change associated with timber removals, as well as catastrophic disturbances.
- Spatially explicit enumerations of the entire landscape (i.e., maps) can be automated.

The FIA Program has national precision standards of 3 percent per million acres of **timberland** and 5 percent per billion cubic feet of growing-stock volume in the Eastern United States. Recent Phase 1 applications using TM-based classifications for the National Land Cover Data (NLCD) indicate that FIA can come very close to meeting the precision standards (Hansen 2001). With a forest/nonforest stratification based on the most recent NLCD, the FIA North Central Research Station region produced sampling errors ranging from 2.83 to 3.71 percent per million acres of timberlands for four States (Indiana, Iowa, Minnesota, and Missouri). For these same States, sampling errors ranged from 6.03 to 6.73 percent per billion cubic feet of growing-stock volume.

Improved Phase 1 techniques offer an efficient opportunity to meet or exceed the stated precision goals, and the FIA Program plans to continue investigating alternative methods for improved stratification. TM image classification can be improved by auxiliary information from other sources (see Web page http://www.fs.fed.us/ne/rsb). Potentially useful auxiliary information currently under study includes the Gap Analysis Program, the Moderate Resolution Imaging Spectroradiometer, the Natural Resource Information System, topographic and ecological data layers, and high-resolution low-altitude photography and satellite images. Use of high-resolution imagery, with either visual or digital interpretation, may increase FIA's ability to classify highly fragmented landscapes more precisely, but it may not be cost effective for more general applications. One alternative to stratification, which has been used with moderate success in Alaska, is use of regression methods to correlate plot data with individual pixel values. This allows pixels to be summed to provide estimates for the area of interest and is actively being investigated for small-area applications. However, because it can become quite cumbersome operationally, this technique is not ready for general application at the State level (Scott 1986).

2.1.3 Phase 2

Phase 2 relates to FIA's network of permanent ground plots, which has a spatial sampling intensity of approximately one plot per 6,000 acres. Field crews install, monument, and measure ground plots if any portion of a plot contains a **forest land** use. Detailed field remeasurements of forest plots are repeated at regular intervals as long as the plots remain in forest (note that protocols for handling plots that cannot be sampled due to access restrictions are discussed in section 3.4.3). Nonforest plots are assigned a **nonforest** use code (**nonforest land**, census water, or **noncensus water**) and checked at each scheduled inventory for potential reversion to forest. Forest plots are installed if reversion occurs. Note that neither LANDSAT imagery nor stratification is used in the decision to visit a ground plot. Field crews physically visit all ground plots that have any chance of being forested. However, to avoid unnecessary costs in extensive areas of nonforest or in inner cities, some FIA regions use recent aerial photography to identify and assign land uses to plots that obviously have no chance of being forested. Phase 2 plots are assigned to strata based on their classification at Phase 1, which may or may not be consistent with the land use assigned by field crews at Phase 2. Discrepancies can result from misclassification or from changes since the imagery was obtained, and are factored into the estimation process described in chapter 4.

FIA's ongoing remeasurement process is designed to accommodate changes in protocols and plot design over time. This is accomplished by remeasuring the previous plot installation at each new inventory. For example, as FIA moves from horizontal point samples to fixed-area **mapped plots**, the program is being careful to preserve change estimates that span the transition period. To complete this calibration over time, the horizontal point samples are remeasured for change estimates when new mapped plots are installed. The mapped plots will be remeasured at future visits.

To be classified as forest, an area must be at least 10 percent stocked with tree species, at least 1 acre in size, and at least 120 feet wide. **Stocking** protocols are further discussed in section 3.3.2.2.1, as well as the supplementary document "National Algorithms for Stocking Class, Stand Size Class, and Forest Type" at http://srsfia2.fs.fed.us/publicweb/statistics_band/stat_documents.htm. Previously forested land that is not stocked, and which has not been developed to another land use, is still considered forest (e.g., clearcuts). Land that meets the minimum requirements for forest, but is developed for a nonforest land use, is considered nonforest (e.g., city parks or campgrounds).

Discussions are underway within the FIA Program about presenting both use and cover estimates of land area. Researchers involved with remote sensing have been exploring the development of landcover estimates based on percent tree-crown cover, but this work has yet to be used operationally. The most significant impediment to estimating **attributes** of interest by cover class is the cost of increasing the scope of FIA such that field crews are required to measure trees and detailed area attributes on land that is simply classified as nonforest under current protocols.

2.1.4 Phase 3

Phase 3 plots include all of the features of Phase 2, plus additional measurements such as tree-crown assessment, soil sampling, lichen communities, understory vegetation structure, ozone **bioindicators**, and **down woody material**. Every 16th Phase 2 plot is also a Phase 3 plot, so Phase 3 sample intensity is approximately one plot per 96,000 acres. All Phase 3 plots are combined with Phase 2 plots for Phase 2-based estimations of attributes common to both plot types (i.e., double sampling for stratification applies). Attributes unique to Phase 3 are estimated directly from the Phase 3 subset. Use of Phase 1 stratification and Phase 2 samples to enhance the estimation of attributes unique to Phase 3 is currently being studied. Because Phase 3 is a subsample of Phase 2, the use of double sampling with regression is being considered for estimating some Phase 3 attributes. Detailed estimation procedures for attributes specific to Phase 3 will be provided in future documentation.

A summary of the general attributes associated with Phases 1, 2, and 3 is provided in table 2.1.

Table 2.1—Summary of general attributes associated with FIA Phase 1, Phase 2, and Phase 3 sampling

Attribute	Phase 1	Phase 2	Phase 3
Sample type	Photo point or satellite pixel	Ground plot, subset of Phase 1	Ground plot, subset of Phase 2
Sample configuration	Point or pixel	Cluster of four 1/300-acre microplots, four 1/24-acre subplots, and optional four 1/4-acre macroplots	Same as Phase 2[a]
Purpose	Stratification[b] of the landscape for the purpose of variance reduction	Samples FIA traditional attributes of interest, primarily related to tree species of all sizes	Samples FIA traditional attributes of interest,[c] plus additional attributes associated with forest health
Tesselation method	Supplemental regional grid superimposed over the population of interest[d]	Systematic national hexagonal cell grid	Systematic national hexagonal cell grid (subset of Phase 2 grid)
Base-grid intensity	At the discretion of each FIA unit	One plot per every 6,000-acre hexagonal cell	One plot per every 1/16 6,000-acre hexagonal cell (i.e., one per 96,000 acres)

FIA = Forest Inventory and Analysis.

[a] Note that additional sample designs associated with forest health indicators (to be described in a future document) are superimposed over the Phase 2 sample configuration on Phase 3 plots.

[b] Most FIA units recognize a minimum of two strata—forest and nonforest. Census water is currently subtracted from the total area prior to any stratification or estimation.

[c] Phase 3 plots also double as Phase 2 plots for estimation of attributes associated with Phase 2. Phase 3 plots are unique only when used to estimate attributes unique to Phase 3.

[d] Regional Phase 1 grids are systematic grids of varying density (up to wall-to-wall) that are not necessarily linked to the national hexagonal grid. The only prescribed requirement is that Phase 2 plot centers must be a subset of the Phase 1 points.

2.2 Development of the Phase 2/Phase 3 Sampling Frame

With passage of the 1998 Farm Bill [The Agricultural Research, Extension, and Education Reform Act of 1998 (Public Law 105–185)], Congress directed major changes in the way FIA conducts inventories. This legislation prescribes an annual inventory where a proportion of plots in each State must be measured every year. The switch from a variety of regional **periodic surveys** to a nationally standardized annual inventory required FIA to implement a new sampling frame. The 1998 law also precipitated the integration of Forest Health Monitoring (FHM) with FIA. When the two programs merged, FHM had already implemented a national sampling frame with a plot network that was systematically divided into panels measured on an annual basis. A national sampling grid was viewed as a more convenient and consistent method for tessellating the landscape and populating the sample frame than the county-by-county approach previously used by most FIA units; especially because county boundaries occasionally change, and counties may be divided into different subpopulations at different times. When the two programs integrated it was decided to build on the existing FHM sampling frame, where the FHM panels were redefined as subpanels of the larger FIA plot network.

2.2.1 Hexagonal Sampling Frame

The U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program originally developed the sampling frame used by FHM (Overton and others 1990, White and others 1992). This framework is actually based on a triangular grid, but the cells surrounding each point on a triangular grid form a hexagonal shape, so the sampling frame can also be viewed as a network of hexagonal cells. The hexagonal frame was projected onto the landscape by centering a large base hexagon over the continental United States (fig. 2.1). Similar hexagons were then extended from the base hexagon to tessellate the planet. The result is described as a truncated icosahedron (White and others 1992) made up of 20 hexagon faces and 12 pentagon faces, which give the framework a "soccer ball" appearance (fig. 2.2). To achieve the desired sample intensity for FHM, the base hexagon was then subdivided into approximately 28,000 smaller hexagons with centers about 17 miles apart. To avoid alignment with property boundaries that follow the public land survey system, the hexagon configuration was randomly offset from cardinal directions. To accommodate the sampling intensity and frequency desired by FIA, the hexagonal sampling frame was further modified as described in the next section 2.2.2.

Figure 2.1—Base hexagon positioned over the conterminous United States.

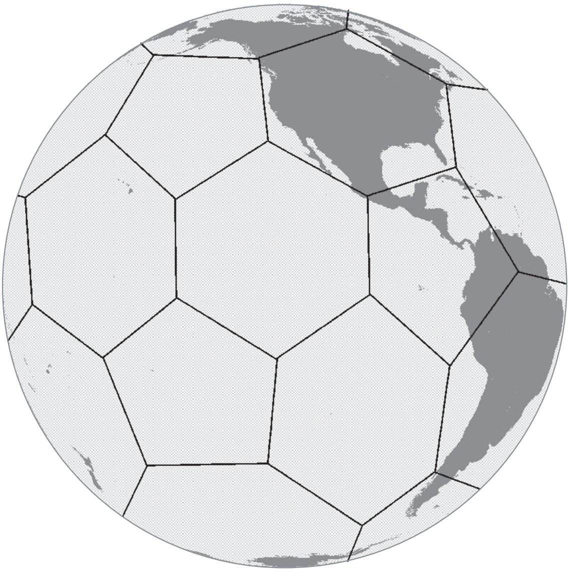

Figure 2.2—Truncated icosahedron made up of 20 hexagon faces and 12 pentagon faces.

2.2.2 Division of the Sampling Frame into Panels

The original FHM sampling frame conveniently accommodated 3-, 4-, 7-, 9-, and 11-panel rotations, and multiples of these. In other words, the centers of the hexagons in a given panel formed a triangular pattern of equidistant points for these panel rotations. Figure 2.3 shows the triangular pattern of the four-panel system originally used for FHM. FIA requires a five-panel rotation to accommodate the measurement frequency mandated by the 1998 Farm Bill (20 percent per year). Unfortunately, the five-panel system does not conform to an equidistant triangular configuration.

To satisfy the desired sampling frequency for FIA, the program used a parallelogram-shaped pattern of hexagon centers to assign hexagons to panels (fig. 2.4). Although hexagons within a given panel are no longer

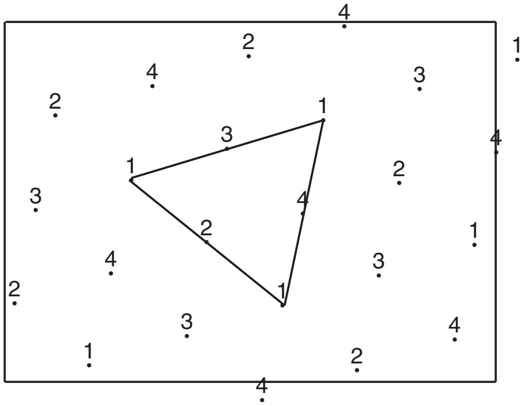

Figure 2.3—Hexagon panel assignments illustrating the triangular pattern of a four-panel rotation.

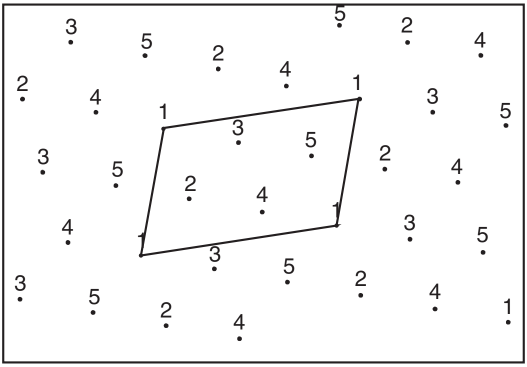

Figure 2.4—Hexagon panel assignments illustrating the parallelogram pattern of a five-panel rotation.

equidistant, the parallelogram configuration provides the most uniform spatial arrangement possible for five-panel rotations, and multiples thereof.

To satisfy the desired sampling intensity for FIA, FHM hexagons (approximately 160,000 acres) were subdivided in 27 smaller hexagons, resulting in hexagons of 5,937 acres. Figure 2.5 [from Brand and others (2000)] shows the spatial arrangement of the FIA hexagons relative to the original FHM hexagons. Figure 2.6 from Brand and others (2000) details the systematic coverage resulting from the panel assignment process. Again, note the parallelogram pattern that results from connecting the hexagons in any given panel.

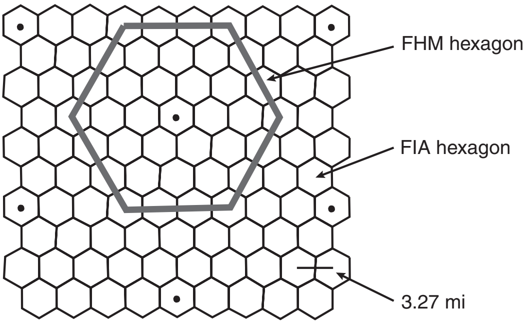

Figure 2.5—The FIA hexagon lattice (each black dot is at the center of an FHM hexagon).

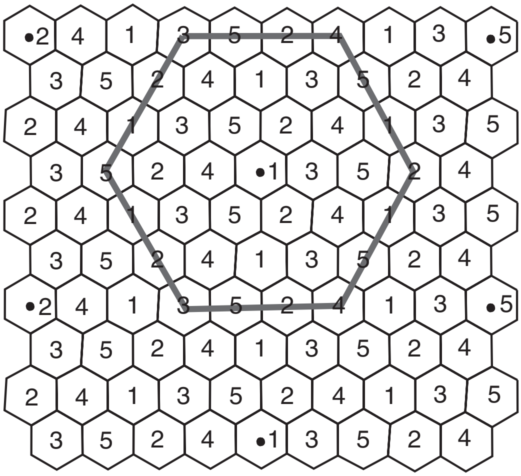

Figure 2.6—Assignment of hexagons to one of five panels (shown by number).

2.2.3 Populating the Sampling Frame

Once the FIA hexagon frame was established, and hexagons were assigned to panels, one field plot was allotted to each hexagon as follows:

1. If the FIA hexagon contained an FHM plot, the existing FHM plot was selected.
2. If not, then an existing FIA plot was selected.
3. If there were multiple FIA plots in the hexagon, the one closest to hexagon center was selected and the others were abandoned.
4. If there were no FHM or FIA plots in the hexagon, a new sample location was selected based on a random azimuth and distance from hexagon center.

Because FHM plots originally were measured on a four-panel annual system, some additional constraints were necessary when reassigning those plots to FIA panels. The following constraints resulted in minor perturbations of the parallelogram pattern, which were accepted so that historic measurement sequences and cohorts would remain unchanged:

1. No existing FHM plots were dropped.
2. FHM panels retained their historic measurement sequence, so colocated Phase 2 and Phase 3 plots kept their preexisting FHM panel number (this constraint was relaxed in States that had intensified FHM sampling frames).
3. The subset of Phase 3 plots was increased by 20 percent to accommodate a fifth panel (to preserve the same annual sampling intensity established under the four-panel FHM system).

Additional technical details related to panel assignments and population of the sampling frame are available in the supplementary document “The Hexagon/Panel System for Selecting FIA Plots Under an Annual Inventory” at http://srsfia2.fs.fed.us/publicweb/statistics_band/stat_documents.htm.

2.2.4 Deviations from the Five-Panel Annual System

Panels and their associated plots, are scheduled for measurement based on their panel assignment. Panels are measured in sequence, one at a time. After all five panels have been completed the process is repeated. Ideally, exactly one panel per year would be completed in each State. However, the realities of budgetary constraints and logistical problems (e.g., forest fires) prevent some States from being inventoried at the prescribed rate of one panel per year. This situation can lead to “panel creep,” where the length of time to complete an inventory panel exceeds 1 year. This situation is most common in States that do not have additional resources to move from the federally financed 7-year **cycle length** to a 5-year cycle length.

The concept of subpaneling the five-panel system is an alternative that will be implemented if the measurement cycle becomes too protracted. A number of subpaneling schemes could be developed to yield timelier inventory results and still retain uniform spatial coverage. For example, the FIA Western Pacific Northwest and Rocky Mountain regions are now funded to collect data on a 10-year cycle. To accommodate the funding disparity, those two regions are using the five-panel design where each panel has been divided into two subpanels (each with complete spatial coverage); one subpanel is scheduled for measurement each year. This is analogous to a 10-panel system.

2.2.5 Theoretical Basis for the FIA Sampling Frame

It is clear from the previous discussion that the current FIA sampling frame was forged from a variety of preexisting regional FIA and national FHM sampling frames. The goal of this approach was to maintain linkage with historical data to the extent possible (to preserve temporal consistency and continuity for trend estimation), and to smooth the transition from the numerous variations of periodic systems. This approach relates to established sampling theory in a number of ways. In this section we give one general description of the joint distribution resulting from the marriage of various periodic designs with the common annual design.

Sample plots are linked to a systematic triangular grid with time-interpenetrating panels. In a triangular grid, the cells surrounding each grid point are hexagonal and the grid is systematically divided into panels. Assuming one panel per year is measured for T consecutive years, then every T years the panel measurement sequence begins again. If panel 1 were measured in 1998, it also would be measured in $1998+T$, $1998+2T$, and so on. Panel 2 would be measured in 1999, $1999+T$, and $1999+2T$. Of the numerous methods that might have been used to choose existing sample-point locations for retention in the new design, the preferred option was to assign existing plots to the nearest triangular grid point (i.e., hexagon center). Extra plots in each grid cell (hexagon) were subsequently deleted, and new plots were randomly added to empty grid cells. Although the methodology does not produce a regular grid of sample points at a fine scale (i.e., grid-point intersections); it does at a coarse scale (i.e., grid-point cells). This feature has the advantage of masking the exact location of ground plots, which is required by law.

Assume that the sample points from the entire collection of periodic inventories constitute a random sample from the infinite set of points contained within the boundaries of the United States. Panel assignments are made to hexagons in a systematic fashion. Although panel assignments are not random with respect to the triangular grid, they are random with respect to the underlying area-based population, due to the random establishment of the grid combined with a scale-dependent assumption of randomly arranged population elements. The entire sampling frame is a three-dimensional cube—two dimensions incorporate the land area and the third represents time.

Assume that random tessellation of the land area into identical, mutually exclusive hexagons (*H*) defines two samples:

$S_1 =$ A selection from the previous randomly chosen plot locations, where each chosen point is assigned to the hexagon from within which it was selected. The individual element of S_1 for each hexagon *j* is denoted s_{1j}.

$S_2 =$ A sample of random points resulting from a random tessellation of the land area into identical, mutually exclusive hexagons. A random point is chosen for the sample from the infinite set of points within each hexagon. The individual element of S_2 for each hexagon *j* is denoted s_{2j}.

Let:

$$I_j = \begin{cases} 1 & \text{iff a previous sample point was selected from within hexagon } j \\ 0 & \text{otherwise} \end{cases}$$

Then a single sample point is chosen for each hexagon *j* such that

$$s_j = I_j s_{1j} + (1 - I_j) s_{2j}, \qquad j = 1, \ldots, N\,.$$

I_j randomly selects an element from 1 of 2 random samples. We also assume that *H* randomly assigns one of the *T* panels to each sample element.

Adding the dimension of time to the two dimensions that constitute the land area of the United States produces a population which is a three-dimensional cube. The primary **sampling unit** (PSU) is a series of line segments, linear in time. That is, when the time dimension is collapsed down onto the area dimensions, each series of line segments collectively appear as a single point on the area. When the area dimensions are collapsed down to the time dimension, each line segment within a series is of an approximate length of 1 day. Individual segments occur every $T \pm 1$ years within each series.

Within a sufficiently small segment of time, all points within the land area dimensions of the volume common to each area segment created by the overlapping inclusion areas of all possible subsets of trees occurring on the land area [in the sense of Roesch and others (1993)] could be viewed as a temporally specific sampling unit. However, because these segments change over time, the PSU appears as a point in the temporally specific land area dimensions of the cube. That is, if we slice the population into, say, annual volumes, such that land area constitutes the base and time constitutes the height, and then view the annual subpopulation from the top, we'll observe a set of 1/T points on the land area base. Each point exists within a temporally specific inclusion area for a specific subset of trees. The temporal slices actually could be of any height; however, the thinner the slice, the smaller the sample per land area of interest. The wider the slice, the fuzzier the segment boundaries, as the subsets of trees change. For most of FIA's purposes, annual slices will constitute the minimum height that forms a reasonable compromise between temporal specificity and land-area generality.

The plot measurements provide support to the point (line) from which they were chosen. The plot measurements for an individual sample point (sample line) are multiplied by the inverse of the land area (land area/temporal volume) upon which they were based, resulting in a value per acre for each sample point (a value per acre per temporal unit for each sample line). The collection of sample points per area of interest (sample lines per area/temporal volume) contributes to the estimates for that area (area/time volume). The sampling units have known inclusion probabilities, which are used in the estimation equations.

This discussion supports the detailed estimation procedures described in chapter 4, which assumes that the FIA **systematic sample** for Phase 2 and 3 can be treated as a **simple random sample**. The systematic coverage provided by the hexagonal grid eliminates the clumping of samples and loss of precision that would occur with a purely random assignment of plots. The use of the hexagonal grid also increases the chances of sampling infrequent forest types. Given that plot locations are randomly assigned within hexagons, the chance of the sample network coinciding with a systematic land feature or spatially periodic phenomenon is greatly reduced. Research on the periodicity concern indicates that the hypothetical has little chance of occurring (Milne 1959). Cochran (1977) provides the following justification for the use of simple random-sample-based estimates for systematic samples:

> Consider all *N!* finite populations which are formed by the *N!* permutations and any set of numbers $y_1, y_2, \ldots, y_N$. Then, on the average over these finite populations, $E(V_{sy}) = V_{ran}$. Note that V_{ran} is the same for all permutations.

Madow and Madow (1944) state that if the order of the items in a specific population can be regarded as drawn at random from the *N!* permutations, systematic sampling is (on average) equivalent to simple random sampling.

2.3 Literature Cited

Bickford, C.A. 1952. The sampling design used in the forest survey of the Northeast. Journal of Forestry. 50(4): 290-293.

Brand, G.J.; Nelson, M.D.; Wendt, D.G.; Nimerfro, K.K. 2000. The hexagon/panel system for selecting FIA plots under an annual forest inventory. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C., eds. Proceedings of the first annual forest inventory and analysis symposium. Gen. Tech. Rep. NC–213. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 8-13.

Cochran, W.G. 1977. Sampling techniques. 3rd ed. New York: John Wiley. 428 p.

Frayer, W.E.; Furnival, G. M. 1999. Forest survey sampling designs: a history. Journal of Forestry. 97(12): 4-10.

Hansen, M.H. 2001. Remote sensing precision requirements for FIA estimation. In: Reams, G.A.; McRoberts, R.E.; Van Deusen, P.C., eds. Proceedings of the second annual forest inventory and analysis symposium. Gen. Tech. Rep. SRS–47. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station: 43-51.

Madow, W.G.; Madow, L.H. 1944. On the theory of systematic sampling. Annals of Mathematical Statistics. 15: 1-24.

Milne, A. 1959. The centric systematic area sample treated as a random sample. Biometrics. 15: 270-297.

Overton, W.S.; White, D.; Stevens, D.L. 1990. Design report for EMAP (environmental monitoring and assessment program). EPA/600/3–91/053. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development. 43 p.

Roesch, F.A., Jr.; Green, E.J.; Scott, C.T. 1993. An alternative view of forest sampling. Survey Methodology. 19(2): 199-204.

Scott, C.T. 1986. An evaluation of sampling with partial replacement. In: Oderwald, R.G.; Burkhart, H.E.; Burk, T.E., eds. Use of auxiliary information in natural resource inventories. SAF 86–01. Blacksburg, VA: Society of American Foresters: 74-79.

Wayman, J.P.; Wynne, R.H.; Scrivani, J.A.; Reams, G.A. 2001. Landsat TM-bases forest area estimation using iterative guided spectral class rejection. Photogrammetric Engineering and Remote Sensing. 67(10): 1155-1166.

White, D.; Kimerling, A.J.; Overton, W.S. 1992. Cartographic and geometric components of a global sampling design for environmental monitoring. Cartography and Geographic Information Systems. 19: 5-22.

Wynne, R.H.; Oderwald, R.G.; Reams, G.A.; Scrivani, J.A. 1999. Optical remote sensing for forest area estimation. Journal of Forestry. 98(5): 31-36.